Towards Health and Comfort: Architectural Design and Indoor Air Quality in Naturally Ventilated Classrooms

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Abstract. The maintenance of adequate indoor environmental quality is crucial for the health and performance of building occupants. In educational buildings, particular attention should be given to air quality due to high occupancy levels and the significant impact that a conducive learning environment can have on a student's lifelong achievements. Existing literature suggests that design strategies can influence air quality by promoting ventilation and air circulation. However, in Brazil, this field of study remains relatively unexplored. Therefore, the aim of this paper is to examine the relationship between architectural features of higher education classrooms and their indoor air quality. To accomplish this, a comprehensive database comprising architectural characteristics of 527 classrooms from a public university that utilizes natural ventilation as the primary air conditioning mode was compiled. The focus was placed on factors that could potentially affect indoor air quality, such as the window-to-wall ratio, the presence of cross ventilation, and occupancy density. The number of air changes per hour was calculated for a representative classroom with and without cross-ventilation, and the results were compared to recommended air renovation rates found in the literature. The findings revealed that only 12% of the database consisted of classrooms with cross-ventilation design in naturally ventilated settings. Moreover, the calculated air renovation rates for cross-ventilated classrooms were 3.8 times higher than those for single-sided ventilated classrooms. Given the limited research on this topic in Brazil, this study aims to contribute to the ongoing discussion and raise awareness about the significance of air quality in academic environments and its correlation with architectural design.

Keywords: Classrooms · indoor air quality · architectonic characteristics · higher education buildings

1 Introduction

In the global context, humanity is confronted with the paradigm of pursuing sustainable development, a concept that was established in 1987 (CMMAD 1991). This concept has gained further traction due to the mounting evidence of rising temperatures, desertification, floods, and other environmental issues (IPCC 2018). Consequently, international

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community has focused its discussions on the themes of environmental conservation and climate change mitigation, recognizing their significance in safeguarding both our built heritage and the survival of humankind (IPCC 2018). To this end, the United Nations (UN) formulated 17 Sustainable Development Goals (SDGs) in 2015, known as the Agenda 2030 (UN 2015), as a means to promote sustainable development.

In view of the significant global impacts caused by the COVID-19 pandemic (Severe Acute Respiratory Syndrome Coronavirus 2 or SARS-CoV-2), the United Nations has reinforced the importance of pursuing the SDGs as a way to foster a profound and systematic transformation towards a more sustainable and resilient global economy (UN 2020). In addition to the challenges caused by climate change, the global situation resulting from the outbreak of COVID-19, which originated in the city of Wuhan, China in December 2019, has brought with it evidence of new challenges for contemporary civilization (Kruger 2020), including the potential persistence of airborne infections. The ramifications of this situation permeate all areas of society, adding to the preexisting challenges the need for adaptations, particularly in the realms of health and economy.

The concept of healthy buildings is gaining prominence in the literature as an emerging paradigm. A healthy building can be defined as a building, including all its systems, that promotes and sustains the health of its occupants, as a "state of complete physical, mental and social well-being" (Awada et al. 2023, p.10). The ability of buildings to promote health is closely related to the Internal Environmental Quality (IEQ), which stems from factors such as air quality, lighting, acoustics, water quality, spatial organization and thermal comfort, as well as their psychological and physiological effects in occupants (Awada et al. 2023).

Issues arising from poor maintenance, such as moisture stains on walls or ceilings, cracks, degradation, and unpleasant odors from adjacent areas, can significantly impact the health of the occupants. Silva and Lanzinha (2020) emphasize that these problems often go unresolved due to a lack of financial resources or simply for administrative convenience. The inadequate quality of the building directly affects the productivity of its occupants, including professors, researchers or technicians in university spaces. This, in turn, has a direct impact on energy consumption, especially when temporary technical solutions such as air conditioning and/or forced ventilation are employed instead of utilizing natural ventilation systems.

The ventilation rate can serve as an indicator for analyzing the propagation risk of airborne transmission of diseases such as the COVID-19 (Hou et al. 2021). In their study, conducted in three schools in Canada, researchers related measured CO^2 levels with air renovation rates. Authors found that three classrooms presented less than 2 ACH (Air Changes per Hour). They indicated that medium CO^2 levels of 450 ppm is equivalent to more than 10 NR/H (air changes per hour) and recommended different ACH for each analyzed room (8, 3 and 6 ACH for room with 165, 236 and 236 m^3, respectively). Values differed depending on the occupancy, schedule and the size of the room. For example, 8 ACH was recommended for the smaller room, while 3 ACH was recommended for a room where students left very often (Hou et al. 2021).

Another study, in schools of Campinas, São Paulo, Brazil, revealed high concentrations of CO^2 from simulation tests. From the findings, authors indicates that a reduction in the number of occupants associated with air renewal rates greater than 6.5 h^{-1}, have been shown to be effective strategies for reducing CO^2 concentrations in the studied case (Franceschini et al. 2021). In the context of COVID-19, the Pan-American Health Organization recommended 12 ACH for preventing airborne transmission in health-care facilities and 10L/person for nonresidential spaces with natural ventilation (OPAS 2021). It can be seen that literature points to different recommendations of ventilation rates, but it is possible to consider them to stablish some comparative thresholds.

In Brazil, studies relating architectural characteristics of existing classrooms to their air quality are still little explored. The aim of this paper is, then, to investigate the relationship between architectural features of existing higher education classrooms and their indoor air quality. The study focuses on public university environments with natural ventilation.

2 Methods

This work is based on part of a thesis research conducted at the Federal University of Minas Gerais, which aimed to develop a benchmarking regarding energy consumption and thermal comfort in university buildings. As for the thermal comfort, a database of architectural characteristics of classrooms was developed (Garcia 2022). This database could be then used to study further aspects of indoor environmental quality. So, while the earlier phase of the research focused on thermal comfort, this paper presents a focus on the interior air quality.

For the purpose of this research, “classrooms” were defined as spaces equipped with desks and blackboards specifically designed for academic teaching activities. The Federal University of Minas Gerais (UFMG) has a total of 687 classrooms. In order to achieve a confidence level of 95%, a minimum sample size of 247 rooms was required. However, a total of 527 rooms were evaluated, representing approximately 77% of the total classrooms at UFMG. This larger sample size allows for a more robust and representative analysis of the architectural characteristics and their impact on indoor air quality.

The development of the database took into consideration the following variables: space dimensions (width, length and height of the ceiling), orientation of the window, existence or not of cross ventilation, type of window, and percentage of opening of the facade with the window. Other aspects raised were the occupancy density (persons per m^2) and the morphology of insertion of the room in the building (Fig. 1). This refers to the position and layout of the room within the building. It includes factors such as whether the room has only one exposed facade, a shaded facade with a corridor, two exposed walls, or three exposed walls.

All variables were collected through a process that involved the analysis of design plans, conducting on-site visits and the utilization of Google Earth. This was necessary because there was a lack of existing data regarding the space uses or the architectural characteristics of the analyzed university buildings. Given the scope of the broader research, the data collection phase spanned approximately three years and involved the assistance of four undergraduate students from the Architecture and Urbanism program at UFMG. It is worth noting that the scarcity of data poses a significant challenge for research on existing buildings in Brazil. Therefore, the presentation of a portion

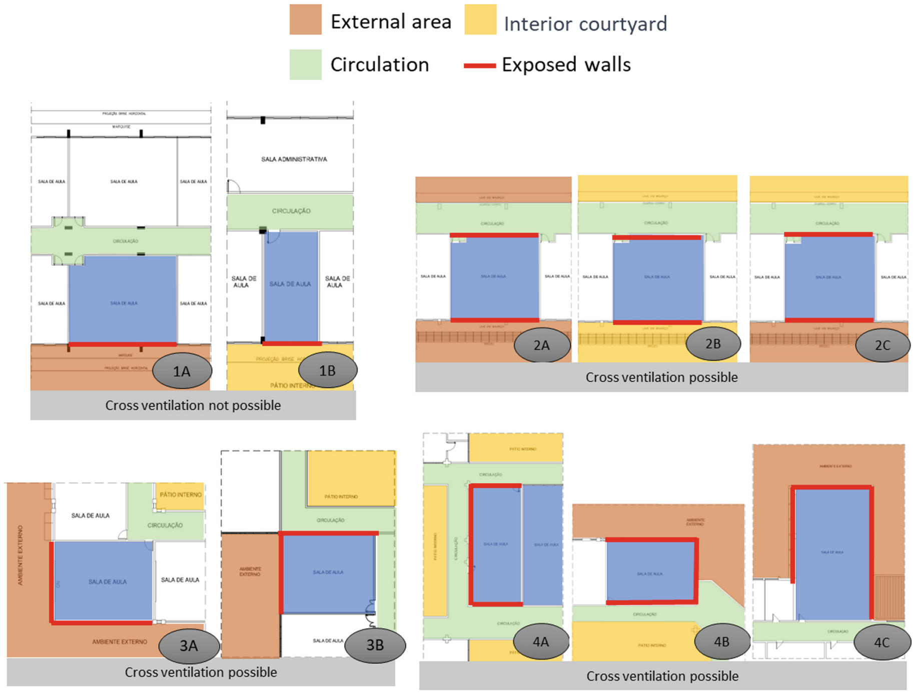


Fig. 1. Classroom morphology. Source: Own authors.

of the collected database aims to contribute to the existing body of knowledge on the architectural characteristics of existing buildings in Brazil.

2.1 Air Renovation Calculation

Using the database, a classroom with architectural characteristics that closely matched the median values was selected for further analysis. The calculation of the number of air changes per hour was performed for two scenarios: with and without cross ventilation (Fig. 2). The selected classroom had the following architectural specifications: an area of 53 m^2, a ceiling height of 3.1 m, a total volume of 164 m^3, and a window-to-wall ratio of 30%. It was assumed that the room would be facing the southeast (SE) direction, as this orientation was found to be the most common among the classrooms studied.

By examining this representative classroom, the study aims to evaluate the potential impact of cross ventilation on the air exchange rate, providing insights into the indoor air quality and ventilation effectiveness of similar classrooms in the university setting.

Table 1 shows the percentage of useful area for natural ventilation in the room according to the type of window. Figure 3 presents the formulas used for cases of cross ventilation and also for unilateral ventilation, presented by Souza and Rodrigues (2012). For calculations, it was assumed that the classroom would be localized on the second floor (height of window from the floor of 4.70 m). The prevailing air flow was considered from East with a velocity measured at 10 m of 3 m/s, based on climatic data from Belo

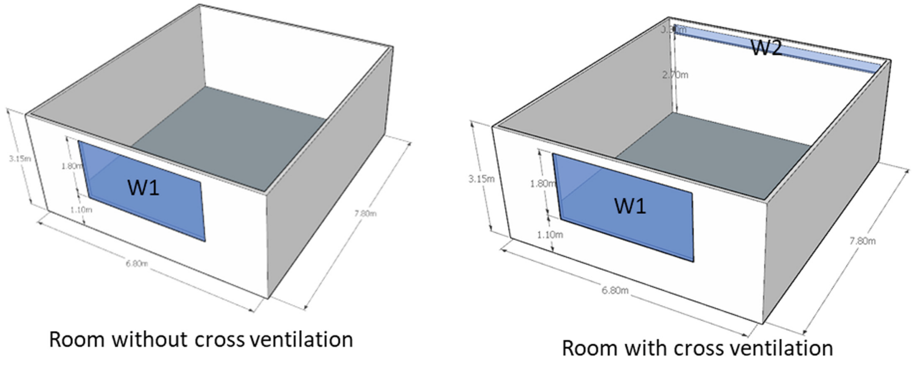


Fig. 2. Two types of scenarios. Source: Own authors.

Horizonte, Brazil (Projeteee 2023). Values of *K* and *a* for V_z calculation was 0.52 and 0.2, respectively (open field with some barriers).

Table 1. Percentage of ventilation according to the type of window.

	Type	Area (m^2)	Percentage of useful area for ventilation (%)
W1	Sliding window	2.93	45%
W2	Awning	0.59	30%

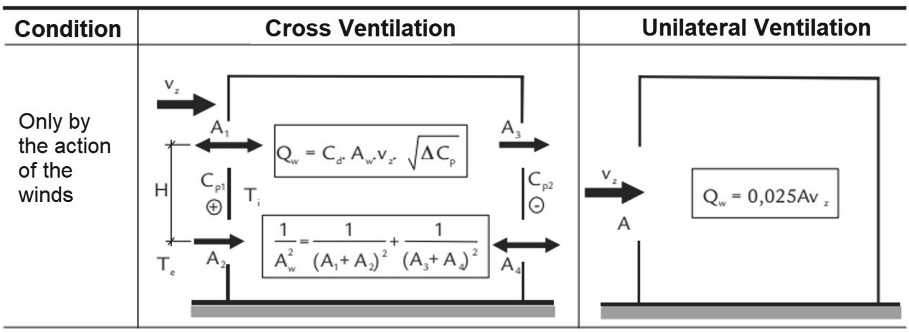


Fig. 3. Empirical equations for calculating air flow in buildings. Where Q_W: air flow due to the action of the wind (m^3/s), C_d: discharge coefficient (0.6), A_W: equivalent area of the openings (m^2), V_Z: resulting external wind speed in the opening (m/s)[$V_z = V_{10}$ K Z^a], and ΔC_p: variation of the pressure coefficients [$\Delta C_p = 0.1 + 0.0183$ (90-incidence angle)]. Source: BS 5925: 1991, apud Souza and Rodrigues 2012.

The number of air changes per hour (ACH) was calculated from the following equation:

$$N = \frac{Q \times 3600}{v}$$

A Where: N = number of air changes per hour (ren/h); Q = air flow (m^3/s); and v = volume of ventilated room (m^3).

3 Results

3.1 Database Description

A database consisting of 527 classrooms was developed, encompassing various architectural features that have the potential to influence both thermal comfort and air quality. Figure 4 presents an overview of the different types of conditioning systems utilized in classrooms across UFMG. This information offers insights into the prevailing approaches employed to regulate the indoor environment within the university's facilities.

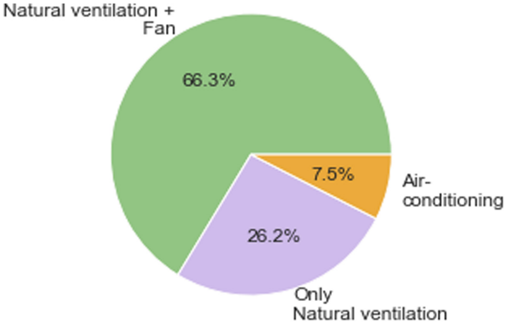


Fig. 4. Conditioning types of classrooms. Source: Own authors.

It is seen that over 90% of classrooms of the analyzed institution have naturally ventilated classrooms. As room design exerts significant influence on the feasibility of cross ventilation, classrooms were categorized based on their morphological characteristics, and based on that, it was identified whether cross ventilation was attainable or not. Figure 5 illustrates the outcomes of the morphological classification. Figure 6 presents the ratio of classrooms that possess cross ventilation among the analyzed sample.

From Fig. 5, it can be concluded that approximately 60% of the analyzed classrooms (morphologies 2, 3, and 4) have architectural characteristics that allow for cross ventilation. In contrast, only 12% of the classrooms possess this feature.

In addition to the presence of cross ventilation, the type of window used in the classrooms can also impact air renewal potential. The most commonly encountered window type at UFMG's classrooms was the sliding window with two panels (Fig. 7). Other window types, such as top-hinged windows and combinations of sliding or top-hinged windows with higher openings like louvered shutters and awnings, were also observed. Figures 8, 9, 10 and 11 provide additional architectural characteristics of the 527 classrooms included in the database.

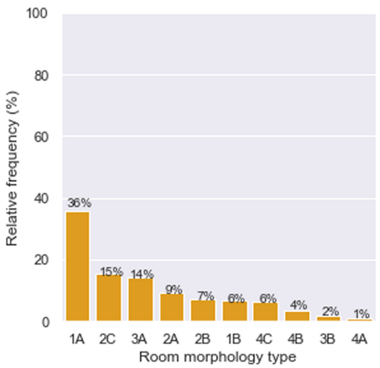


Fig. 5. Morphology classification of classrooms. Source: Own authors.

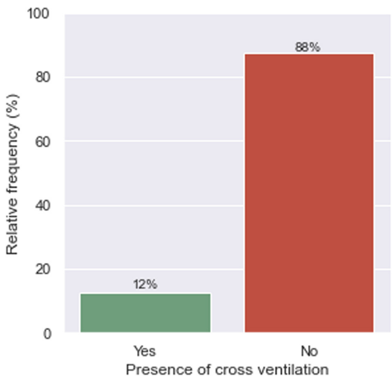


Fig. 6. Presence of cross ventilation in classrooms. Source: Own authors.

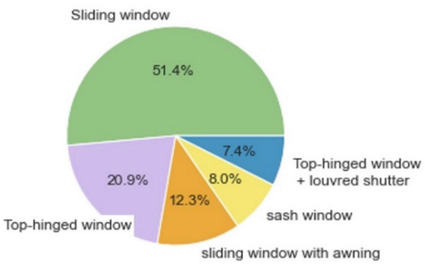


Fig. 7. Window types of classrooms. Source: Own authors.

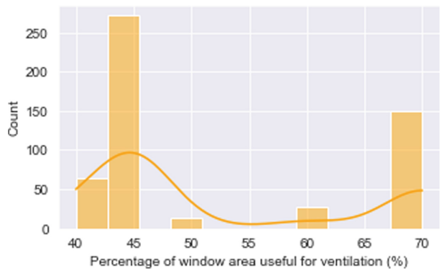


Fig. 8. Percentage of window area useful for ventilation. Source: Own authors.

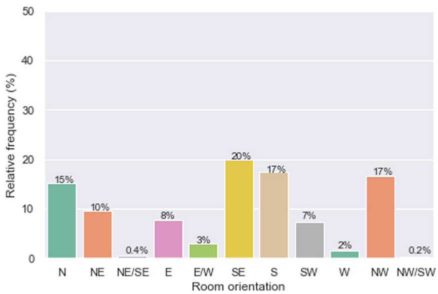


Fig. 9. Orientation of UFMG classrooms. Source: Own authors.

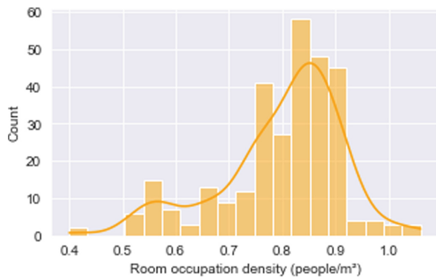


Fig. 10. Occupation density of UFMG classrooms. Source: Own authors.

3.2 Air Quality and Thermal Comfort in Classrooms

Table 2 shows the results of calculation of the number of air changes per hour in a classroom with typical architectural characteristics of the database. These calculations provide insights into the potential airflow and ventilation rates within the space, which

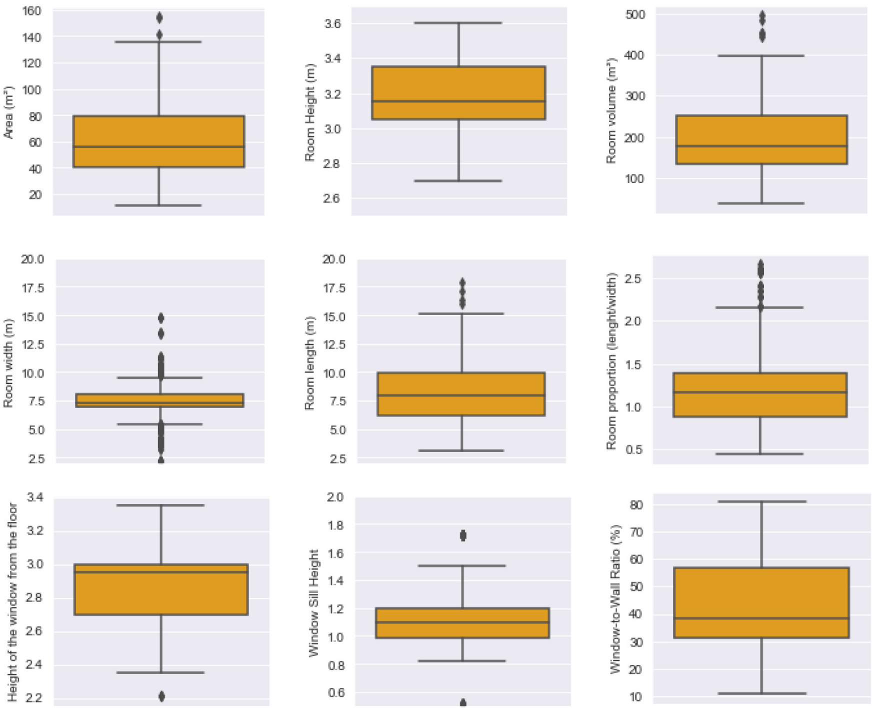
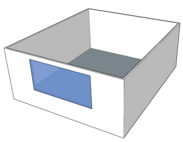
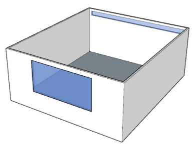


Fig. 11. Architectural characteristics of UFMG classrooms (n = 527). Source: Own authors.

are essential factors in ensuring adequate indoor air quality and thermal comfort for the occupants.

Table 2. Air renovations per hour for a representative classroom without cross ventilation and with cross ventilation

	Room without cross ventilation 	Room with cross ventilation 
N° of air changes per hour (ACH)	3.69	14.15

The analysis of the calculated ACH revealed that the typical classrooms in the study (164 m^3) exhibited insufficient air renovation rates compared to the recommendations provided by Hou et al. (2021), both considering 10 ACH (equivalent to CO^2 levels of 450 ppm) or 8 ACH (recommended for the classroom with 165 m^3). Also, the number was inferior to the 6.5 ACH cited by Franceschini et al. (2021). This finding, coupled with the observation that almost 90% of the classrooms at UFMG lacked cross ventilation, suggests a potential for inadequate air quality in the majority of classrooms within the institution.

On the other hand, when cross ventilation was considered, calculations showed a number of air renovations that was aligned with literature recommendations. The reached ACH is close to the 12 ACH value recommended for naturally ventilated health-care facilities to avoid COVID-19 contamination (OPAS 2021). The calculated air renovation rates for cross-ventilated classrooms were 3.8 times higher than those for single-sided ventilated classrooms. From the database, it was seen that approximately 60% of classrooms could have cross ventilation and 12% of classrooms presented this feature. This observation indicates that there is significant potential for improving air quality in approximately 48% of classrooms at UFMG through architectural retrofit measures.

Architectural retrofit measures that aim the health of occupants also exert influence on the thermal comfort of those spaces. For example, as seen in Table 3, UFMG's classroom users indicated feeling high levels of thermal discomfort from heat during the summer period. This discomfort could be alleviated if all the classrooms were rehabilitated, offering the occupants an environment with adequate ventilation, which would increase convective cooling. Hence, it can be understood that architectural parameters should be analyzed in a holistic manner, as they can influence different aspects of internal environmental quality. Also, architectural parameters should not be analyzed individually (e.g., room area, window type and orientation), as they are a set of factors that need to be considered in an integrated way both in initial phases of projects and in rehabilitations aimed at the thermal comfort and health of its occupants.

Table 3. Values of Thermal Sensation Votes (VST) and Percentage of Uncomfortable People (PPD) calculated based on votes from users of UFMG classrooms. Source: Garcia et al. (2021)

	Thermal sensation vote	Percentage of Dissatisfied People (PPD)
Summer	2.4	90%
Winter	−0.6	12%

4 Final Considerations

This article aimed to highlight significant aspects related to the analysis of academic environments, particularly classrooms, with the objective of contributing to the ongoing discussion and raising awareness about the crucial role of air quality and thermal comfort in these spaces. The study emphasizes the importance of considering these factors in the design and maintenance of academic spaces.

The findings of the research indicate the potential impact of architectural features, such as the presence of cross ventilation, on the air quality of classrooms. The insufficient air renovation rates observed in a significant portion of the classrooms studied highlighted the need for attention and potential architectural retrofitting measures to improve indoor air quality. It is known that many of these environments were not designed considering cross ventilation due to various cultural, administrative, economic or other factors.

Moreover, by promoting adequate air renewal rates by natural ventilation, the risk of contamination by airborne transmission of various diseases can be minimized and the thermal comfort by convective cooling can be increased. This has become relevant in the context of the COVID-19 pandemic, where ensuring healthy indoor environments gained even more significance. Furthermore, it is necessary that these environments have adequate rehabilitation due to the thermal quality, since climate changes are already felt and observed in most of the tropical and subtropical regions, such as Brazil.

By shedding light on these issues, the article aimed to contribute to the body of knowledge regarding the importance of air quality and architectural design in academic environments. It is hoped that the findings and insights presented in the article will encourage further research, discussions, and actions aimed at creating healthier and more comfortable learning spaces for students and faculty.

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