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INDOOR ENVIRONMENTAL QUALITY IN AN APULIAN KINDERGARTEN

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Abstract

Indoor environmental quality (IEQ) in school buildings is crucial for the health and well-being of students, educators, and staff. Poor air quality and inadequate thermal conditions compromise students' comfort and can lead to potential long-term health issues. Since children's comfort differs from adults', it is important to consider surveys on IEQ in school buildings. For this reason, this paper focuses on air quality and thermal comfort in kindergartens in Italy. An IEQ monitoring campaign was conducted within a kindergarten, with data used for thermal comfort and IAQ analyses, including CO_2 levels generated by occupants and thermal discomforting hours. The simulations of carbon dioxide levels showed that the amount of CO_2 accumulated in the classrooms exceeds the threshold recommended by ASHRAE guidelines. During the winter seasons, CO_2 levels are significantly higher than those accumulated in summer due to the limited ventilation practiced during the colder months. Moreover, thermal comfort analyses indicate that the summer season can be problematic due to overheating: 42% of the occupied hours during the monitoring period exceeded the temperature threshold, causing thermal discomfort for the occupants. The winter thermal comfort analyses demonstrated that heating systems are essential to maintain temperatures within comfort thresholds.

Keywords

School buildings, Indoor environmental quality, Ventilation strategies, Carbon dioxide levels, Sustainable design.

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1. INTRODUCTION

School buildings serve a social and educational purpose as centres for learning and development, carrying the liability of ensuring a safe and comfortable environment for students, educators, and staff. However, the COVID-19 pandemic has posed significant challenges to these principles [1]. The implementation of restrictive measures, the necessity for social distancing, and an increased understanding of the risks posed by viruses have underscored the issues in the design of indoor spaces [2].

In recent years, growing concerns about the health impacts of poor indoor air quality (IAQ) have highlighted the need for better ventilation and regular air quality monitoring, as high CO_2 levels can impair cognitive function and increase student absenteeism [3]. Alongside IAQ, research underscores the equal importance of thermal comfort for occupant well-being and performance. Ensuring optimal IEQ in educational settings is often challenging due to outdated building designs, poor insulation, and inefficient HVAC systems [4]. These challenges are even more pronounced in Mediterranean climates, where school buildings are typically ventilated naturally without cooling systems [5]. During the summer months, indoor climate control depends only on natural ventilation; however, when outdoor temperatures are excessively high, this approach can cause thermal discomfort within classrooms. Although natural ventilation in the warm months effectively maintains CO_2 levels below threshold limits, it frequently results in thermal discomfort. Conversely, natural ventilation is minimized during winter to retain the heat generated by heating systems [5]. Consequently, while thermal comfort is preserved, CO_2 levels tend to be significantly higher than in summer [5]. These issues are particularly relevant in Italy, where many school buildings are outdated, overcrowded, and inadequately ventilated, further complicating efforts to create environments conducive to learning and occupants' comfort [6]. In a specific way, kindergartens are emblematic buildings for managing IEQ because they host preschool-aged children who are particularly sensitive to environmental factors [3]. Children have a different thermoregulation capacity than adults: their body surface area is larger in proportion to their weight, causing them to lose heat more quickly and making them more susceptible to temperature fluctuations. Their respiratory systems are still developing, so prolonged exposure to poor air quality can negatively affect their growth and development [7]. Moreover, the nature of preschool activities, such as group play, increases their exposure to pathogens, including viruses [8]. Therefore, kindergartens represent a significant challenge in terms of ensuring high IEQ. Acknowledging the issues underscored by the pandemic, it becomes imperative to introduce new design strategies for buildings that ensure healthful, safe environments, offering both optimal air quality and proper thermal comfort [1]. To develop effective new design guidelines, the first action should be a detailed examination of the current conditions of school facilities to identify critical areas for enhancement. In this context, the research presented in this article focuses on evaluating the indoor environmental quality of a naturally – ventilated kindergarten in Bari, Southern Italy. By aligning with the current state of the art, this research aims to assess air quality and thermal comfort in a preschool building, analyse the effectiveness of natural ventilation strategies, and provide recommendations for improving IEQ in similar settings. The paper is divided into several sections: the initial section explains the methodology applied in the study, along with a description of the school used as the monitoring sample; the following section presents the analysis results; the last section discusses the outcomes and their implications.

2. METHODS AND MATERIALS

The methodology of this study is structured into four key phases. First, data was gathered through a real-time monitoring campaign conducted in two classrooms of the selected kindergarten. Following this, the collected data were analysed. The third phase involved developing an energy knowledge-based model of the kindergarten, which was subsequently calibrated in accordance with the ASHRAE 14:2014 standard. Finally, simulations of accumulated CO_2 levels were performed during the occupied hours in the monitored classrooms, and the thermal comfort was evaluated using the Daily Discomfort Hours (DDH) metric.

The following sections provide a more detailed explanation of each phase of the methodology.

2.1. THE MONITORING CAMPAIGN

The school building selected for the monitoring campaign is the John Fitzgerald Kennedy kindergarten (Viale Kennedy 46, Bari BA - 40°45'36", 73°59'2.4"). The facility operates from 8:00 am to 1:30 pm and is open from September to June.

The school, constructed in 1982, is a single-story building with a compact design and includes a basement level used as a technical room. It has a surface-to-volume ratio (S/V) of 0.33. The building envelope consists of brick with an air gap but lacks thermal insulation, as confirmed by the Apulian Regional Portal for School Buildings (ARES) [9]. The interior and exterior are both finished with plaster, while the floors are made of concrete slabs with a ceramic tile finish. According to the ARES portal, the envelope includes metal frames for windows and French doors, which are reported as requiring replacement. The monitoring campaign involved measuring indoor and outdoor temperatures and relative humidity (RH) using three EL USB Data Loggers (designated in this study as sensors A, B, and C). Data collection occurred over 15 days during the spring-summer season in two occupied classrooms: classroom A was monitored from June 13, 2023, to June 27, 2023, and classroom B from May 23, 2023, to June 6, 2023. The classrooms have metal fixtures (doors and glass doors) with single glazing and roller shutters, and the ARES portal has indicated that a complete replacement is necessary. Classroom A has a 40 m^2 surface area, 118 m^3 of volume, hosts 20 children, and is oriented to the South-East, while Classroom B has a 44 m^2 surface area, 133 m^3, hosts 22 children, and is oriented to the South-West. All the IEQ analyses presented in this paper refer to Classroom A, as it is representative of the building. Additionally, among the two monitored classrooms, Classroom A has the most challenging orientation for overheating, being south-east facing, and is the one most exposed to solar radiation during occupancy hours.

The sensors were installed at key locations within the classrooms (Fig. 1), each placed at a consistent height of 2 meters above the floor. Sensors A and C were placed respectively outside and inside the windows most frequently opened by educators during occupancy hours for ventilation. Sensor B was located on the opposite side to sensors A and C. The sensors were programmed to record IAQ parameters at 2-minute intervals, and during the analysis phase, the data was averaged into 20-minute segments.

The comparison of temperature readings from sensors B and C allowed the determination of the temperature fluctuations that the classrooms experienced during the monitoring period. Sensor A and sensor C data were analysed to assess the ventilation strategies employed in the classrooms during school hours. Occupied days were consolidated into a single standard occupancy model, referred to as *OC Day*, which represents the actual classroom usage conditions for that season. Likewise, temperature readings from unoccupied days were merged into a standard model known as *N-OC Day*, representing an unoccupied classroom.

2.2. THE SCHOOL BUILDING ENERGY MODEL AND INDOOR TEMPERATURE TRENDS

The school's geometric model was created using Autodesk Revit software. Once the 3D model was created in Revit, it was transformed into an analytical and energy model, then exported to the energy simulation software Design Builder. The energy model in Design Builder was supplemented with Ventilation, Occupation, and Lighting Schedules, with the heating and cooling system turned off. Cooling systems were excluded from the analysis as they were not present in the building. Heating systems were also omitted to better assess the building's passive thermal behaviour without the aid of mechanical systems. To proceed with the calibration of the energy model, a current climatic file was generated using the actual weather data measured from the monitoring stations, specifically from station 467 (Bari Osservatorio) [10], to be used as boundary conditions for the simulations [11]. The calibration process was conducted manually,

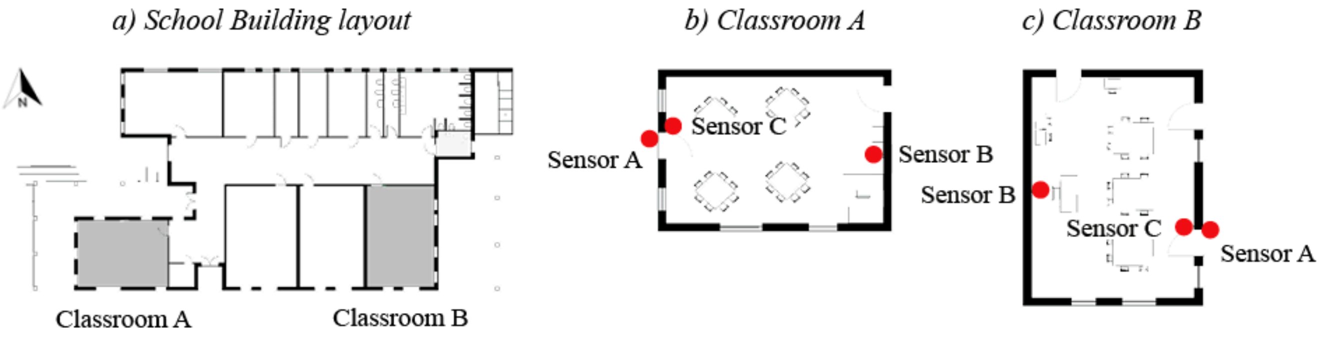

Fig. 1. *Positioning of the sensors in the monitored classrooms.*

following the guidelines of ASHRAE 14:2014, ensuring the NMBE and CV(RMSE) indices were within the acceptable ranges for hourly calibration, with the NMBE within ±10% and the CV(RMSE) below 30%.

After constructing the energy model, further analyses were carried out on the calibrated energy model. Ventilation Schedules were established and applied to the energy model according to the ventilation hypotheses *Hp.1*, *Hp.2*, and *Hp.3* as defined in paragraph 2.4. Simulations were performed for each ventilation hypothesis to assess the indoor temperature trend of classroom A under the different ventilation strategies. The *Hp.1* and *Hp.2* ventilation simulations were performed during classroom A's monitoring period (from 13/06/2023 to 27/06/2023); the *Hp.3* simulation was carried out over a sample period of winter conditions (from 23/02/2023 to 6/03/2023). Data generated from the simulations were aggregated into a single standard model for each ventilation hypothesis, averaged hourly across all days, and then compared with the external dry bulb temperature data using the same energy model.

2.3. THERMAL COMFORT ANALYSIS

Daily Discomfort Hours (DDH) [12] were adopted to assess thermal comfort during summer and winter. The simulations were conducted from 13/06/23 to 27/06/23 for the summer period and from 23/02/23 to 9/03/23 for the winter period, adopting the *International Weather for Energy Calculations 2* (IWEC2) weather file for Bari as boundary condition [13]. The DDH index was used to quantify the number of hours in a day when the Indoor Operative Temperature ($T_{o,in}$) surpassed a defined thermal comfort limit (T_c): with this logic, it quantified the intensity and duration of thermal discomfort. DDH was calculated according to the below equation (1):

$$DDH = \sum_{i=1}^{24} (T_{o,in} - T_c) \qquad (1)$$

where, $T_{o,in}$ [°C], was obtained from energy simulations, while T_c [°C], the daily temperature limit, was calculated according to the EN 16798-1 standard for comfort Class I. During summer, *discomfort hours* occur when $T_{o,in}$ exceeds the upper threshold limits; during winter, *discomfort hours* occur when $T_{o,in}$ is below the lower limit [14].

2.4. ESTIMATION OF THE CARBON DIOXIDE LEVELS

Assessing indoor air quality requires careful consideration of the carbon dioxide levels within the confined area. Carbon dioxide acts as a proxy for air quality, and in the absence of precise monitoring tools, its levels can be estimated using the following equation (2) [15]:

$$C(t) = C_{ext} + \frac{G \times 10^6}{\frac{ACH \times V}{3600}} - \left(C_{ext} - C_0 - \frac{G \times 10^6}{\frac{ACH \times V}{3600}} \right) e^{\frac{-ACH \times t}{3600}} \qquad (2)$$

where, C_{ext} ([ppm]) is the external carbon dioxide level, C_0 ([ppm]) is the threshold CO_2 concentration for classrooms in this study, G ([m^3/s]) represents the estimated CO_2 production rate (which varies by age, sex, and physical activity) [16], V ([m^3]) is the volume of the classroom, ACH ([h^{-1}]) indicates the air changes per hour, and t ([s]) denotes time. C(t) indicates the level of carbon dioxide present in the confined environment at a specific time t. These parameters were applied in simulating carbon dioxide levels: ACH of 2.5 h^{-1}, $C_{ext} = 450$ ppm [17], $C_0 = 1000$ ppm [16], V = 118 m^3, G = 0.0029 l/s. This value was derived by averaging the CO_2 production of a male child aged 3 to 6 years, which is 0.0030 l/s, with that of a female child of the same age, which is 0.0028 l/s [16].

Different ventilation hypotheses, *Hp.1*, *Hp.2*, and *Hp.3*, were considered for estimating CO_2 levels (Fig. 2). *Hp.1* and *Hp.2* ventilation strategies mirror typical summer ventilation practices, where the environment is continuously ventilated during classroom occupancy. Under *Hp.1*, windows are opened once the children have arrived, while in *Hp.2*, they enter classrooms that have already been ventilated. *Hp.3* represents a winter-specific ventilation strategy characterized by short, intermittent air exchanges throughout the classroom occupancy period. In this scenario, windows are partially opened for 10-minute intervals (from 09:16 am to 09:26 am, from 10:16 am to 10:26 am, from 11:16 am to 11.26 am, from 1:16 pm to 1:30 pm) [18]. CO_2 level simulations were repeated using a hypothetical classroom volume, *Vol.2*, which is larger

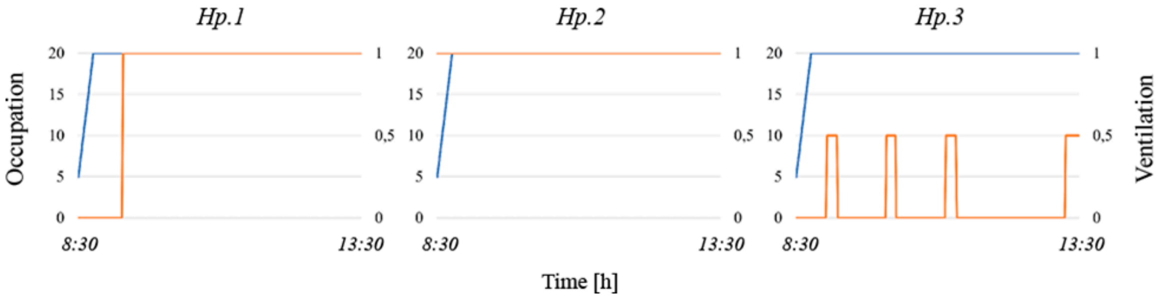

Fig. 2. *Ventilation strategies implemented in this case study,* Hp.1, Hp.2 *and* Hp.3.

than the actual volume of classroom A, to assess the impact of room size on CO_2 levels. *Vol.2* is set at 170 m^3, representing a 44% increase in the volume of Classroom A.

3. RESULTS

The results of this study are outlined in this section, and they refer to the monitoring and analyses related to Classroom A, as it was previously indicated to be representative of the case study. The first part provides a summary of the kindergarten monitoring campaign results. The second part shows the findings from the calibration of the energy model. The third section presents the results from the thermal comfort analyses, while the final part focuses on the outcomes of the indoor air quality evaluation, with the results of the carbon dioxide levels simulations.

3.1. RESULTS FROM THE MONITORING CAMPAIGN: ΔT, RELATIVE HUMIDITY, AND USERS’ BEHAVIOUR

As previously noted in the Methodology section, the data gathered from the monitoring campaign were analysed to assess the current condition of the kindergarten. This paragraph presents the results related to the temperature deltas measured in Classroom A by the data loggers and the humidity levels the room was subjected to during the monitoring period. The data loggers’ temperature data analysis is also discussed, providing insights into the users’ behaviour regarding ventilation, specifically when and how ventilation was practiced during the classroom’s occupancy hours.

Figure 3a shows the temperature differences, or deltas, recorded by sensors C and B in the two monitored classrooms during the experimental period. It is assumed that the negative ΔT values are caused by air leaks through the fixtures, especially noted during the night. The presence of outdated fixtures, which require complete replacement as noted by the authority on the ARES portal, supports this hypothesis. The analysis results of the relative humidity data are shown in Figure 3b. The graph displays a discontinuous curve, indicating a peak RH of 74% and a minimum value of 44.5%. The average relative humidity was approximately 61%, slightly above the health and safety regulations’ recommended limit for maintaining healthy school environments. The recommended range for RH is 40-60%, as indicated by the green area in the graph (Fig. 3b) [19].

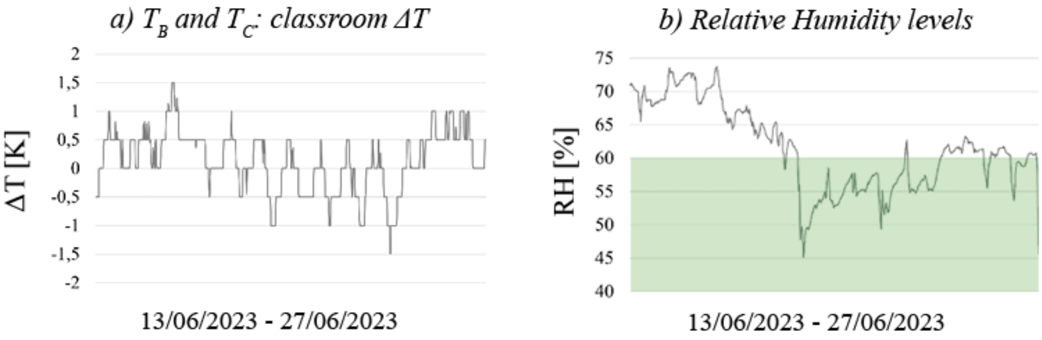

Fig. 3. *(a) Temperature differences recorded between sensors A and C, indicative of the temperature deltas to which Classroom A was subjected during the monitoring period, and (b) Relative Humidity (RH) levels measured inside Classroom A.*

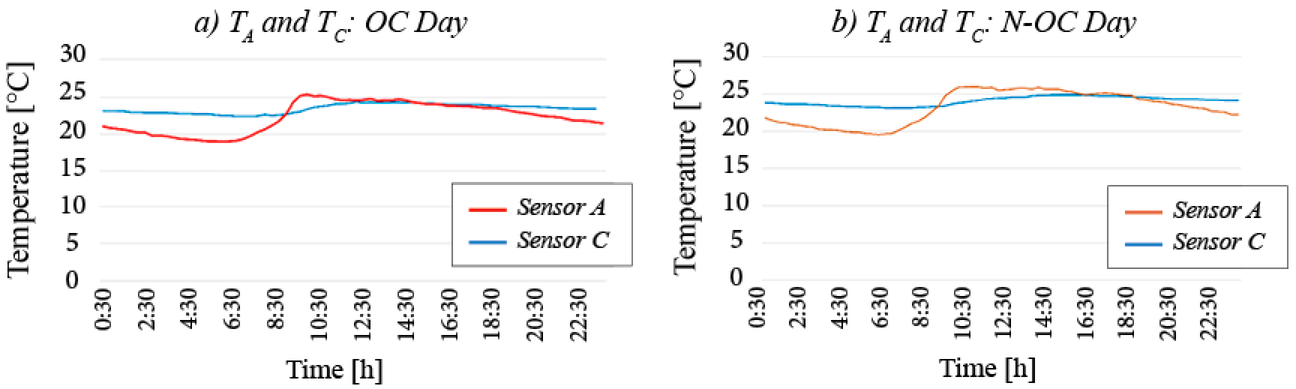

Fig. 4. *Trends of indoor temperature (Sensor C) and outdoor temperatures (Sensor A) of Classroom A on (a) days with occupancy* (OC Day) *and (b) days without occupancy (*N-OC Day*).*

Based on the temperature analysis from sensors A and C, standard ventilation models were developed for both the day with occupancy (*OC Day*) and the day without occupancy (*N-OC Day*). These models allowed us to understand that during the monitoring period, the users maintained constant ventilation during the classroom's occupancy hours. The temperature variations for both daily models are depicted in Figure 4. In the early part of the occupied day, the indoor temperature trend in the classroom is lower than that of the outdoor temperature. During occupancy hours, this pattern reverses: as the windows are opened, the classroom temperature increases due to the external thermal load heating the space. The *N-OC Day* ventilation model shows a similar trend between external and indoor temperatures, but indoor temperatures do not increase as they do in the occupied scenario because the classroom remains unoccupied, and ventilation is not carried out.

3.2. CALIBRATION OF THE SCHOOL BUILDING'S ENERGY MODEL AND INDOOR TEMPERATURE TRENDS

The calibration results of the energy model, as shown in Figure 5, compare simulated temperature data with measured ones on days when the building is occupied (Fig. 5a) and unoccupied (Fig. 5b). The indices defined by the ASHRAE Guideline 14:2014 [11] comply with the standards, as they fall within the established ranges for both occupied and unoccupied days (Tab. 1).

Standard Day Model	*NMBE*	*CV (RMSE)*	*Maximum percentage error*	*Maximum ΔT*
OC Day	0.23%	0.27%	2.18%	0.5 °C
N-OC Day	0.46%	0.53%	2.33%	0.55 °C

Tab. 1. *Calibration index results defined by the ASHRAE 14:2014 Guidelines for energy models that use hourly data.*

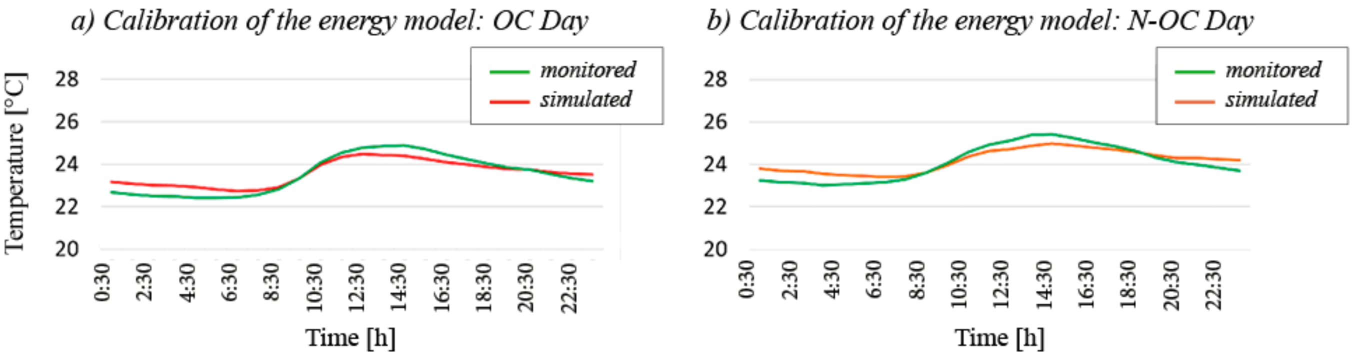

Fig. 5. *Comparison between the monitored and simulated temperatures using the energy model for both occupied and unoccupied days.*

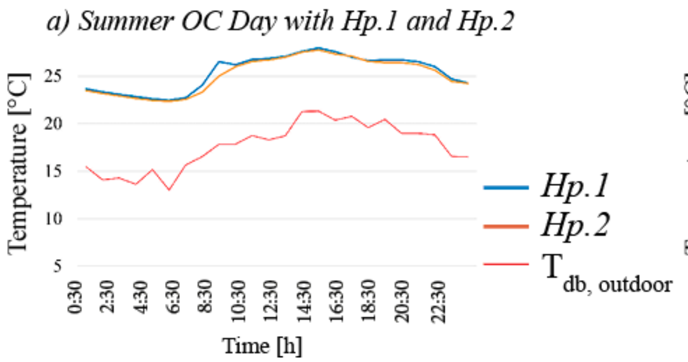

Fig. 6. *(a) Simulation of the occupied days using the* Hp.1 *and* Hp.2 *ventilation strategies and (b) Simulation of the occupied days using the* Hp.3 *ventilation strategy.*

The simulations of indoor temperature trends in classroom A resulted in different curves for each summer ventilation hypothesis, as described earlier in Section 2.4. The results for the summer ventilation strategies *Hp.1* and *Hp.2* are depicted in Figure 6a. The comparison of the two curves (Fig. 6a) reveals that both ventilation hypotheses produce similar trends. The temperature increases steadily in the morning, then levels off during the day and remains stable thereafter. At 7:00 am, both curves start with temperatures near 20°C. In the *Hp.1* curve, the temperature steadily rises until it peaks shortly after the classroom becomes occupied since the windows are closed when students arrive under this ventilation scenario. When the windows are opened, the temperature decreases. The curve under *Hp.2* remains stable throughout the day. The curves differ at the start of the school day: the *Hp.1* hypothesis shows an increase in the initial phase, whereas the *Hp.2* hypothesis maintains a more consistent trend throughout the day.

The temperature curve in Figure 6b corresponds to the trend produced by the winter ventilation hypothesis *Hp.3*. During the morning hours, the temperature steadily increases. The peak temperature occurs around midday, reaching slightly above 20°C. Following the peak, the temperature gradually declines for the rest of the day.

3.3. THERMAL COMFORT EVALUATION: DAILY DISCOMFORT HOURS ANALYSES RESULTS

The thermal comfort analyses of the classroom reveal significant seasonal differences. During the winter (Fig. 7), the $T_{o,in}$ fluctuates, often exceeding the limits of the thermal comfort zone indicated in grey. This suggests that the children may have experienced suboptimal cold conditions, indicating a potential need for improved insulation or better heating management. Out of 360 simulated hours, 45% fall within the thermal comfort zone, while the remaining 55% represent hours of discomfort. However, when narrowing the analysis to the 90 hours of actual classroom occupancy, it is observed that 65% of these hours provide comfortable conditions, while 35% fall into the discomfort zone.

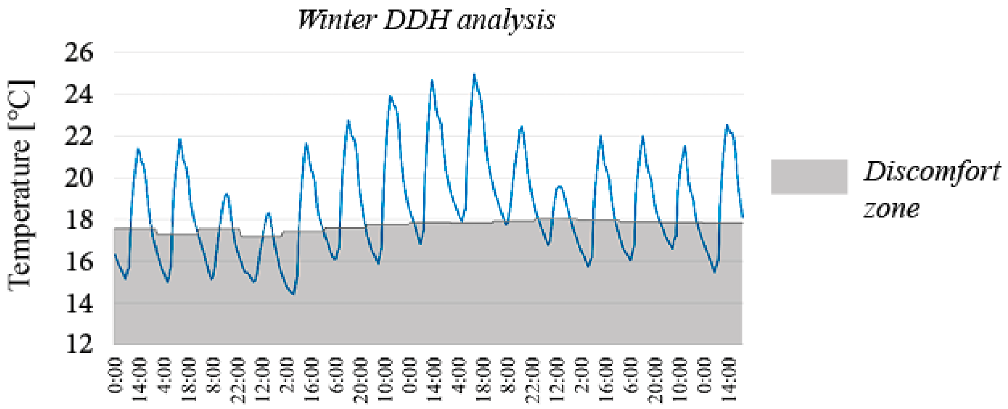

Fig. 7. $T_{o,in}$ *trend during the sample winter period. The grey area represents the thermal discomfort zone for cold months (EN-16798).*

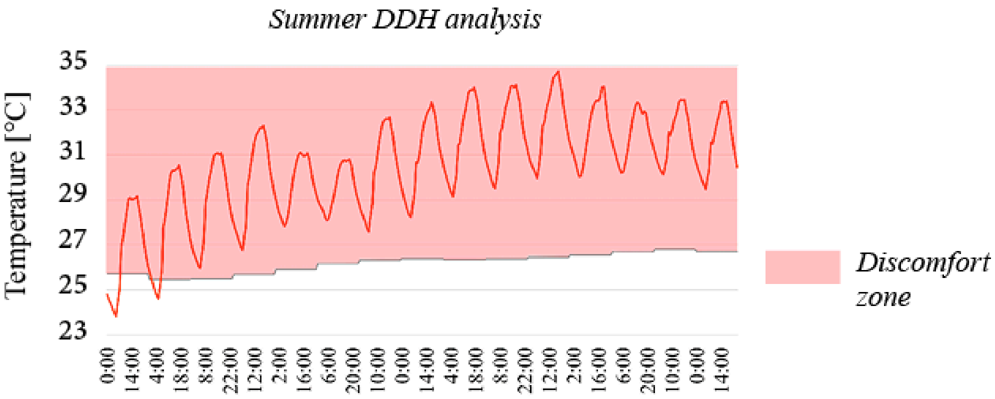

Fig. 8. *$T_{o,in}$ trend during the Classroom A monitoring campaign period. The red area represents the thermal discomfort zone for warm months (EN-16798).*

In the summer period (Fig. 8), the situation appears even more critical, with the $T_{o,in}$ frequently surpassing the thermal comfort zone indicated in red. Discomfort conditions characterized 96% of the total hours. When considering only the hours of actual classroom occupancy, all of them fall within the discomfort zone.

3.4. INDOOR AIR QUALITY EVALUATION: RESULTS FROM THE CO2 LEVELS SIMULATIONS

The carbon dioxide simulations in classroom A resulted in varying scenarios. Under the summer ventilation scenarios, *Hp.1* and *Hp.2*, the carbon dioxide levels generated by the occupants stay constant since they are continuously produced and ventilated out. The distinction between the two ventilation strategies becomes particularly clear during the initial occupancy hours: in the *Hp.1* scenario, children arrive gradually in a room with closed windows, which are only opened later, maintaining constant ventilation after that. As a result, the CO_2 concentration curve under the *Hp.1* scenario shows a spike in the early phase. Under the *Hp.2* ventilation strategy, the initial CO_2 spike does not occur because the children arrive in a room that has already been ventilated, allowing the CO_2 produced to be directly expelled without accumulation. In each case, the carbon dioxide concentrations exceed the set threshold of 1000 ppm (Fig. 9).

Using the *Hp.3* ventilation strategy, the carbon dioxide level simulation produced an irregular CO_2 trend. Specifically, the simulated CO_2 levels are considerably higher than those observed under typical spring and summer environmental conditions (Fig. 10).

The simulations of CO_2 levels conducted with the increased volume of Classroom A, *Vol.2*, demonstrate how indoor pollutants accumulate more slowly. As a result, the curves representing these levels in the graphs are lower than those obtained with the original volume. However, despite the slower accumulation, CO_2 concentrations still exceed the established limit of 1000 ppm.

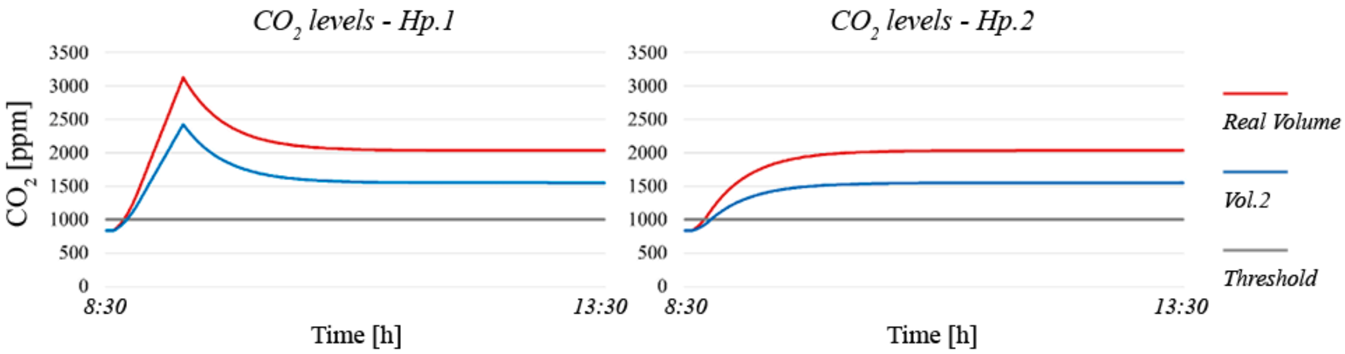

Fig. 9. *Carbon dioxide levels simulations with summer ventilation strategies,* Hp.1 *and* Hp.2. *The red curves represent the simulations conducted with the actual volume of Classroom A, while the blue curves represent the simulations performed with the increased volume,* Vol.2.

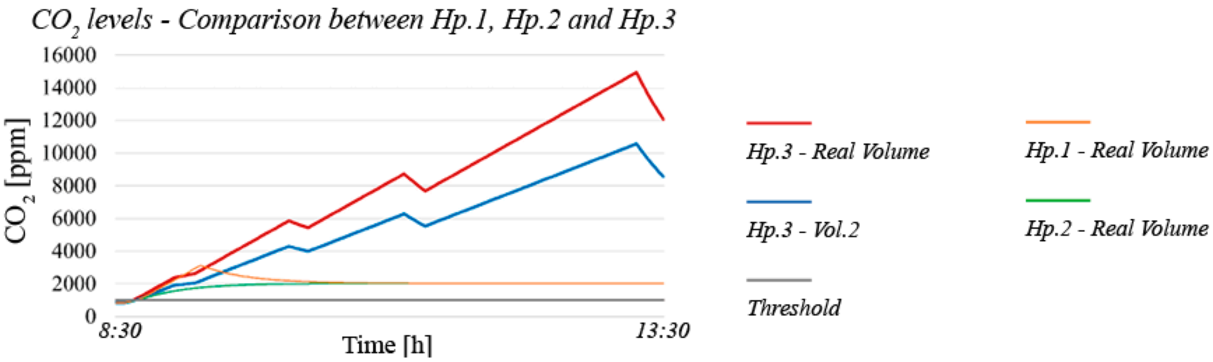

Fig. 10. *Comparison between the carbon dioxide levels simulated with all the ventilation hypotheses.*

4. DISCUSSION

This paper provides a comprehensive overview of the indoor environmental quality at the John Fitzgerald Kennedy kindergarten in Bari. The monitoring campaign in the kindergarten, along with the data analysis and the simulation of thermal comfort and indoor air quality, provided interesting insights into the current state of this school building. Analysis of the collected data (Fig. 3a) indicates that classroom temperature variations hinder the maintenance of a stable indoor temperature. It was hypothesized in this study that the observed negative temperature variations result from air infiltration through windows, particularly at night. The presence of outdated windows, as noted in the ARES portal, supports this hypothesis.

The collected data on relative humidity reveal that, throughout much of the monitoring period, the levels fell short of the standards set by both Italian and international regulations to ensure safe and healthy indoor environments (Fig. 3b) [19]. Maintaining proper control over indoor relative humidity levels is crucial, particularly in buildings occupied by fragile users, as is this case.

The analysis of the trends in internal and external temperatures suggests that the occupants maintain constant ventilation during the warm season (Fig. 4a). This is a common strategy in buildings without cooling systems and under favourable wind conditions (in terms of direction and speed), it can have positive effects on thermal comfort within the classroom [5]. However, a more in-depth comparison between outdoor and indoor temperatures reveals a more complex situation: during periods of occupancy, the indoor temperature of the classroom tends to increase not only due to the activities inside but also because outdoor heat infiltrates the environment. As a result, by opening the windows, the classroom quickly reaches thermal equilibrium with the outside, reducing the effectiveness of natural ventilation as a cooling strategy. Instead of lowering the internal temperature, this practice can facilitate the entry of external heat, thereby compromising the potential benefits of natural ventilation in maintaining a comfortable indoor climate. However, among the ventilation strategies analysed, some stand out as particularly effective in ensuring a more uniform level of comfort within the classroom. Simulations of indoor temperature trends under different ventilation strategies have yielded valuable insights into indoor thermal comfort. The *Hp.2* summer ventilation strategy is particularly effective in maintaining consistent indoor temperatures throughout the day (Fig. 6a), indicating that a well-managed ventilation approach can prevent potential classroom overheating during summer and enhance internal thermal comfort. In this scenario, the windows are opened before the occupants arrive, allowing for a pre-cooling effect that contributes to the overall stability of indoor temperatures. The *Hp.1* ventilation strategy results in more significant temperature fluctuations early in the school day; without ventilation upon the arrival of users, temperatures increase due to passive overheating caused by the influx of occupants and rising external temperatures. Except for this early difference, the two curves reflect similar thermal behaviour in space, as both assume a constant ventilation regime.

The curve for the winter temperature trend under *Hp.3* shows a distinct pattern compared to the summer models

(Fig. 6b). The simulated rise in temperature during classroom occupancy hours is attributed to passive heating from solar gain and occupants' activity, leading to heat buildup in the absence of natural ventilation. This pattern is adjusted by brief ventilation periods that result in minor heat loss; nevertheless, in the *Hp.3* regime, these intervals are insufficient to properly dilute indoor pollutants or remove the carbon dioxide generated by occupants, as illustrated in the CO_2 simulation analysis. This finding highlights the need for scheduled natural ventilation that balances air quality and heat retention, particularly during the colder months, to provide comfortable indoor conditions [20].

The analysis of thermal comfort during the summer period reveals that relying solely on natural ventilation is insufficient to prevent thermal discomfort (Fig. 7). Although classrooms with natural ventilation have lower CO_2 levels than those with mechanical ventilation, they tend to experience higher temperatures [21]. The south-east exposure exacerbates this issue, leading to all occupied hours falling within the thermal discomfort zone. This critical situation necessitates targeted interventions to improve summer conditions, such as implementing cooling strategies and solar shading [23]. While the south-east exposure is less problematic in winter and generally allows for greater thermal comfort compared to summer (Fig. 8), maintaining optimal conditions for the children still requires a reliable heating system.The CO_2 level simulations highlight the necessity of effective ventilation strategies to maintain CO_2 concentrations below the threshold. Between the two summer ventilation strategies, *Hp.1* and *Hp.2*, the latter was more effective in lowering carbon dioxide levels, owing to the pre-ventilation of the space before occupants enter (Fig. 9). By avoiding CO_2 concentration spikes, this strategy ensures a well-ventilated and clean environment. On the other hand, the *Hp.3* winter ventilation strategy is typically used during the colder months when the heating system is operational. During the winter, ventilation is minimized to avoid heat loss and energy waste from open windows, leading to a notable decline in indoor air quality [5]. The simulations using the third ventilation strategy demonstrate how winter CO_2 accumulation can surpass the acceptable threshold (Fig. 10). Therefore, it is essential to implement an effective natural ventilation strategy to limit indoor pollutants produced by occupants [20]. In crowded spaces, the COVID-19 Report No. 33 from the Italian National Institute of Health advises that ventilation systems be activated before occupants enter. This approach can be integrated into naturally ventilated buildings, allowing occupants to arrive in a pre-ventilated space, thereby improving pollutant removal, as shown by the CO_2 simulations [24]. The volume of the enclosed space is another critical factor in indoor air quality analysis. Environments with smaller volumes are observed to reach saturation faster compared to larger ones [25]. While the carbon dioxide simulations with the increased classroom volume (*Vol.2*) show that even with a larger space, CO_2 levels still exceed 1000 ppm, this approach can nonetheless contribute to improving air quality.

5. CONCLUSION

This study identified critical issues in Italian school buildings that negatively affect occupant comfort, emphasizing the need for energy retrofitting and fixture replacement to improve indoor environmental quality. The research highlighted that seasonally adapted ventilation strategies are crucial to enhancing both thermal comfort and air quality. Finally, the study demonstrated the importance of comprehensive monitoring and data analysis in developing efficient management programs and ventilation systems that optimize building performance and occupant well-being.

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Authors contribution

E.C. contributed to the writing of the manuscript, the creation of the figures, and data analysis. L.M.C. and F.C. were responsible for reviewing the manuscript. F.M. and F.F. coordinated work.

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