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INDOOR AIR QUALITY, THERMAL COMFORT AND ENERGY CONSUMPTION TRADE-OFF FOR EDUCATIONAL BUILDINGS

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In recent years, poor indoor air quality and thermal comfort have been widely reported in related studies on indoor environmental quality in classrooms. Improving indoor air quality through ventilation is common and effective. However, it compromises occupant's thermal comfort and well-being, thereby consuming more energy to meet increased heating or cooling demand and challenging energy conservation for Sustainable Development Goal 7. The existing researches imply the significance of conducting an extensive review on the three domains mentioned above (indoor air quality, thermal comfort, and energy consumption) in educational buildings, as individual cases are of peculiarity due to the specific characteristics of buildings and occupants. In contrast, the standards for indoor air quality and thermal comfort in educational buildings are not explicit and unified for all countries. This paper summarizes relevant features from reviewed cases, including: the geographic and demographic characteristics, field investigation parameters, indoor air quality and thermal comfort standards, ventilation protocols, heating and cooling strategies, energy consumption, as well as important and valuable findings in order to investigate the progress on such a topic.

Keywords: Educational Buildings; Indoor Air Quality (IAQ); Thermal Comfort (TC); Energy Consumption (EC).

COMPENSACIÓN DE LA CALIDAD DEL AIRE INTERIOR, EL CONFORT TÉRMICO Y EL CONSUMO DE ENERGÍA PARA EDIFICIOS EDUCATIVOS

En los últimos años, los bajos niveles de calidad del aire y confort térmico en interiores han sido ampliamente evaluados en investigaciones relacionadas con la calidad ambiental en aulas. La mejora de la calidad del aire a través de la ventilación es común y efectiva. Sin embargo, se compromete el confort térmico y el bienestar del usuario, por lo que se consume más energía para satisfacer una mayor demanda de calefacción o refrigeración y se desafía al ODS7 (Objetivo de Desarrollo Sostenible). Los estudios existentes implican la importancia de realizar una revisión exhaustiva sobre los tres dominios mencionados anteriormente (calidad del aire, confort térmico y consumo energético) en edificios educativos, dadas las características específicas tanto de los ocupantes como de las edificaciones. En lo que se refiere a las normativas, estas no son explícitas ni unificadas para todos los países. Este artículo resume los aspectos más relevantes de los casos revisados, incluidas: características geográficas y demográficas, parámetros típicos en campañas experimentales, estándares de confort térmico y calidad del aire, protocolos de ventilación, estrategias de calefacción y refrigeración, consumo de energía, así como los hallazgos más significativos para analizar los avances en un tópico como este.

Palabras clave: Edificios educativos; Calidad del Aire Interior; Confort Térmico; Consumo de Energía

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1. Introduction

Indoor air quality (IAQ) and thermal comfort (TC) have drawn wide attention of relevant researchers. For educational buildings, the challenges regarding these two aspects are well-recognized: students spend most of the daytime inside the classroom, where the occupancy density reaches 3-4 times higher than the residential and commercial buildings (Jia et al., 2021), while poor indoor air and thermal conditions can impose them a series of negative impacts. By way of examples, some researches highlighted physiological health problems: the obvious sense of discomfort, loss of concentration, the decline of cognitive ability, fatigue, allergy, as well as infection of respiratory diseases (Zomorodian, Tahsildoost, and Hafezi, 2016; Tran, Park and Lee, 2020).

Ventilation is the most common and effective way to improve indoor air quality. However, it leads to a significant change of indoor thermal conditions and compromises the comfort of occupants. Hence extra energy will be consumed to compensate the rise of heating and cooling demand, which could eventually result in the decline of the overall energy efficiency of buildings. This problem is also known as the "Indoor Air Quality - Thermal Comfort - Energy Efficiency (IAQ-TC-EE)" dilemma (Becker et al., 2007; Yu, Kang, and Zhai, 2020; Jia et al., 2021). Identifying a promising solution for the "IAQ-TC-EE" dilemma is of well-appreciated social significance, which not only benefits human health and welfare but also promotes energy conservation, contributing to the sustainable development goals (SDGs) 3 and 7 (United Nations, 2018).

Nevertheless, it is emphasized that the proper strategy for addressing the IAQ-TC-EE" dilemma should be based on the premise that both indoor air quality and thermal comfort can be properly handled, whereas most of the previous studies failed to achieve such a trade-off (Becker et al., 2007). Existing researches have pointed out the obstacles from the perspective of indoor air quality and thermal comfort respectively. On the one hand, 1000 ppm of indoor CO_2 concentration is generally adopted as the threshold to symbolize good ventilation, whereas most schools worldwide are not able to meet this limit (Salleh et al., 2011). Also, existing studies have pointed out that this CO_2 concentration value cannot fully guarantee a good indoor air quality. In addition, relevant standards with different CO_2 limit recommendations are potentially contradictory and misleading (Barnett, 2014; Khovalyg, 2020). On the other hand, the existing thermal comfort models of current standards have been criticized in terms of their reliability to predict the thermal sensation and comfort temperature of child and teenager students (Zomorodian, Tahsildoost, and Hafezi, 2016). Accordingly, massive energy waste will be inevitably caused by the over-heating and over-cooling due to the lack of explicit guidance and the misuse of standards (Alnuaimi, Natarajan and Kershaw, 2022). Furthermore, previous studies indicated that individual cases are of peculiarity due to the specific characteristics of buildings and occupants' backgrounds (Singh et al., 2019).

Based on the information exposed, this paper aims to investigate the current research progress on the above issues so as to provide the reference for future research addressing the "IAQ-TC-EE" trade-off. To achieve this, the paper is structured in 4 sections. Section 2 explains the research methodology applied in this study. Section 3 presents the results with the corresponding discussion, while Section 4 concludes with the main findings.

2. Research Methodology

The research on indoor air quality, thermal comfort, and energy efficiency of educational buildings covers a broad range and scope with different emphases. Taking as a reference the methodology adopted in review articles of other research fields (Jia et al., 2021; Kakoulli, Kyriacou, and Michaelides, 2022; Tejedor et al., 2022), this paper assesses the case studies of the mentioned three domains through two steps: preliminary search and review selection.

In the preliminary search stage, the studies on indoor air quality, thermal comfort, and energy efficiency of educational buildings were retrieved respectively from the Scopus database, with the time span from 2000 to 2022. In order to narrow down the scope and to focus on the aim of this study, the obstacles indicated by previous studies were fully considered at this stage. Firstly, for the indoor air quality domain, the studies should adopt CO2 concentration as the indicator to symbolize the ventilation effects and indoor air quality. Secondly, for the thermal comfort domain, the publications are expected to contain explicit neutral temperature or comfort temperature as keywords, performing field surveys or investigating the reliability of exiting thermal comfort standards. Lastly, the expected studies need to be related to energy efficiency and energy saving in terms of HVAC systems. Therefore, the queries in the Scopus database and the retrieval results are shown in Table 1:

Table 1. Queries Used in Preliminary Search and Number of Publications Obtained

Aspect	Query	Publications (2000-2022)
Indoor Air Quality	TITLE-ABS-KEY ("educational building" OR "school" OR "classroom" AND "indoor air quality" AND "ventilation" AND "CO_2")	298
Thermal Comfort	TITLE-ABS-KEY ("educational building" OR "school" OR "classroom" AND "thermal comfort" AND "neutral temperature" OR "comfort temperature")	100
Energy Efficiency	TITLE-ABS-KEY ("educational building" OR "school" AND "energy consumption" AND "energy saving" AND "ventilation" OR "heating" OR "cooling" OR "HVAC")	126

In the review selection stage, it is required to develop certain criteria to screen out the most relevant literature. Regarding indoor air quality, the criterion is that the study needs to clearly indicate the selection of IAQ standards that determine the CO_2 thresholds, with detailed discussions about field measurement results. Hence, 43 publications were selected for the detailed review. Then, the selection criterion for thermal comfort publications is that there are detailed calculations obtaining neutral or comfort temperature presented in the literature, preferably including the discussion or comparison with relevant thermal comfort standards adopted. Thereby, a total of 38 publications were obtained. Finally, for the studies of energy efficiency, it is required to indicate the standards or reference basis for the optimization of energy efficiency on HVAC systems. In this case, 25 publications were undertaken.

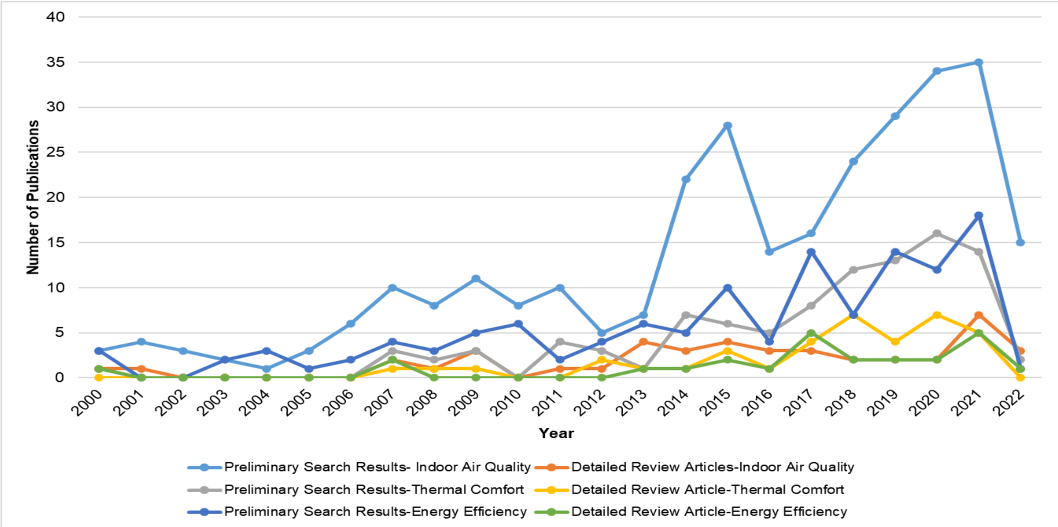
3. Results and Discussion

This section first performs a bibliometric analysis of publications in three domains, then summarizes the results of this review from individual aspects of indoor air quality, thermal comfort, and energy efficiency and discusses the "IAQ-TC-EE" issue for educational buildings in combination with all three perspectives.

3.1 Bibliometric Analysis of Publications

Figure 1 presents the number of publications distributed throughout the period of time from 2000 to 2022. It can be seen that the number of publications in the 3 aspects demonstrates a growing trend, especially in 2021 when the figures reached the peaks. The potential reason for this phenomenon is because, as some researchers indicated, the outbreak of the COVID-19 pandemic had brought the concerns about the air quality in schools back to the public and research community (Miranda et al., 2022), while recent studies reflect a sign that the evaluation of indoor air quality and thermal comfort were performed simultaneously (Ma et al., 2020; Jiang et al., 2020; Wang et al., 2021). In comparison, the number of selected articles over the period is generally in line with the preliminary search results.

Figure 1: The Distribution of Publications During 2000 to 2022

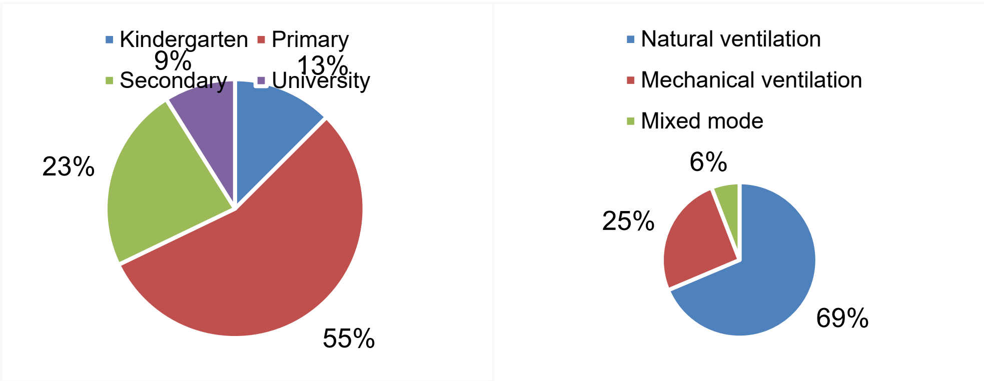


In addition, the geographical distribution of publications was analyzed. It is found that the United States has the highest number of papers (42 publications) published on IAQ from 2000 to 2022, followed by China, with 31 publications. There are 3 other countries with more than 20 papers, including the United Kingdom, Italy, and Portugal. Besides, it is worth noting that if classifying countries in the publication ranks according to their geographical locations, 7 of the top 10 countries are located in the European continent (taking the United Kingdom into account), absolute advantage with over 133 publications in total, while the same is also true for the 43 selected articles, in which more than 65% were published by European countries, followed by Asia and North America, with 23% and 7% respectively. Regarding publications on TC, China published a total of 34 papers between 2000 and 2022, which is 2 times more than that of the second-ranked country the United Kingdom. Also, most of the TC studies were published by Asian nations, with more than 80 papers in total, which is a completely different scenario in comparison with the case of IAQ publications. Within the 38 selected articles, China, India, and the United Kingdom own 14, 6, and 4 publications respectively, while the other countries only have 1 for each. Lastly, regarding EE publications, European countries once again prevail over other continents and nations, sharing approximately 80% in total publications during the period, while nearly half of the 25 selected articles for review were also from European researchers.

3.2 Indoor Air Quality in Educational Buildings

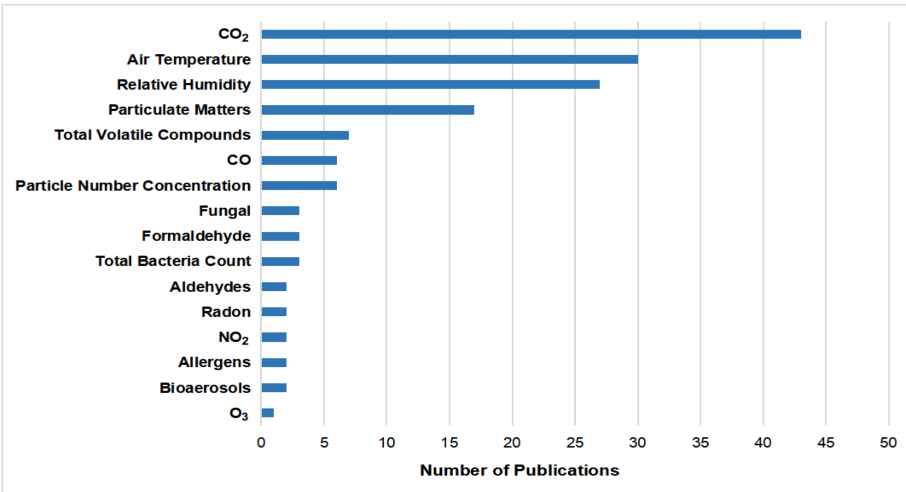
Figure 2 illustrates the analysis of 43 selected studies in terms of the educational level and building ventilation type. Statistics shows that primary school is covered in 55% of the cases, which became the major research object in comparison with the university, to which only 9% of publications were related. In terms of building ventilation types, approximately 70% of the publications involved natural ventilation, despite a few cases also compared mechanical ventilation (Asif, Zeeshan, and Jahanzaib, 2018; Alonso et al., 2021), whereas only 6% of studies investigated the mixed ventilation modes. Apart from these, it is notable that merely around 1/3 of natural ventilation cases explicitly indicated the ventilation protocols adopted or performed comparative analyses, which actually exerts significant influences on the effects of ventilation and deserves more attention (Asif, Zeeshan, and Jahanzaib, 2018; Miranda et al., 2022).

Figure 2. The Percentage of Publications Regarding Educational Level and Ventilation Type



Then, the parameters for the field investigations were summarized referring to the number of cases, as shown in Figure 3.

Figure 3. Measured Parameters in Selected Indoor Air Quality Publications



As seen, CO_2 was measured in all the cases because it is defined as the prerequisite for review selectionl However, some other parameters related to air quality were frequently measured as well, including air temperature and relative humidity, particular matters (both $PM_{2.5}$ and PM_{10}), total volatile compounds, CO, etc. In theory, air temperature and relative humidity are physical properties characterizing the air, while CO_2 cannot be considered an air pollutant when its indoor concentration is below 10,000 ppm with only short-term exposure (Becerra et al., 2020). As far as air pollutants are concerned, total volatile compounds, CO, formaldehyde, and total bacterial count were investigated in parts of the publications, in which significant correlations between these pollutants and indoor CO_2 concentrations were discovered (Yang et al., 2009; Madureira et al., 2016). Nevertheless, for the widely concerned pollutant particulate matters, some studies have identified its correlation with CO_2 concentration while others found contradictory results, as the reason is that unlike aforementioned air pollutants, the pollution source of particulate matters generally exists in both indoor and outdoor environments (Mainka et al., 2015; Fuoco et al., 2015).

Furthermore, IAQ standards with corresponding recommended reference values for indoor CO2 concentration adopted in the selected publications were reviewed. The large-scaled misuse of IAQ standards is confirmed. On the one hand, different interpretations of the same standard were observed in various cases. There are over 20 papers adopted ASHRAE 62 and its updated version ASHRAE 62.1, but CO2 limit was interpreted as 3 different versions, including 700 ppm below outdoor value, 1000 ppm, and 1100 ppm that perhaps based on the presumption that outdoor CO2 is constant at 400 ppm (Jones and Kirby, 2012; Stabile et al., 2016; Korsavi and Montazami, 2020). Such phenomenons can also be identified in other cases, including the "WHO IAQ Guidelines" (Mainka et al., 2015; Peng, Deng, and Tenorio, 2017), "EN 13779", "EN 15251", etc. (Turanjanin et al., 2014; Canha et al., 2015). On the other hand, some cases referred to regional standards by other nations. For instance, Cornaro et al. (2013) adopted the British standard "Building Bulletin 101 'Ventilation in School Buildings' (BB101)" in their study of Italian schools, while Hänninen et al. al. (2017) used the "German Guideline of Indoor Hygiene in School Buildings" in the study of Albania study. It should be noted that the reasons and justifications for such applications were not specified. In addition, there are certain conflicts among recommended CO2 limits. The CO2 limit in different IAQ standards varies, thus there might be confusion about the choice of value, especially for the European researchers, as the recommended limit of CO2 in EN 13779 and EN 15251 may conflict with that of national standards. In contrast, there are also cases in which the identical value is indicated in different national standards. By way of example, the study of schools in Beijing, China by Cai et al. (2021) adopted "GB /T-17226 Chinese Hygienic Requirements of Classroom Ventilation in Middle and Elementary School", "GB/T-18205 Comprehensive Appraisement for Health in Schools", and "GB 30533 General Health and Safety Specification for School Design" at the same time, which all recommend the exact same CO2 limit of 1000 ppm.

Lastly, it is important to note that the most widely used IAQ standard ASHRAE 62.1 was misunderstood in most cases. Andrew Persily, former chair of ASHRAE, criticized that researchers did not completely understand the purpose and limitations of using CO2 of 1000 ppm as an indicator to symbolize indoor air quality, while the CO2 limit was actually removed from ASHRAE 62.1 for almost 30 years due to the confusion it caused (Persily, 2020)

3.3 Thermal Comfort in Educational Buildings

Figure 4 summarizes the educational level and the building operation mode corresponding to the 38 selected publications. Statistics demonstrate that university and primary school have become the main research object on this topic, accounting for 37% and 35% respectively, while only 1 case targeted at the kindergarten (Nam et al., 2015). The possible reason may be that, as pointed out by other researchers, children are not able to properly comprehend the concept of “thermal comfort” so as to perceive and express their sensation (Martinez Molina et al., 2017). Regarding building operation mode, only 21% of the publications evaluate purely air-conditioned indoor environment, whereas nearly 80% investigated the non-air-conditioned scenario that relies on natural ventilation to adjust the indoor climate. However, only nearly half of the selected papers explicitly stated the heating and/or cooling strategy of the buildings or spaces.

Figure 4. The Percentage of Publications Regarding Educational Level and Operation Mode

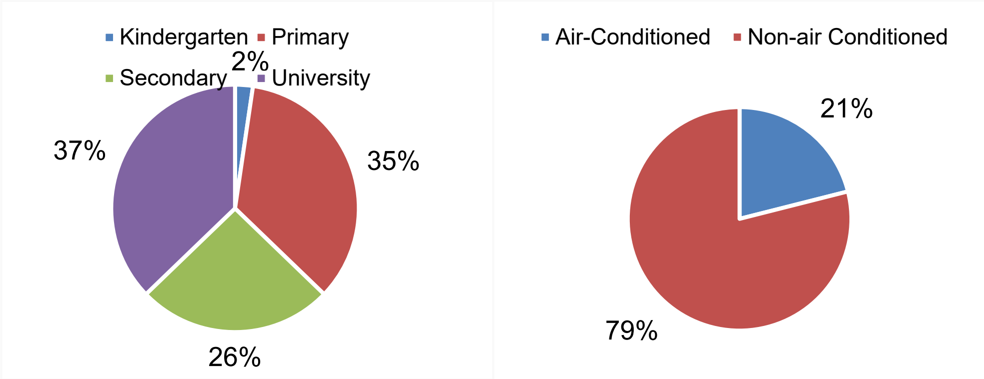
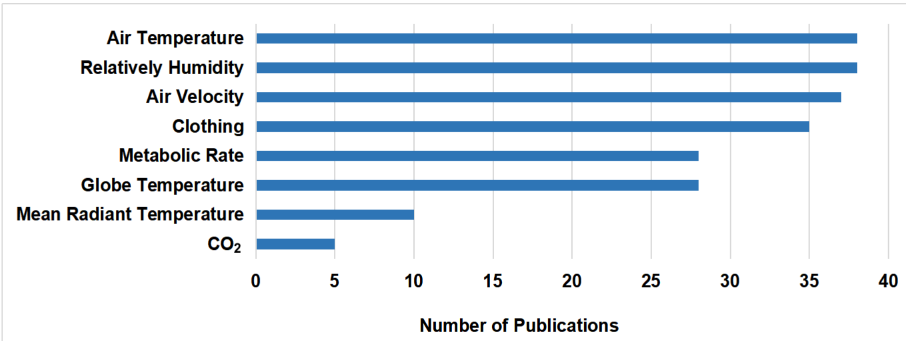


Figure 5 summarizes the parameters measured in the field survey corresponding to the number of cases. As seen, air temperature and relative humidity were measured in all cases. As the mean radiation temperature is indispensable for calculating the operative temperature, it was directly investigated by instruments in 10 cases, while the rest of cases measured the globe temperature to calculate it indirectly. In general, most cases identified the clothing insulation and metabolic rate, but a few cases only involved descriptive text of “sedentary state” instead of giving the specific value. Apart from these variables, the outdoor parameters are detrimental for validating the adaptive thermal comfort models, accordingly, all these studies chose to refer to the weather data provided by the weather station directly.

Figure 5. Measured Parameters in Selected Thermal Comfort Publications

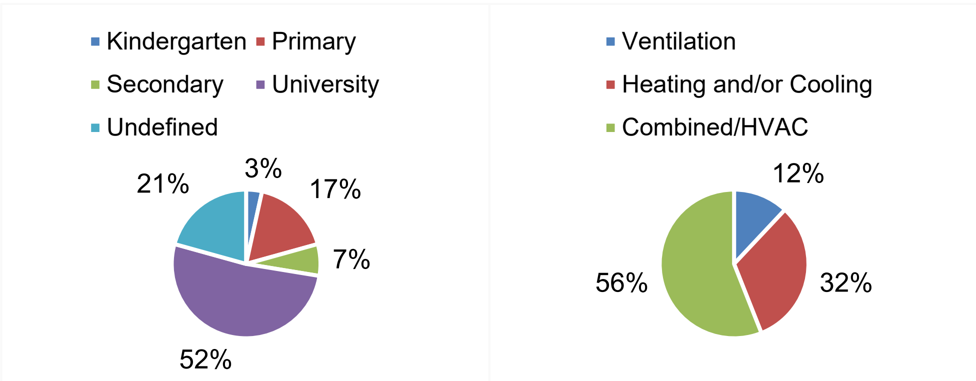


Finally, TC standards and models used in the selected papers were reviewed. In general, there are 4 standards that have been widely adopted, namely ASHRAE 55, ISO 7730, EN15251, and its updated version EN 16798, while some national standards have also been identified in cases, including GB/T 50785 of China, National Building Code (NBC) of India and Chartered Institute of Building Services Engineers (CIBSE) Guide of the United Kingdom (Kumar et al., 2018; Liu et al., 2019; López-Pérez, Flores-Prieto, and Ríos-Rojas, 2019). However, the result of this research confirms that the comfort temperature exceeds the upper or lower limits of the comfort band of models in all studies that involve adaptive thermal comfort models (including adaptive PMV model), even the same for the university cases where the adult represents the main occupants, reflecting a high potential of adaptability of people. Meanwhile, it is found that the PMV model often overestimates or underestimates the neutral temperature of occupants, and quite a few cases achieved a difference between the predicted and actual neutral temperature within 1 degree Celsius (Haddad, Osmond and King, 2019; Wang et al., 2021).

3.4 Energy Efficiency in Educational Buildings

Figure 6 illustrates the analysis of the educational level and optimization aspects indicated in the 25 selected papers. From statistics, more than 52% of the cases involved university buildings, while only 3 % of studies were performed at the kindergarten level. Nevertheless, it is notable that a considerable amount of studies did not explicitly indicate the educational level of the buildings in their documents. Actually, these papers assumed or pointed out that the buildings or spaces selected were regarded as the typical cases of educational buildings in the region. Along this line, more than 50% of cases consider both ventilation and heating and/or cooling strategies to analyze and optimize the energy-saving potential. In contrast, the studies that purely considered ventilation or heating and/or cooling perspective only account for 12% and 32% respectively.

Figure 6. The Percentage of Publications Regarding Educational Level and Optimization Aspect



From the analysis of the energy consumption and energy efficiency in the selected cases, a considerable number of publications did not perform comprehensive energy audits of the entire building nor HVAC systems. A potential reason may be that the standards for review selection require publications to indicate the IAQ or TC standards or basis referred in HVAC optimization, rather than showing the figure of energy consumed. However, it can be determined that the energy demand of the HVAC system of buildings shares a substantial proportion of the total energy consumption, with approximately 70% to 80%, which is consistent with the findings of previous studies (Al-Saadi, 2021; Jia et al., 2021). Besides, the potential for energy efficiency optimization of educational buildings is well-appreciated, with more than 3/4 of the cases achieving over 20% of energy savings.

At last, the standards or reference bases used for HVAC optimization in selected publications were reviewed. CO_2 is no longer the only indicator to evaluate the ventilation effect and IAQ. Nevertheless, misinterpretations and misuse of standards were still frequently identified, and some cases even directly stated using 1000ppm of CO_2 concentration as the reference value without indicating the source and explanations (Merema et al., 2018; Franco, Miserocchi, and Testi, 2021). Concerning the thermal comfort, most cases directly adopted the temperature ranges or thermal comfort models recommended in the standards, while only 3 cases verify and improve the models as the reference basis through field survey results (Wang et al., 2014; Zhang et al., 2017; Irulegi et al., 2017). The reason for this phenomenon may be that, as some researchers stated, the validity of recommended values in the standards is beyond the research scope(Becker, Goldberger and Paciuk, 2007). However, such applications may lead to the problem that the priority is given to energy efficiency optimization instead of balancing all three aspects, eventually failing to address the “IAQ-TC-EE” trade-off.

4. Conclusion

This paper investigated the progress of research on the topic of indoor air quality, thermal comfort, and energy efficiency of educational buildings in the past two decades (2000-2022). The review considered the potential obstacles implied by previous studies connecting all three perspectives together for addressing the “IAQ-TC-EE” trade-off, while valuable findings obtained are summarized as follows:

For indoor air quality (IAQ), naturally ventilated buildings have been found to be the focus of the topic. However, the significance of ventilation protocols was not adequately considered in most cases. Among the parameters of field measurements, CO_2 concentration is not the only indicator involved, as a group of air pollutants were also widely investigated, considering the significant correlation identified between them and indoor CO_2 concentration. Besides, the results of this review confirmed the concern of previous studies that the CO_2 indicator and indoor air quality standards were frequently misinterpreted and misused.

For thermal comfort (TC), non-air-conditioned buildings have become the main research target, but it is found that there is a lack of proper consideration of heating and cooling strategies. In the literature review, a few cases analyzed the indoor climatic conditions kindergartens, taking into account the incapacity of children to comprehend and express their thermal sensations. In terms of field surveys, some researchers investigated both indoor air quality and thermal comfort simultaneously, which reflects the sign of combining the two domains in recent years. Nonetheless, the review of standards revealed the lack of reliability of existing models in predicting thermal sensations of students, even the same for the models that were specifically developed for the local people.

For energy efficiency (EE), more than half of the publications combined both indoor air quality and thermal comfort, rather than purely focusing on single aspects. The findings pointed out that most publications did not perform comprehensive energy audits of buildings, but they confirmed the well-appreciated energy-saving potential of educational buildings with regard to HVAC systems. Regarding the building energy optimization, no enough attention was paid in the validity of IAQ and TC standards, while too much weight was given to energy efficiency.

Considering the aforementioned aspects, several recommendations for future research steps are proposed. Firstly, new studies should combine both IAQ and TC when conducting field surveys, which provides valuable references for building energy optimization in certain regions. Secondly, the potential influence of existing ventilation protocols, heating, and cooling strategies should be sufficiently considered in the investigations. Lastly, relevant researcher need to be aware of the reliability and limitations of existing IAQ and TC standards, so as to properly address the “IAQ-TC-EE” trade-off.

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