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EXPLORING THE RELATIONSHIP BETWEEN INDOOR AIR QUALITY AND PHYSICAL SETTING IN SCHOOLS: A MINI REVIEW

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ABSTRACT

Indoor air quality (IAQ) is essential in improving the well-being of pupils, as they spend a significant amount of time inside schools than in any other indoor environment except their home. However, many schools face issues related to insufficient ventilation, improper layout design, and opening position which contribute to elevated indoor pollutant levels and potential long-term health effects. These challenges highlight the need for a systematic literature review to critically analyze and synthesize existing studies, providing a comprehensive understanding of how these physical factors of schools impact IAQ parameters such as carbon dioxide and particulate matter. A systematic review was done by analyzing papers from the SCOPUS database. Information on indoor pollution levels and physical settings were extracted from 34 studies. The findings demonstrate the complex relationships between IAQ parameters and different physical factors such as ventilation strategy, window opening, tightness of door and window, floor height, building design, and finishes. By elucidating the complex relationship between IAQ and the physical setting of buildings, this study provides valuable insights for researchers, building designers, and policymakers aiming to enhance the indoor air environment and promote pupils' health and well-being.

Keywords: *Indoor air quality, Physical setting, School, Indoor pollutant, Building design*

INTRODUCTION

The indoor environment plays an important role in human health, especially in the school context. Schools need to provide an optimal environment for children's learning and development. Since children spend nearly 12% of their time inside the school building, especially in the classroom, it is important to ensure suitable indoor environmental conditions to support their health and well-being (Sadrizadeh et al., 2022). A healthy environment is essential for effective and efficient learning, particularly for children who are susceptible to air pollution (Masekela & Vanker, 2020). Over time, it has been demonstrated that a clean-air environment boosts a pupil's attention span and leads to more participation in the pupil's learning and growth (Salthammer et al., 2016). Hence, it is essential to ensure that the environment is always clean and conducive to optimal health. IAQ characterization in school environments has received particular attention from the scientific community in recent years. In 2015, the World Health Organization (WHO) published a document titled "School Environment: Policies and Current Status" to highlight the importance of IAQ to school administrations (World Health Organization Regional Office for Europe, 2015). The document shows that the degraded IAQ in schools often exceeds the guidelines set by the WHO. Previously, Chatzidiakou et al. (2012) concluded that IAQ levels in schools often do not comply with recommended standards.

Indoor areas tend to allow pollutants to accumulate at higher concentrations than open areas, as noted by Kankaria et al. (2014). This is due to most of the pollutants resulting from indoor sources (Branco et al., 2016; Nunes et al., 2015; Portela et al., 2021; Villanueva et al., 2018). Studies show that schools contain various types of organic and inorganic contaminants, which are potentially toxic and allergenic (Baharfar et al., 2021; Oluchi & Jalaludin, 2018). This finding is in line with the study of Basińska et al. (2019) and Salthammer et al. (2016), who found that IAQ in most classrooms was below acceptable levels. Exposure to poor IAQ can increase the risk of developing allergies, asthma, airway hyperreactivity, and cardiovascular disease. School children's lung health suffers significantly from exposure to fine suspended particles like PM10 and PM2.5, causing significant lung inflammation (Isa et al., 2020).

A global literature review on IAQ in schools shows that carbon dioxide (CO2) and particulate matter (PM), particularly PM10 and PM2.5 are among the most studied pollutants. Three main regions, Asia, Europe, and North America, exhibit the highest concentrations of this PM. Furthermore, Anake & Nnamani (2023) identified CO2 as the second most common pollutant in these regions, often surpassing the threshold limits. For example, a study by Salleh et al. (2016) reported that in air-conditioned classrooms in preschools in Malaysia, concentrations of CO2 exceeded 1000 ppm. Zaeh et al. (2021) added that 26 schools in the United States recorded median CO2 values that exceeded the thresholds recommended by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). The indoor CO2 concentration should be 700 ppm above the outdoor CO2 levels (300–500 ppm). A further study by Monge-Barrio et al. (2022) in 9 secondary schools in Spain also showed similar concerns. They found that CO2 concentrations in the schools did not meet national regulations, with recorded values twice as high as allowed. This happens because of the lack of proper ventilation protocol.

The concentration of suspended PM2.5 and PM10 in schools was also recorded to exceed the allowable threshold. For example, mean indoor PM2.5 (46.9 μg/m3) and PM10 (397.2 μg/m3) concentrations at 6 primary schools in Sari, Northern Iran were higher than the EPA's 24-hour standards (PM2.5:35 μg/m3, PM10:50 μg/m3) (US EPA, 2006) (Mohammadyan et al., 2017). In China, the average indoor PM2.5 and PM10 concentrations in occupied classrooms range from 199 μg/m3 to 149 μg/m3 and 205 μg/m3 to 138 μg/m3, respectively, which is 5 times higher than the requirements of the WHO's (50 μg/mg3 and 25 μg/mg3 for PM10 and PM2.5, respectively) (Peng et al., 2017). These findings indicate widespread problems related to IAQ management in the school context globally (Miao et al., 2023).

Numerous studies have examined the health effects of indoor air pollution, given its high levels in schools. However, the building design perspective's solution to this problem remains underexplored. Several studies suggest that architectural design factors play an important role in determining comfort levels, IAQ, and learning quality in schools (Catalina & Iordache, 2012; Mohammadi, 2022). Based on this issue, the study aims to explore the existing literature on IAQ research in schools, with a specific focus on elements of physical settings that contribute to IAQ. The research objective is to identify the elements of the physical setting that contribute to IAQ in schools.

METHODOLOGY

This literature review uses a content analysis method to collect and categorize research papers to get the most relevant articles (Fauzi et al., 2024). The first stage of this review is collecting research articles from the decade 2010–2024 collected from SCOPUS with the following search strings (Table 1):

Table 1. Search Strings from SCOPUS

Search strings from SCOPUS	TITLE-ABS-KEY (((("Schools" OR "Kindergartens" OR "Preschools") AND ("indoor air pollution" OR "indoor air quality") AND ("architecture" OR "window" OR "space" OR "design")))) AND PUBYEAR > 2009 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j")). Result = 468 articles

This study exclusively focuses on educational institution buildings, which include kindergartens, preschools, and schools only. This focus is chosen due to schools play an important role in the development of learning and their physical environment, including IAQ, has a direct impact on health and learning. From the initial search, a total of 468 results were obtained from the database. These results are then sorted based on the most recent date and closest relevance to IAQ topics and schools using the "relevance" tool provided by SCOPUS.

Next, the screening process is carried out by examining the title and abstract of each result to ensure that only the most relevant studies are selected. Through this process, a total of 24 articles were identified as the most suitable for further study.. The data from this database search is stored in Excel format, while the articles that have been selected for the final analysis are transferred to the Mendeley online reference manager to facilitate reference management and a more systematic literature compilation process. Figure 1 provides a more detailed explanation of this review process.

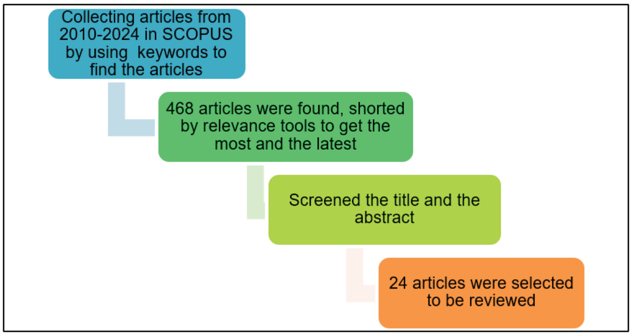

Figure 1. The Stages of the Review

RESULTS AND DISCUSSION

Relationship of Indoor Air Quality Parameter and Physical Setting

Figure 2 is derived from a systematic literature review and illustrates the factors influencing IAQ in schools. Through the review, carbon dioxide (CO2) and particulate matter (PM) were identified as two primary IAQ parameters. In architectural perspective, Berg and Kreiner (2017), simplify the physical setting as 'the immediate built environment' in which organizations operate and with which they are identified. By physical setting, they mean the exterior and interior design of corporate buildings. In this research context, discussion of physical setting includes the setting of spaces that involve architectural aspects. The literature emphasizes that CO2 levels are influenced by the existence of flexible windows and doors, and window opening areas. PM levels are affected by tightness of window/door, type of window, building design, floor level, and floor finishes.

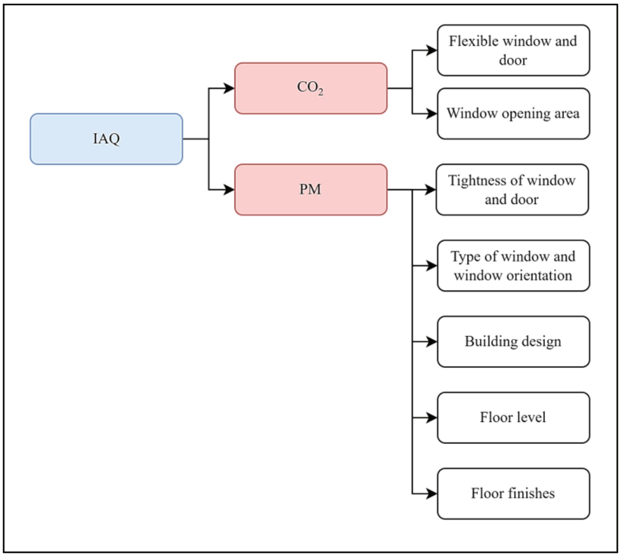

Figure 2. The Relationship between Carbon Dioxide, Particulate Matter and Physical Setting

Carbon dioxide

Every day, humans encounter carbon dioxide (CO2), a naturally occurring gas in the atmosphere. Emissions of CO2 by humans constitute a major portion of indoor pollutants of CO2, in the absence of other sources (e.g., burning fuel) (Shen et al., 2020). Besides the main contribution of CO2 arises from human respiratory, this gas is also emitted by building infrastructure, including sanitation infrastructure, deterioration and/or degradation of building materials, furniture, and lighting (Samudro et al., 2022). CO2 concentrations are often used as a surrogate for the rate of outside air supply to occupants. The oldest known recommendation on IAQ and CO2 level is the one developed by Max von Pettenkofer in 1858. He recommended a maximum level of 1000 ppm for indoor spaces, which is currently also the recommended maximum level in classrooms (Nazaroff, 2012). Levels above 1000 ppm are generally regarded as indicative of ventilation rates that are unacceptable.

Flexible Window and Door

Building openings play an important role in reducing indoor CO2 concentrations. One simple and effective strategy is to open at least a small window for a few minutes during a 60-minute class session or during a break. Research by Sánchez-Fernández et al. (2023) in schools showed that various ventilation strategies had different effects on the level of CO2 concentration reduction. The results of this study found that cross-ventilation was the fastest method to lower CO2 levels, followed by opening windows and doors simultaneously and only opening doors. Figure 3 illustrates the difference in the level of reduction. Korsavi et al. (2022) added that by opening more available windows, not only could the CO2 level be reduced (by 28% of the time), but the operating temperature in the classroom could also be controlled (34% of the time), especially during the non-heating season. These findings overall emphasize the importance of flexible windows and doors that can be easily opened should be incorporated in the design to improve natural ventilation.

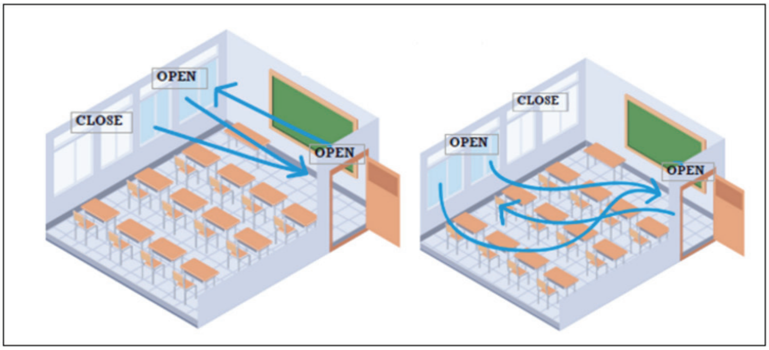

Figure 3 Different Type of Natural Ventilation
Source: Sánchez-Fernández et al. (2023)

Window Opening Area

A strong statistical correlation has been found between the air change rates and the windows opening configuration by means of a window-to-volume ratio between the total opening area and the volume of the classroom. Results show that the European Standard recommendation for air renewal could be achieved by a window opening area of at least 1.5 m2, in the most prevailing Italian classrooms (Ferrari et al., 2023). Miao et al. (2023)

analysed a negative correlation with the opening of windows and doors in the classroom. The correlation is statistically significant with p-values of less than 0.001. These results collectively highlight the importance of optimizing window opening areas to improve IAQ, emphasizing that careful consideration of window and door configurations is essential for achieving effective ventilation.In another research in 785 Danish classrooms, it was shown that leaving the classroom and airing out during breaks reduced the percentage of classrooms with a CO2 concentration higher than 1000 ppm from 60% to 39% compared to a condition when no windows were ever open (Toftum & Clausen, 2023). However, for classrooms operating at or near nominal capacity, longer opening periods and larger window areas become necessary as highlighted by Rodrigues and Feliciano (2019). Therefore, the design of schools needs to pay close attention, particularly in ensuring that windows and doors are designed to maximize natural ventilation.

Particulate Matter

A mixture of microscopic solid and liquid particles suspended in the air is known as particulate matter (PM). Kim et al. (2015) explain that PM is categorized into "inhalable coarse particles" (PM10) with a diameter of 10 micrometers or less, and "fine particles" (PM2.5) smaller than 2.5 micrometers in diameter. When airborne particulates combine with various substances in the air, a chemical reaction occurs, which results in the formation of inorganic (carbon, chlorides, nitrates, sulphates, metals) and organic (polycyclic aromatic hydrocarbons, dioxins, benzene, 1-3 butadiene) compounds (Manisalidis et al., 2020). The source of indoor PM is known to be migration from the outdoor environment as well as certain indoor activities. Different studies worldwide reported that human movement indoors could lead to particle resuspension and deposition (Alves et al., 2013; Hazrin et al., 2017; Othman et al., 2019; Ye et al., 2017). Findings at school environment by Lazović et al. (2015) and findings from other researchers such as Canha et al. (2016), Dumała et al. (2024) and Heudorf et al. (2009) showed that airborne particulate concentration in a classroom increased during its occupied period. In classroom, outdoor pollutants can migrate to the indoor environment through open doors and windows, ventilation and leaks in the building (Mohammadyan et al., 2017; Othman et al., 2019).

Tightness of Window and Door

In recent years, several schools have undertaken window upgrades primarily for aesthetic improvements. Unfortunately, these repairs often neglected considerations of airtightness. As a result, the low airtightness of these rooms permits PM from the outside to infiltrate the indoor environment easily (Jo et al., 2024). This oversight highlights a critical gap in retrofit strategies, emphasizing the need to prioritize airtightness to improve IAQ effectively. Particle penetration is greatly influenced by the air exchange rate, particle size, and crack structure in the building envelope (Sung et al., 2023). Joe et al. (2022) conducted a study on Korean primary schools, providing evidence of the effectiveness of retrofit measures in reducing PM inflows. In particular, the installation of airtight entrance doors and exterior windows results in a lower input/output (I/O) ratio of PM. In addition, the modification reduces the effect of external conditions on internal temperature and humidity. Despite these improvements, unintentional air infiltration and exfiltration can still occur. This issue has been observed in classrooms of three schools, where outdoor air infiltrates and indoor air escapes through the cavity ceiling with acoustic mineral fiber board tiles or perforated ceiling panels, as well as through gaps in doors and windows (Andamon et al., 2023). Therefore, it is crucial to address these additional infiltration pathways to ensure a comprehensive improvement of PM in indoor spaces.

Type of Window and Window Orientation

The type of window was found to correlate with the concentration of fine particles in the classroom, where classrooms equipped with double-glazed windows showed higher concentrations of ultrafine particles (UFP) than classrooms with single-glazed windows (Rufo et al., 2015). Additionally, studies have shown that adjusting window openings can increase the velocity of air entering the classroom. By changing the angle of the louvre, the wider opening area can promote better air flow, which in turn helps in more even distribution of wind throughout the classroom space (Ang et al., 2024). In an external context, a study in Barcelona showed that the contribution of weekday traffic to indoor PM2.5 concentrations varies greatly, with concentrations ranging between 1–10 $\mu g/m^3$ indoors (Amato et al., 2014). The study also found that classrooms with windows oriented directly onto the main road recorded a significantly higher traffic contribution to PM2.5 concentrations, more than double, compared to classrooms with windows facing the inside of a school block or playground. This suggests that window orientation plays an important role in controlling indoor PM levels in schools located near high-traffic areas.

Building Design

School design with hallways plays a crucial role in the overall functionality, safety, and IAQ of the building. Hallways serve as the primary arteries of a school, connecting classrooms, administrative offices, cafeterias, libraries, and other essential spaces. Proper ventilation in hallways is critical to maintaining good IAQ. One critical aspect of achieving this is ensuring secure airflow between hallways and classrooms to prevent pollutants from entering learning spaces (Sung et al., 2023). Extended periods of open hallway windows and doors can mimic the outdoor environment in terms of contaminants, temperature, and humidity.

To combat this issue, replacing classroom external windows and adding insulation can enhance envelope airtightness, thus preventing infiltration and pollutant penetration through the airflow path from outdoors-to-classroom-to-hallway. However,establishing a reverse airflow path from the hallway to the classroom can lead to a degradation in Indoor Air Quality (IAQ) due to the trapping of hallway contaminants within the classroom. To avoid backflow contamination, it is crucial to keep hallway openings closed, install air-conditioning and mechanical filtration systems, or construct a more airtight enclosure between the classroom and the corridor (Figure 4).

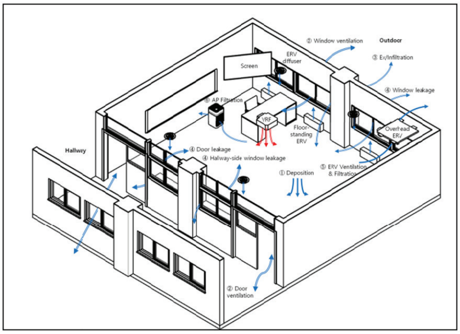

Figure 4. Airflow and Contaminant Transportation in Typical Domestic Classroom

Source: Sung et al. (2023)

Floor level

Understanding the dispersion of PM within school premises is essential for assessing IAQ. Recent research has investigated how PM concentrations vary across different levels of school buildings, offering insights into potential sources and influencing factors. During school hours, the average PM10 levels were recorded as 18 ± 15 µg/m³ on the ground floor, 19 ± 14 µg/m³ on the first floor, and 20 ± 12 µg/m³ on the third floor. Similar patterns were observed for PM2.5 and PM1, indicating that factors beyond building height, such as surrounding building geometry and local weather conditions, significantly affect IAQ (Hama et al., 2023). Elbayoumi et al. (2015) highlighted that the height of the building significantly affects pollutant concentrations, showing that pollutant levels are higher on lower floors than on higher ones. Therefore, the lower floor level had a higher risk of exposure to higher PMs. These contrasting findings underscore the complex nature of indoor pollutant distribution.

Floor Finishes

The average PM concentrations for different types of floors were observed in classrooms. Lower PM10 concentrations were observed by Che et al.(2020) in classrooms with carpet and wood floor materials compared to those with PVC and ceramic tiles. This matter was also observed by Branco et al. (2019), where having hardwood flooring in classrooms, significantly contributed to the increase in both PM2.5 and PM10 concentrations during occupancy in kindergarten. The average PM10 concentrations were 17 ± 12 µg/m3, 25 ± 20 µg/m3 and 33 ± 19 µg/m3 carpet, vinyl and wooden, respectively. Average PM2.5 (PM1) levels were 9 ± 3 (5 ± 2), 12 ± 6 (7 ± 4) and 14 ± 5 (9 ± 4) µg/m3 for carpet, vinyl and wood, respectively. Despite having the lowest PM concentrations, carpet classrooms have the potential to retain more dust and allergens than hard floors, and they may also resuscitate these particles during cleaning activities like vacuuming or sweeping. Due to the three-dimensional structure of the carpet, it has the potential to act as a trap for particles and air pollutants. This makes the carpet a kind of "sink" that keeps dust, allergens, and other contaminants from the air. Therefore, Becher et al. (2018) recommended constant caution should be taken when considering the use of wall-to-wall carpeted floors in schools or kindergartens.

Future Direction

In order to enhance comprehension of the correlation between IAQ and physical settings, it is recommended that future studies broaden the scope beyond CO2 and PM. This expansion should encompass additional pollutants like total volatile organic compounds (TVOC), carbon monoxide (CO), and ozone (O3). Further examining the interaction of these pollutants with building orientation, floor area, and ventilation systems. The orientation of a building has a significant influence on solar exposure and the resulting effects on temperature-related pollutants. The emissions of TVOC are influenced by various architectural designs and room layouts. Studying the impact of window placement on natural ventilation efficiency and pollutant dispersion can offer valuable insights into optimizing window design. By incorporating these elements, future research can formulate comprehensive approaches to improve IAQ.

CONCLUSION

In conclusion, the mini review conducted on IAQ parameters (CO2 and PM) and their correlation with the physical characteristics of buildings reveals a complex relationship that significantly impacts pupils' well-being. The analysis of past research underscores the importance of considering various factors such as flexible window and door, window opening area, tightness of window and door, type of window and window orientation, building design, floor level and floor finishes in order to enhance IAQ in educational settings. By shedding light on this relationship, this study provides valuable insights for researchers, building designers, and policymakers seeking to optimize IAQ. Moving forward, continued research and implementation of evidence-based strategies will be essential in advancing IAQ standards and creating healthier indoor air environments.

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AUTHOR CONTRIBUTIONS

In this study, Intan Bayani spearheaded the conceptualization and searching phase, Nazhatul zalkis and Norazura ensuring the selection of articles within the stipulated keywords and time. The initial draft of the manuscript was primarily crafted by Intan Bayani, with significant contributions from Nadira and Siti Zubaidah, who aided in synthesizing the findings and organizing them into a coherent narrative. Subsequently, Intan Bayani played pivotal roles in critically revising the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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