

Is evaporative cooling an efficient solution for ensuring air quality and thermal comfort in overheated classrooms in a dry Mediterranean climate? ☆

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ARTICLE INFO

Keywords:

Overheating
Evaporative cooling
School buildings
Building performance simulation
Adaptive thermal comfort
Indoor air quality
Computer-aided design

ABSTRACT

A large percentage of school buildings in Mediterranean climates that rely solely on natural ventilation face critical issues related to indoor overheating and poor air quality. Despite the severity of these challenges, there is limited research quantifying the problem and exploring viable cooling solutions that align with nearly zero-energy building (nZEB) standards. This study aims to fill that gap by presenting a case study on the environmental performance of a classroom with a direct evaporative cooling system. The school is located in southern Spain, a region characterised by a hot and dry Mediterranean climate. The primary objective is to assess whether such a system can ensure both thermal comfort and adequate indoor air quality during periods of overheating. Based on on-site monitoring data, an EnergyPlus simulation model was calibrated and validated. This model was then used to test a range of current and future climate conditions, as well as different ventilation strategies, including natural ventilation and evaporative cooling with different air change rates. The results demonstrate the effectiveness of the direct evaporative cooling system compared to conventional natural ventilation, reducing overheating hours by up to 26% and lowering indoor temperatures by as much as 6 °C.

1. Introduction

1.1. Overview

Climate change is intensifying the phenomenon of overheating in buildings. The sustained increase in outdoor temperatures compromises the habitability, thermal comfort and health of their occupants, and leads to an increase in energy demand for cooling in buildings [1]. For this reason, different thermal mitigation strategies are being considered in different latitudes: at the urban level [2], from the use of cool materials to urban vegetation enhancement; at the building level, with resilient buildings thanks to Sustainable Energy Technologies, thermal storage, heat pumps, or smart control [3]; and with solutions adapted to

the preservation of cultural heritage [4], such as passive and evaporative cooling strategies.

A large part of our building stock was designed under energy standards and climatic conditions that differ from the present ones. The necessary energy adaptation of the building stock must face new challenges, such as the increasing intensity and severity of heatwaves [5]. Therefore, there is an important need to investigate the risk and consequences of global warming on buildings, not only under current climatic conditions, but also under future scenarios, as some researchers suggest these may be worse than initially estimated [6].

This new overheating scenario is exacerbated in buildings such as schools [7], with high occupancy densities and continuous periods of use. Moreover, overheating in these buildings affects students' air quality and thermal comfort [8,9], their well-being [10], and academic

☆ This article is part of a special issue entitled: 'Rethinking Resilience' published in Energy & Buildings.

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Nomenclature

Symbols

η	efficiency
RH	relative humidity [%]
T	temperature [°C]
U	U-value, i.e., thermal transmittance [W/m ² K]

Acronyms

AC	air conditioning
ACH	air change per hour
CV(RMSE)	coefficient of variation of the root mean square error
DEC	direct evaporative cooling
EC	evaporative cooler
HVAC	heating, ventilating and air conditioning
IAQ	indoor air quality
MBE	mean bias error
MM	mixed mode
MV	mechanical ventilation
NV	natural ventilation (no thermal treatment)
PMV	predicted mean vote
PPD	percentage of persons dissatisfied

performance [11,12]. Energy retrofitting actions aimed at achieving the requirements of nearly zero-energy buildings (nZEB) usually focus on energy consumption [13], with little attention given to the indoor environmental quality of the building [14]. However, a combined approach is necessary to address the assessment of indoor air quality

(IAQ) and thermal comfort, as the occupants of school buildings are more vulnerable than adults and have less control over the quality of the indoor environment [15]. Furthermore, the COVID pandemic highlighted the difficulty of ensuring both aspects and the importance of adequate IAQ conditions [16,17]. Adequate ventilation rates therefore have beneficial effects on health and well-being, although they come at an energy cost and a generalised worsening of comfort conditions [18].

Passive retrofit strategies in school buildings vary depending on the climate zone. Thus, the usual passive measures of high levels of insulation and airtightness with double-pane glass windows are effective in reducing demand in winter, but lead to an increase in overheating hours, as found by Baba et al. [19] in a study with simulation models in desert schools or Barbosa et al. [20] in a school with a Csb climate.

The need to mitigate and adapt to the impacts of climate change in mild climates will be more pronounced in the Mediterranean region, where, according to the 6th Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) [21], cooling requirements will continue to increase over time. Furthermore, incorporating information communication technology (ICT) in classrooms leads to an increase in internal heat gains, consequently leading to a higher risk of overheating [22].

Singh et al. [9] compiled the extensive literature on thermal comfort studies in schools, concluding that climate zone and geographical region are influential and differentiating factors. However, in general, energy efficiency measures are not based on effective ventilation strategies. Nevertheless, a review by Diaz-Lopez et al. [23] noted that, in hot climates, research focuses on natural ventilation, and that in recent years, increased concern about climate change and numerical measurement methods have prompted works about comfort and IAQ.

However, as can be seen in Table 1, studies conducted during periods of overheating in the Mediterranean climate subtypes “hot dry-summer”

Table 1

Summary of studies on Mediterranean climate and overheating periods with a combined assessment of IAQ and comfort conditions.

Year	Reference	Köppen climate zone	School type (sample size)	Operation type	Monitoring period	Indoor T ^a [°C] (min–max or max)	Indoor HR [%] (min–max or max)	Indoor CO ₂ [ppm] (min–max or max)
2011	Zahiri et al. [24]	Csa Tehran (Iran)	Primary (2)	NV	Spring*	29.5	–	–
2013	D'Ambrosio et al. [25]	Csa Campania (Italy)	Primary + secondary (6)	NV	Summer*	–	–	–
2014	Dias Pereira et al. [26]	Csa Beja (Portugal)	Secondary (1)	NV	Spring*	17–24	–	917–2222
2014	Dhalluim and Karim [27]	Csa, La Rochelle (France)	University	MM	Summer*	19–25	20–70	<1000
2015	Dorizas et al. [28]	Csa Athens, (Greece)	Primary	NV	Spring*	25.6	52.7	>1000
2016	Almeida et al. [29]	Csb Viseu (Portugal)	Primary (10) + secondary (7)	NV	Spring*	–	–	–
2017	Treblicock et al. [30]	Csa Santiago (Chile)	Primary (12)	NV	Winter* Spring*	8–20 16–32	–	–
2017	Duarte et al. [31]	Csb Lisboa (Portugal)	Secondary (1)	NV	Spring Summer	–	–	–
2018	Tahsildoost et al. [32]	Csa Tehran (Iran)	University (3)	NV NV + EC	Spring* Summer*	27 31.7	– 39	521–861 506–1489
2019	Calama-González et al. [33]	Csa Seville (Spain)	Secondary (1)	NV	Spring Summer	9.5–24.9 15.7–30.8	29–84 25–67	312–2000 369–2000
2021	Gil-Baez et al. [34]	Csa Seville (Spain)	Primary (3) + Secondary (5)	NV	Spring	18.6–24.4	32.3–67.9	667–2919
2021	Aparicio-Ruiz et al. [35]	Csa Seville (Spain)	Primary	NV AC	Summer*	33	43.5	–
2023	Miao et al. [36]	Csa Barcelona (Spain)	Primary (9) + Secondary (7)	NV	Spring* Summer*	19.9–23.3 23.7–28.4	25.1–46.0 30.3–50.2	347–2446 341–4015
2024	De la Hoz-Torres et al. [37]	Csa Granada (Spain)	University	NV	Spring* Summer*	18.1–28.9 20.6–29.2	21.3–54.0 19.6–50.1	–
2025	Alonso et al. [38]	Csa Seville (Spain)	Secondary (7)	NV	Spring* Summer*	25.4 32.6	33	<900 <600
2025	Romero et al. [39]	Csa Beja (Portugal)	Secondary (1)	NV/AC	Summer	22.9–31.3	32.7–63.1	–

AC: Air Conditioning; EV: Evaporative Cooling; MM: Mixed Mode; MV: Mechanical Ventilation; NV: Natural Ventilation. * Monitoring for subjective evaluation of thermal conditions.

(Csa) and “cool dry-summer” (Csb) remain scarce. The assessment of indoor overheating conditions is more accurate when on-site measurements are taken. In general, studies are often limited to short monitoring periods, as most measurements are taken for the subjective evaluation of thermal conditions.

Natural ventilation is usually the primary ventilation strategy, being beneficial when outdoor conditions are within the comfort zone [28,40]. It is therefore configured as the main strategy to reduce overheating during the spring period or in climates with moderate summers [27]. However, when outdoor temperatures exceed comfort temperatures (above 34–35 °C), indoor comfort in school buildings is compromised, with clear situations of overheating [24] and indoor temperatures reaching 32–33 °C [32,35,38].

Although these studies assess overheating conditions, few studies further relate indoor comfort conditions to IAQ. In those that do, it is observed that an increase in CO₂ concentration occurs when outdoor temperatures rise, as window opening is reduced to avoid overheating [32,36]. Some authors suggest that an adequate ventilation protocol is the key to balancing IAQ and thermal comfort, which could be an effective solution when outdoor temperatures do not exceed 24–25 °C [36]. However, due to the high summer temperatures in a Mediterranean climate, natural ventilation cannot overcome internal thermal loads. Thus, authors such as Becker et al. [41], Baba et al. [19], and Baglivo et al. [42] have emphasised the need to activate mechanical cooling systems. Calama et al. [43] proposed CO₂-based optimised demand solutions, which guarantee better environmental conditions and lower energy consumption.

In this scenario, some studies have proposed evaporative cooling systems as a solution to reduce overheating in buildings in hot and dry climates. These systems reduced energy consumption compared to conventional heating, ventilating, and air conditioning (HVAC) solutions. However, it is usually a very limited [44] and rarely implemented solution in schools in Mediterranean climates [45], appearing in only 2% of the studies as reported by Díaz-López et al. [46] in a critical review. In hot climates, the effectiveness of the system is usually linked to a significant increase in the ventilation rate, generally through the combined use of windcatchers [47] or solar chimneys [48]. Thus, Jaber and Ajib [49] evaluated the effectiveness of indirect evaporative cooling in Jordanian dwellings with temperatures up to 34 °C.

Despite the lack of specific studies on the performance and effectiveness of evaporative cooling systems in Mediterranean schools, the Regional Government of Southern Spain (through the use of European Regional Development Funds) has actively supported their installation in a significant number of schools located in hot and dry climates. This initiative is part of the Bioclimatisation Law for schools in southern Spain [50], which aims to mitigate the effects of heat in classrooms.

1.2. Objectives of the study

This literature review has identified key gaps related to overheating in schools located in Mediterranean climates:

- Few studies focus on this region, and even fewer rely on on-site measurements to develop a combined assessment of thermal comfort and IAQ.
- Passive measures and natural ventilation are generally insufficient to guarantee both IAQ and thermal comfort during overheating periods.
- Although evaporative cooling systems show potential to solve this problem (see Appendix A), there are hardly any studies that assess their effectiveness in schools under current and future climate scenarios.

This lack of research poses a major challenge in the search for appropriate solutions to address the problem within the requirements for achieving nZEB.

In order to address these knowledge gaps, the main objective of this work is to offer a viable option for ensuring IAQ and effectively mitigate the risks of overheating in current and future climatic conditions in Mediterranean classrooms. The major novelty of this study is the practical evaluation of the performance of a direct evaporative cooling (DEC) system in educational buildings, by means of building simulation models validated with on-site measurements. A comparative evaluation of air quality and thermal comfort between different ventilation scenarios will be carried out in a classroom in southern Spain.

2. Case study description

A high school located in the city of Seville, southern Spain (Csa Köppen climate zone), built in 1996, was selected as the case study (Fig. 1a). Two classrooms, one facing north and the other one facing south, were analysed in detail (Fig. 1b), following the spatial scheme most commonly used in educational buildings in this region: classroom-corridor-classroom [51]. The area of each classroom is approximately 45.80 m² (5.80 m width × 7.85 m length), with a height of 2.75 m. The corridor that separates both classrooms is 2 m in width.

The main constructive parameters used to define the thermal envelope of the simulation models are summarised in Table 2. Another parameter of great relevance in the thermal behaviour of the models is occupancy, which has been defined as 24 students plus the teacher (approximately 1.8 m²/ person). The use schedule is from 8:15h to 14:45h.

An evaporative cooling system was installed in both analysed classrooms to assess its performance in the Mediterranean climate of Seville. On the monitoring day (3 June 2024), the average outdoor temperature reached 31.8 °C, and the mean relative humidity was 30.9%.

Fig. 2 shows the direct evaporative cooling (DEC) system installed on the roof of the educational building, which is used to condition several classrooms in the same school (seven classrooms in total), despite this work focuses specifically on the performance of the system in one southern and one northern classroom. In this case, TECNA QA160D and QA255D Coolbreeze models were installed, and their main characteristics are summarised in Table 3.

3. Materials and methods

This section presents the methods and concept for the realisation of the evaporative cooler model (Section 3.1), its validation (Section 3.2) using on-site measurements, and the comfort evaluation (Section 3.3).

3.1. Model description

After creating the geometric and thermophysical model representation of the two classrooms analysed (i.e., the northern classroom and the southern classroom of the aforementioned school), a model was created to simulate the behaviour of the direct evaporative cooling (DEC) system, installed in the same school to serve the classrooms.

In particular, the model developed and existing in the case study consists of a rigid media evaporative pad, with water recirculated from a reservoir (see Fig. 3). The water is pumped from the reservoir to a water distribution header for a gravity-fed water supply from above the media. The evaporative pad provides the surface area where the air undergoes adiabatic saturation. Although the process results in a lower dry-bulb temperature, the moisture content of the outgoing air is higher than that of the incoming air. The direct stage is used for comfort cooling buildings where adding humidity to the air can be tolerated. This thermodynamic process is a simultaneous heat and mass transfer, or adiabatic cooling, and follows a constant enthalpy line on the psychrometric chart (see Appendix A, Fig. A.1). Since the deviation between the constant wet-bulb and the constant enthalpy lines is small, it is assumed that the wet-bulb temperature is constant throughout the direct evaporative stage.

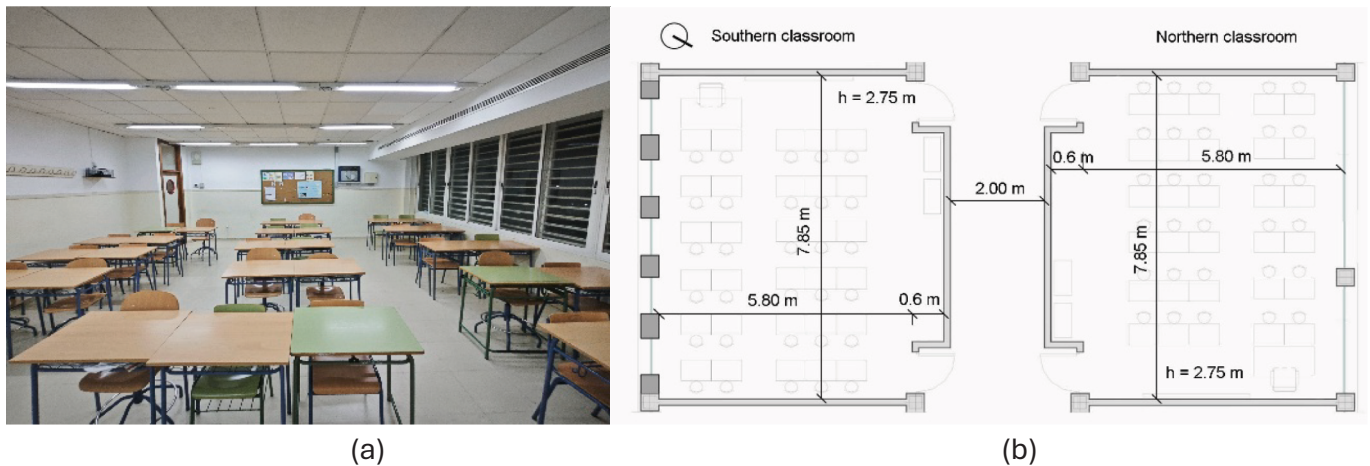


Fig. 1. (a) Image of one of the analysed classrooms; (b) Floor plans of the analysed classrooms.

Table 2

Thermal envelope description.

Thermal envelope component	Description	U-value [W/m ²]
Windows	Sliding single-glazed and aluminium frame. Window-wall ratio: 45% (southern classroom) – 65% (northern classroom).	5.00–5.50
Solar protection	External movable horizontal slats in all windows.	–
Façade	Brick wall (11.5–24 cm) + non-ventilated air chamber (3–5 cm) + hollow brick partition (7–8 cm) + gypsum plastering.	1.05–1.45

The element selected in the EnergyPlus software to model the behaviour of the DEC system is: *EvaporativeCooler:Direct:CelDekPad*. The element describes the system as a direct evaporative cooler with a rigid media evaporative pad and a recirculating water pump. In addition, it is also able to define a system availability schedule, which will then

correspond with those of the other elements of the system. It is clearly possible and necessary to define the input and output nodes, but the two most important and sensitive fields are the direct pad area [m²] and the direct pad depth [m].

The scheme shown in Fig. 4 summarises the operation of the air ventilation and cooling system developed, based on a Direct Outdoor Air System (DOAS).

The system is divided into two main sections, each with a specific function:

I. Supply side

This section is responsible for treating the air before it is released into the rooms. The process follows these steps:

- Air intake: the system draws fresh air directly from the outside (*Outside Air Inlet*), a distinctive feature of DOAS, ensuring a constant supply of outdoor air.

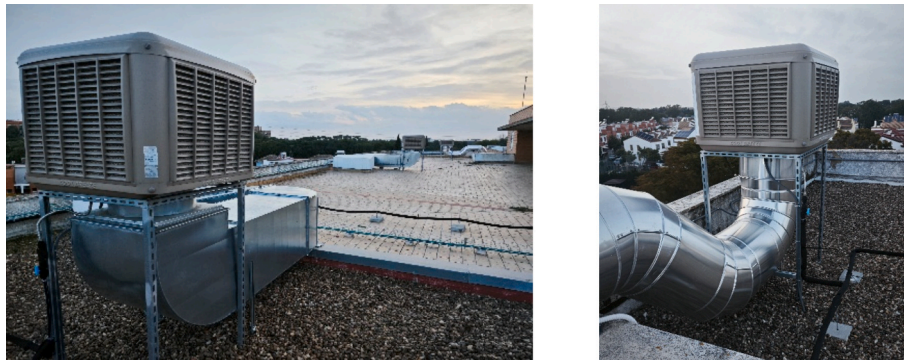


Fig. 2. Direct evaporative cooling system installed in the school.

Table 3

Main technical characteristics of the DEC system installed in the school.

Model	Total rate [m ³ /h]	Fan power [W]	Cooling capacity [kW]	Classroom (total number of conditioned classrooms in the school)	Rate per classroom according to % operation [m ³ /h] (ACH)				
					10%	25%	50%	100%	IDA2
QA160D	13,000	750	11	Southern (3)	650 (4.2)	1625 (10.5)	3250 (21)	6500 (41.9)	950 (6.1)
QA255D	20,500	1000	17	Northern (4)	680 (4.4)	1700 (11)	3400 (21.9)	6800 (43.9)	1250 (8.1)

Note: IDA2 refers to the minimum ventilation rate established by the applicable Spanish regulation.

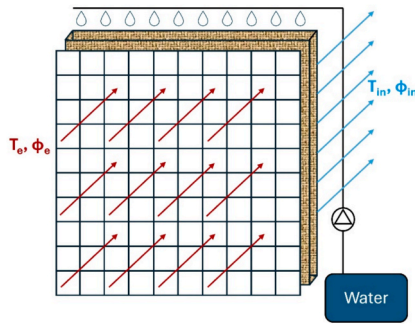


Fig. 3. Example of a direct evaporative cooler working flow.

- Fan: once inside, the air passes through a fan that regulates its flow and ensures the necessary pressure for effective distribution to the classrooms.
- Evaporative cooler (EC): after being pushed by the fan, the air enters an *Evaporative Cooler*, which lowers its temperature while simultaneously increasing its relative humidity, thereby improving perceived comfort.
- Distribution of treated air: once cooled, the air is sent to the outlet node on the supply side (*Supply Outlet Node*), ready to be distributed to the different areas of the building.

II. Demand side

After treatment in the *Supply Side* section, the air is sent to the indoor spaces through a complex distribution system:

- The airflow is conveyed to two distinct environments (classrooms), the northern classroom and the southern classroom, each requiring independent ventilation.

- Distribution system: the *Zone Supply Air Splitter* divides the air into two separate channels, directing it to the two classrooms through their respective entry points (*Inlet Node N* and *Inlet Node S*).

Thanks to this configuration, the system enables the environmental conditions to be controlled separately, ensuring that the airflow can be managed effectively in each space. Moreover, the use of a DEC system also helps reduce energy consumption compared to traditional air conditioning systems, making it particularly advantageous from a sustainability perspective.

3.2. Validation

Once the model was developed, it was validated using data obtained from on-site measurements conducted at the analysed school on 3 June 2024, as described in the case study section.

Specifically, temperature and relative humidity measurements were collected to evaluate the evaporative cooler's performance under different operating conditions: namely, at 25%, 50%, and 100% of its nominal volumetric airflow rate. The measured data, presented in Table 4, were then compared with the simulated results from the EnergyPlus model. This comparison allowed the identification of the

Table 4
Applied measurement protocols and time.

Protocol			Hour [h]
I	No	Windows opened (100%)	11:28–11:48
II	occupancy	Windows closed (0%)	11:48–11:58
III		Windows closed + DEC (25% – 1625 m ³ /h)	11:58–12:28
IV		Windows closed (0%)	12:28–12:48
V		Windows closed + DEC (50% – 3250 m ³ /h)	12:48–13:18
VI		Windows closed + DEC (100% – 6500 m ³ /h)	13:18–14:01

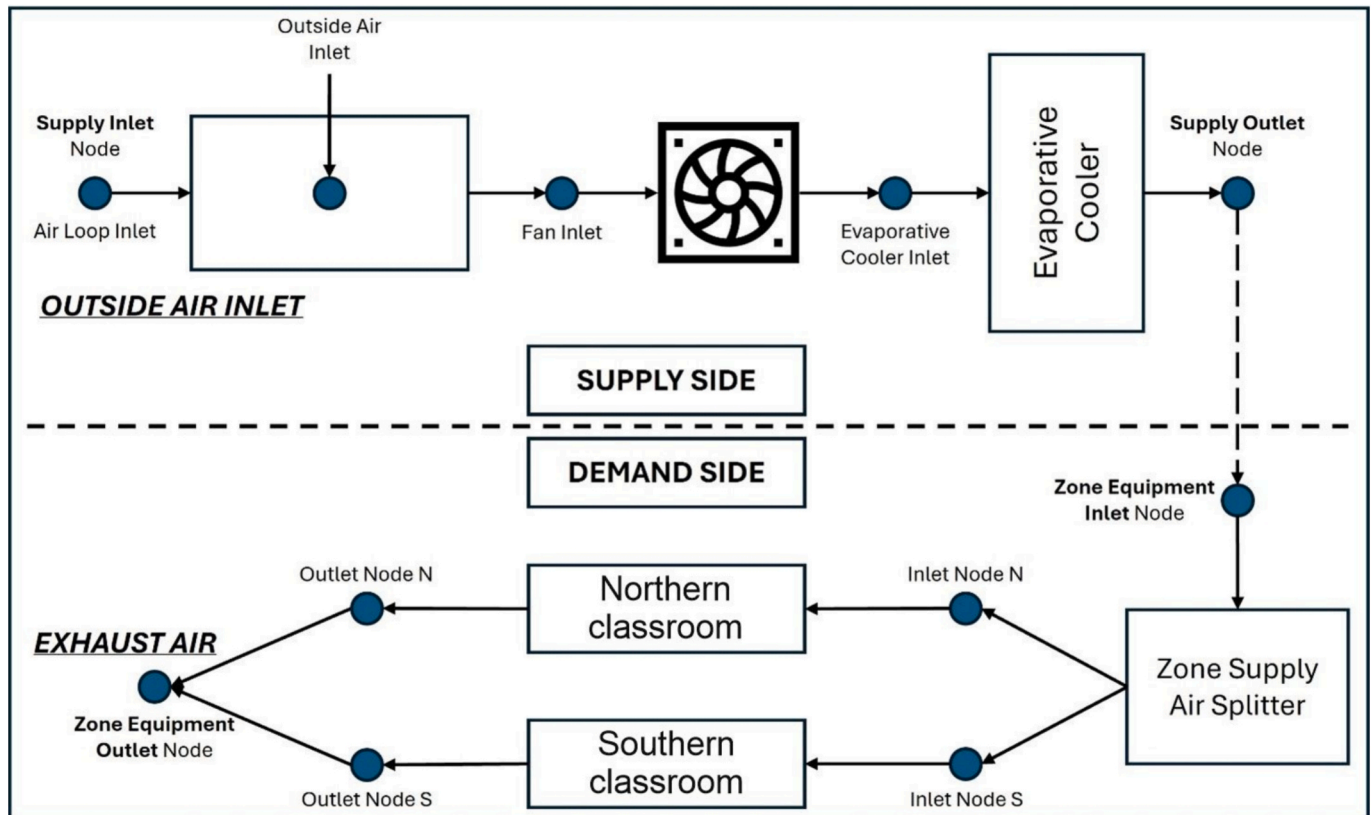


Fig. 4. Description of the supply-side and demand-side system concepts.

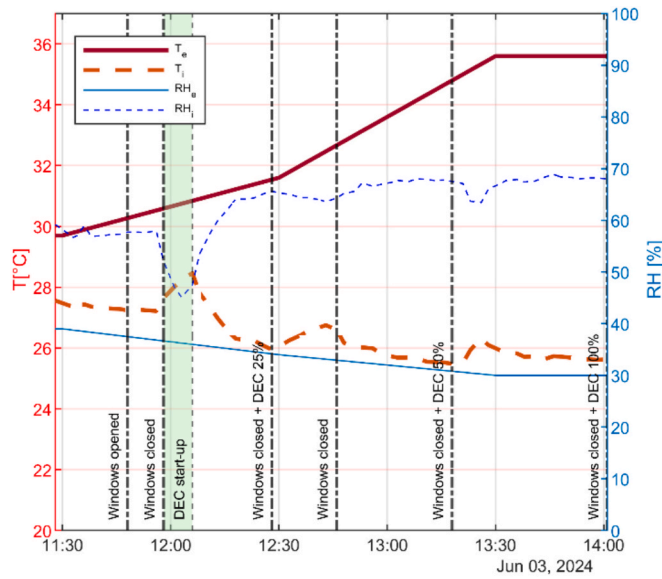


Fig. 5. On-site measured temperature and relative humidity, both indoor (dotted line) and outdoor (continuous line).

optimal calibration parameters, to ensure that the simulated behaviour of the DEC system closely reflected its real performance.

As shown in Table 4, the measurement campaign was conducted in the southern classroom between 11:28 and 14:01, following different

$$T_{rm} [^{\circ}\text{C}] = \frac{(T_{rm1} + 0.8 \times T_{rm2} + 0.6 \times T_{rm3} + 0.5 \times T_{rm4} + 0.4 \times T_{rm5} + 0.3 \times T_{rm6} + 0.2 \times T_{rm7})}{3.8} \quad (2)$$

testing protocols while maintaining a zero occupancy. The experimental procedure consisted of the following steps:

- (I) The classroom was fully ventilated with all windows open 100% for the first 20 min.
- (II) The windows were then closed for approximately 10 min.
- (III) The DEC system was activated at 25% airflow for about 30 min.
- (IV) The windows were closed again for 20 min.
- (V) The DEC system was set to 50% airflow and operated for 30 min.
- (VI) Finally, the DEC system was operated at 100% airflow for approximately 45 min.

Fig. 5 shows the measured outdoor and indoor temperatures and relative humidity during the monitored period. As can be seen, at the start of protocol III, i.e., when the DEC system is firstly activated, there is a slight increase in indoor temperature (T_i) and a decrease in indoor relative humidity (RH_i). This behaviour is most likely associated with the system start-up phase, i.e., the porous medium of the evaporative pad is initially dry, and therefore the fan provides only mechanical ventilation; without any evaporative cooling effect.

To ensure a consistent comparison of the system's behaviour under the same conditions, the climate file used for the simulation (EnergyPlus) was modified by inserting the on-site measured outdoor conditions: outdoor temperature (T_e) and relative humidity (RH_e). The calibration process has been carried out according to the ASHRAE Guideline 14 (explained in detail in Appendix B).

3.3. Comfort evaluation

Once the simulation model was validated, the standard climate file

for the city of Seville, obtained from the Meteororm v.8.0 software database, which collected hourly measured data between 2010 and 2020, was used. This enabled the evaluation of the thermal behaviour of the case study under current climatic conditions, applying different ventilation scenarios: natural ventilation without thermal treatment, and evaporative cooling with the DEC system. In addition, in order to assess the long-term effectiveness of the DEC systems in the climate of southern Spain, an hourly climate projection file for the year 2050 (RCP8.5) was also applied, generated by the Meteororm v.8.0 software using statistical data from 2020 to 2100. The Intergovernmental Panel on Climate Change (IPCC) defines the RCP8.5 (based on Representative Concentration Pathways [52]) as the most unfavourable scenario.

Two approaches have been used for the evaluation of indoor thermal comfort: the static design criterion established in the current Spanish regulations for thermal installations in buildings (RITE [53]), and the adaptive method defined by Barbadilla et al. [54], which adjusts the EN 16798-1:2019 standard [55] to Mediterranean climate case studies. The first approach sets a summer indoor design temperature of between 23 and 25 °C for people with a sedentary metabolic activity of 1.2 MET, a clothing level of 0.5 CLO, and a PPD (percentage of persons dissatisfied) of less than 10%. In the second, the optimal indoor comfort temperature (T_{opt}) is defined by Eq. (1). This is calculated as a function of the running mean external temperature (T_{rm}) defined in Eq. (2), which must be maintained between 10 and 30 °C in order for the calculation of the T_{opt} to be applicable.

$$T_{opt} [^{\circ}\text{C}] = 0.24 \times T_{rm} + 19.3 \quad (1)$$

where T_{rmX} represents the running mean external temperature of the previous 7 days.

This adaptive criterion considers an occupant metabolic rate between 1.0 and 1.3 MET and a degree of clothing between 0.4 and 1.0 CLO (which can be adapted by the users). As recommended for existing buildings, this work establishes an acceptability range of $T_{opt} \pm 3.5$ °C, which corresponds to a PPD below 20%.

4. Results and discussion

4.1. Model validation

During the model validation process, as explained in Section 3.2, the climate file was modified to align the measured external temperature values with those used in the simulation. Then, several simulations were performed to identify the optimal configuration of the direct evaporative cooler (DEC) in terms of surface area (direct pad area) and length (direct pad depth). For fixed volumetric flow values and considering the size of the installed DEC, partialised according to the simulation at 25, 50 and 100%, the values of 0.75 m² (as direct pad area) and 0.20 m (as direct pad depth) were selected.

Although two classrooms were modelled, the results presented refer to the southern classroom, which represents the most critical condition due to its higher thermal load. Figs. 6, 7, and 8 illustrate, for each volumetric flow rate, the comparison between measured (solid line) and simulated (dashed line) indoor temperature (top) and relative humidity (bottom). As shown, the model reproduces the DEC system's behaviour with a high level of accuracy on a minute scale. Table 5 confirms this through MBE and CV(RMSE) values that fall within the acceptable

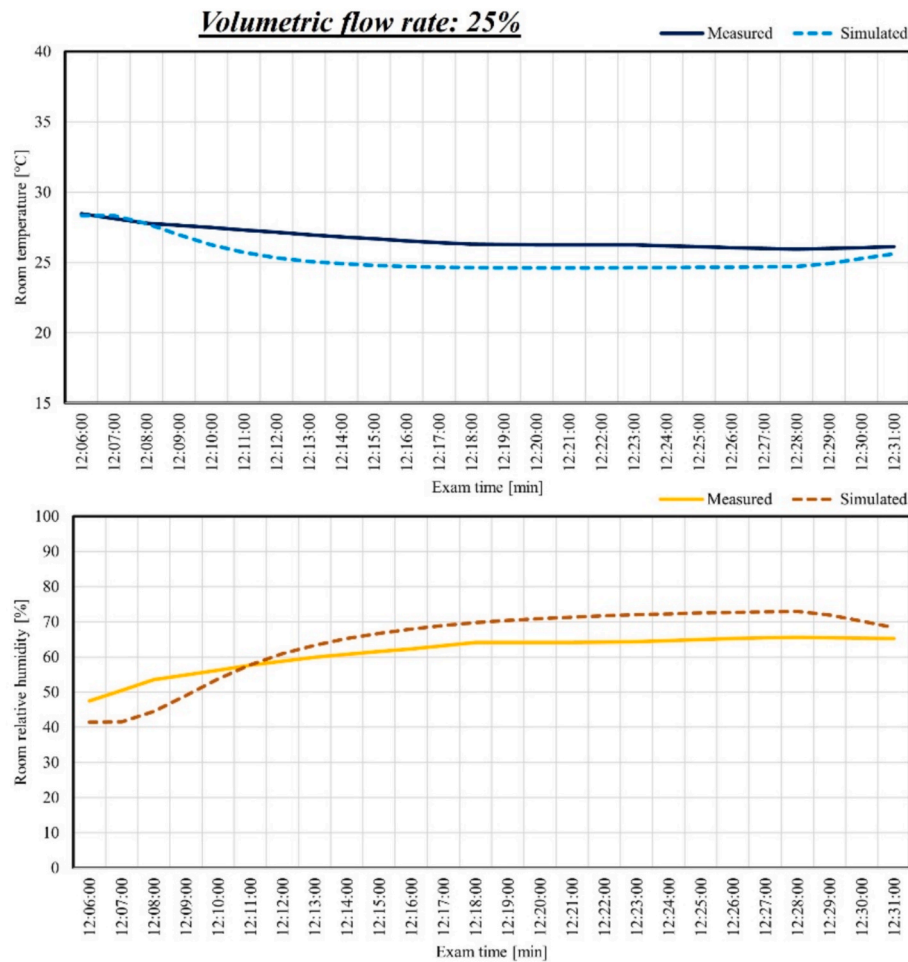


Fig. 6. Comparison of indoor temperature and relative humidity (measured vs simulated) with a volumetric flow rate at 25%.

ranges defined by ASHRAE Guideline 14 for all 3 configurations, indicating that the model is calibrated and usable for other studies. The MBE values, for each flow rate, for the T_i vary from -0.1% at 100%, up to $+4.9\%$ at 25%, while for the RH_i they are at -5.5% at 25% and -10.5% at 50%. Conversely, the CV(RMSE) is always within the acceptability ranges of ASHRAE Guideline 14: for T_i it is again at a minimum with 1.6% at 100% and a maximum of 5.4% at 25%, while for the RH_i , it is at a minimum at 100% with 7.9% and a maximum at 50% with 12.1%.

Beyond these quantitative indicators, a closer examination of the results reveals systematic biases that offer insights into the model's limitations and possible areas for improvement.

For instance, at lower volumetric flow rates (25%), the model tends to slightly overestimate cooling performance, leading to simulated temperatures up to $1.5\text{--}2\text{ }^{\circ}\text{C}$ lower than measured values. This deviation could be linked to several factors: (i) the assumption of uniform air distribution in the simulation, which might not fully capture stratification and non-homogeneous mixing in the real classroom; (ii) uncertainties in the evaporative pad's actual efficiency under partial load. Similarly, the model tends to slightly overpredict indoor relative humidity where differences can reach about 10 percentage points. This behaviour likely reflects simplifications in the moisture balance modelling, such as the neglect of adsorption/desorption phenomena by interior surfaces and furniture, as well as potential differences in infiltration rates not fully captured by the model. Additionally, measurement uncertainties and sensor response times could contribute to observed discrepancies, particularly during rapid transients (in the order of the minute in this case).

While these deviations do not compromise the validity of the model,

as demonstrated by the strong agreement in overall trends and the compliance with ASHRAE calibration criteria, they reflect the intrinsic limitations of building performance simulation tools in fully reproducing real operating conditions. In particular, the slight overestimation of cooling capacity and relative humidity observed in the simulations is likely due to the simplified representation of some physical phenomena. These include assumptions of uniform air distribution, idealised evaporative pad performance, and simplified moisture dynamics that do not account for complex interactions such as surface adsorption or infiltration variability. Such simplifications are inherent to the modelling process and explain why some discrepancies arise between measured and simulated data, especially during transient phases. Acknowledging these limitations is essential for correctly interpreting the model's results and for understanding the range of accuracy achievable when using simulation tools to reproduce real-world behaviour.

4.2. Thermal comfort assessment

With the model already validated, simulations were carried out to evaluate different ventilation scenarios, combining the use of natural ventilation (without thermal treatment) and thermal treatment using a direct evaporative cooling system. In addition, different air renewal rates were evaluated to assess their influence and potential improvement of the thermal performance of the classrooms, as detailed below:

- 'NV_1125': air renewal without thermal treatment and with a rate of $1125\text{ m}^3/\text{h}$, which corresponds to the minimum rate required by

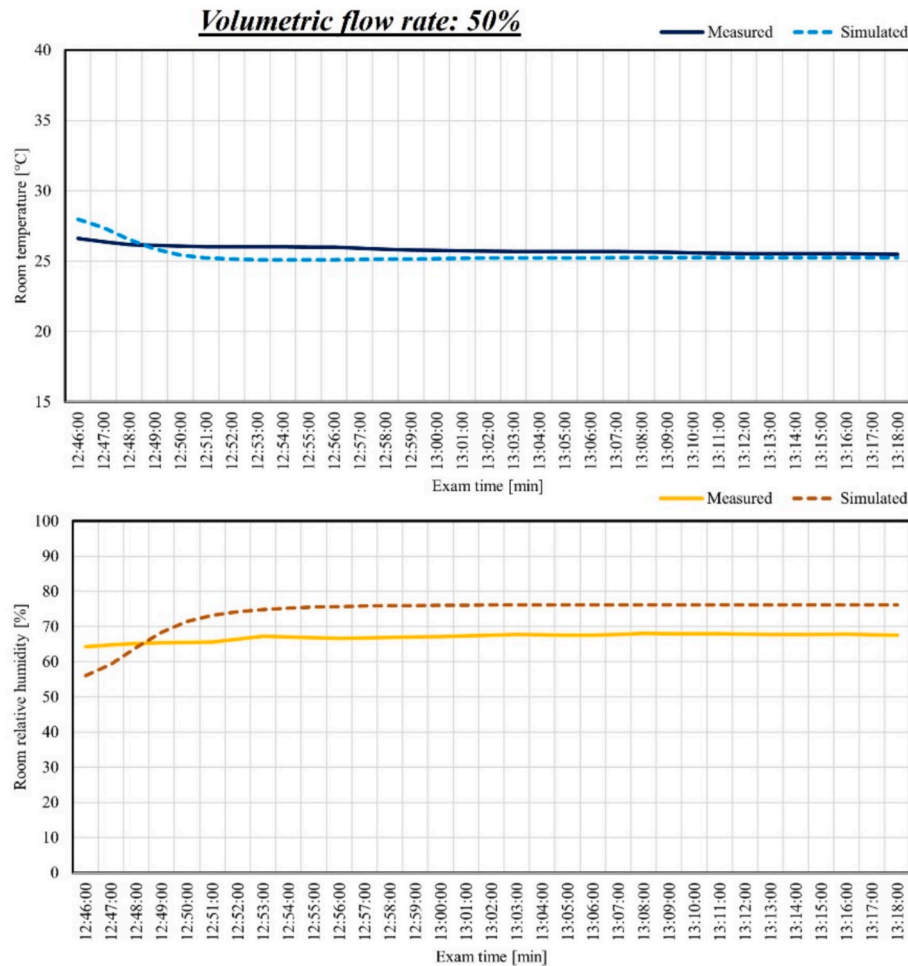


Fig. 7. Comparison of indoor temperature and relative humidity (measured vs simulated) with a volumetric flow rate at 50%.

current Spanish regulations [49] to maintain good air quality in classrooms (12.5 l/s per person).

- 'NV_1800': no thermal treatment and with a flow rate of 1800 m³/h, which is higher than the Spanish standard requirement for classrooms. This flow rate (20 l/s per person) is required for spaces occupied by more vulnerable people, such as hospitals or nurseries.
- 'EC_1125': during the cooling period, the DEC system is activated at a rate of 1125 m³/h (12.5 l/s per person), ensuring good air quality according to Spanish regulations. During the rest of the year, the conditions of the 'NV_1125' scenario are used to ensure air quality.
- 'EC_1800': during the cooling period, the DEC system is activated at a rate of 1800 m³/h (20 l/s per person), and the rest of the year, the conditions of the 'NV_1125' scenario are used.
- 'EC_2700': during the cooling period, the DEC system is activated at a rate of 2700 m³/h (30 l/s per person), and the rest of the year, the conditions of the 'NV_1125' scenario are used.
- 'EC_3600': during the cooling period, the DEC system is activated at a rate of 3600 m³/h (40 l/s per person), and the rest of the year, the conditions of the 'NV_1125' scenario are set.

In all these scenarios, the ventilation is only active during occupied periods.

Firstly, to establish a suitable period of operation for the DEC system, the model is simulated for a full year under both 'NV_1125' and 'EC_1125' conditions. Fig. 9 shows the results obtained in both simulations (as in the validation section, only the results from the southern classroom are presented, as these are the least favourable). The summer holiday period with no occupancy and no ventilation is marked with

dashed black vertical lines. It can be observed that when outdoor temperatures start to regularly exceed 25 °C, the DEC system has a positive effect on thermal comfort. Thus, the operating period of the DEC system is established between 1 April and 31 October (marked in the figure with green dashed vertical lines).

Afterwards, the thermal behaviour of the simulation models was evaluated by applying the different ventilation scenarios, focusing on the comfort analysis during the periods while the DEC system was operational. It was observed that, when only natural ventilation is applied (Fig. 10a), indoor temperatures outside the adaptive comfort limits are obtained when outdoor conditions exceed 25 °C. Increasing the air renewal rate without thermal treatment does not significantly influence indoor comfort, especially at high outdoor temperatures. However, substantial differences in the indoor conditions are obtained when comparing the use of the different ventilation systems (Fig. 10b). The DEC system clearly reduces indoor temperatures, especially when outdoor temperatures are high, ensuring adaptive comfort conditions for most of the occupied hours.

Although the adaptive comfort standard used does not directly consider indoor humidity conditions, a one-off assessment was performed using the predictive mean vote (PMV)-PPD standard defined in EN 16798-1:2019 [55] (Fig. 11). For this analysis, air speed was set to 0.1 m/s, metabolic rate to 1.2 MET, and clothing level to 0.57 CLO, in line with the conditions set by the standard for adaptive comfort. As expected, the DEC system increases the indoor relative humidity level compared to natural ventilation. However, comfort conditions are not worsened as a result. Most of the occupied hours fall within categories I-III of the standard (PPD < 15%), and those that fall outside are generally

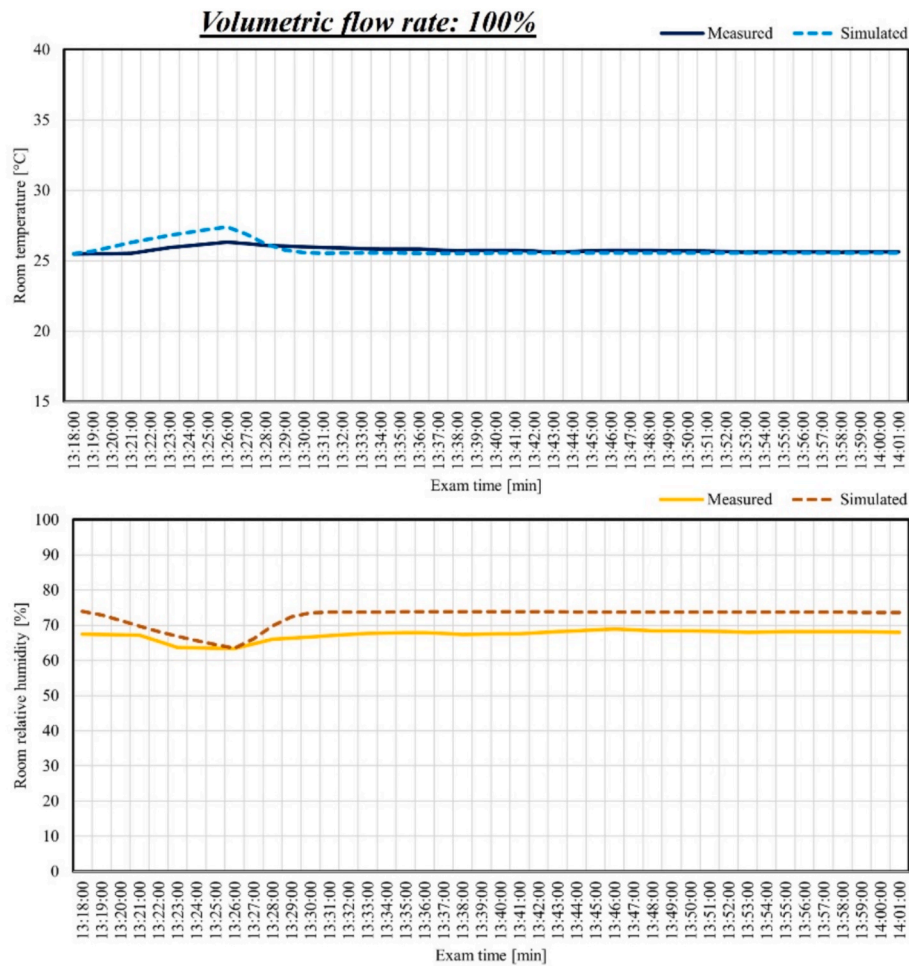


Fig. 8. Comparison of indoor temperature and relative humidity (measured vs simulated) with a volumetric flow rate at 100%.

Table 5

MBE and CV(RMSE) for the different simulated DEC volumetric flow rate configurations.

Volumetric flow rate		MBE [%]	CV(RMSE) [%]
25%	Temperature	+4.9	5.4
	Relative Humidity	-5.5	10.2
50%	Temperature	+1.5	2.4
	Relative Humidity	-10.5	12.1
100%	Temperature	-0.1	1.6
	Relative Humidity	-7.5	7.9

under the comfort band due to temperature.

Once the effectiveness of the DEC system had been proven, the influence of the air renewal rate on comfort conditions was evaluated (Fig. 12). Increasing the air rate leads to a clear decrease in indoor temperatures, which benefits comfort conditions significantly when outdoor temperatures are high. However, it can also lead to indoor temperatures that are too low when outdoor temperatures remain below 20 °C. The results show that the use of the DEC system becomes necessary when the outdoor temperature exceeds 20–25 °C (according to the RITE comfort standard and adaptive criteria, respectively). At outdoor temperatures above 25 °C, higher air renewal rates (2700–3600 m³/h) are more beneficial.

The simulations with the current climate file demonstrate the effectiveness of the DEC system in the hot and dry climate of southern Spain. However, it is necessary to analyse what will happen in the near future, taking into account the effects of global warming. For this

purpose, the different ventilation scenarios have also been simulated for the case study using a climate projection for the year 2050, comparing the indoor temperature results with those for the present climate (Fig. 13). Given the significant increase in outdoor temperatures, indoor conditions generally worsen in 2050. In 2020, the use of the DEC system with a renovation rate of 1125 m³/h (the minimum required by Spanish regulations to ensure good air quality) was sufficient to keep indoor temperatures below 30 °C for almost 100% of the occupied hours. However, in 2050, the rate would need to be increased to 3600 m³/h to ensure the same level of indoor comfort. The average indoor temperature during occupied hours decreases 2–2.5 °C when using the DEC system compared to natural ventilation (with the same air renewal rate), in both the present and in 2050.

Table 6 summarises the results of the comfort analysis for the different ventilation and climate scenarios, according to the static design criteria of Spanish regulations (RITE [53]) and the adaptive criteria of Barbadilla et al. [54], as described in the methodology section. In the current climate scenario, the use of the DEC system with the minimum air renewal rate reduces the number of occupied hours in overheating by 22–26.6% (according to the adaptive and static criteria, respectively). The percentage of overheating hours according to the adaptive criterion is less than 1% when using the DEC system at all evaluated renovation rates. With the static design standard (stricter), the percentage of overheating drops from 30 to 8% when the air change rate is increased from 1125 to 3600 m³/h. In the 2050 climate scenario, the effectiveness of the DEC system is still demonstrated, although higher air change rates are required to keep the percentage of overheating hours below 1% with the adaptive criterion (≥ 2700 m³/h).

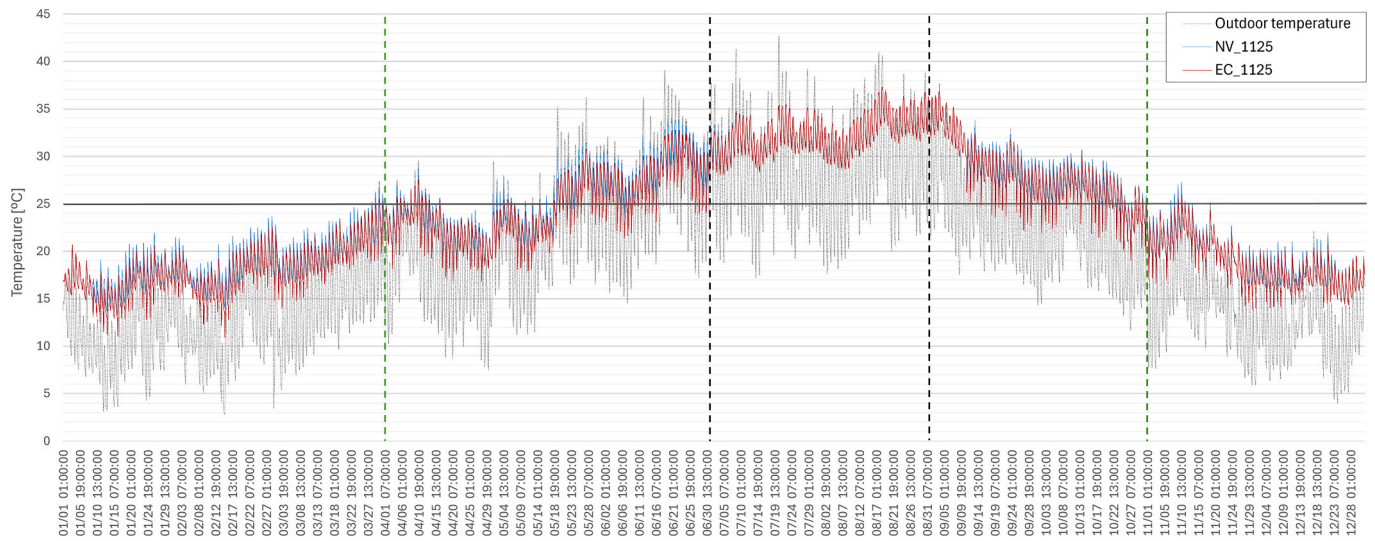


Fig. 9. Outdoor and indoor temperatures with natural and DEC ventilation systems.

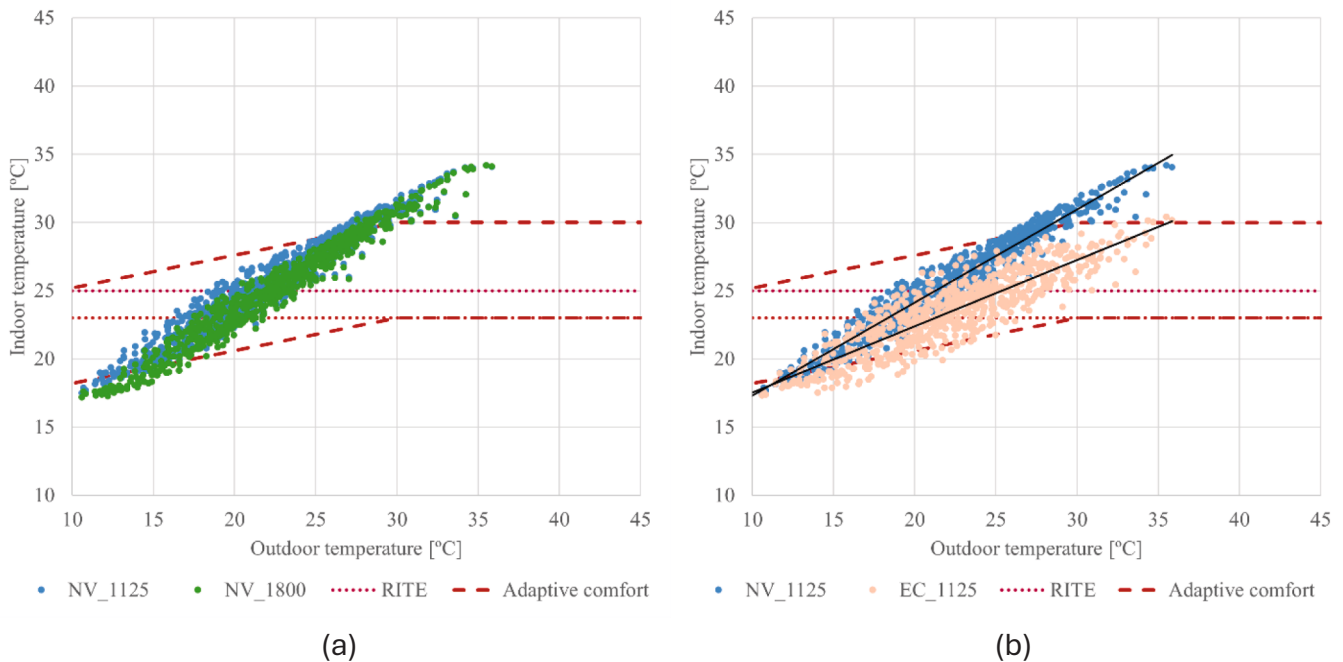


Fig. 10. Comfort analysis: (a) Natural ventilation with 1125 m³/h vs 1800 m³/h; (b) Natural ventilation (1125 m³/h) vs evaporative cooling (same rate).

As was done for the current climate scenario, an evaluation of the impact of the use of the DEC system on indoor humidity conditions has been carried out for the 2050 scenario (Fig. 14), based on the EN 16798-1:2019 (PMV)-PPD standard (conditions: 0.1 m/s, 1.2 MET, 0.57 CLO). When increasing the air change rate of the DEC system to achieve lower temperatures to comfortable levels, the indoor relative humidity of the air logically increases. But comfort conditions are not specially worsened as a result. The occupied hours that fall under the comfort band are mostly due to low temperatures. Therefore, it would be necessary to adjust the air renewal rate according to the outdoor temperatures, using the highest rate only during extreme periods.

4.3. Discussion of results

When analysing other similar studies, the relevance of the climatic context in the problem of overheating is evident. But the issue of

overheating in naturally ventilated classrooms has also been studied in milder climates during the summer, as shown by Mohamed et al. [8] in English schools where temperatures below 24 °C are registered at the beginning of the day, rising to 26–27 °C. This results in overheating conditions for 40% of the day. This problem will increase in the upcoming years; however, there are few studies that relate future climate scenarios to natural ventilation, particularly in hot climates.

Several studies show that passive strategies are not sufficient to tackle overheating problems during critical periods. Romero et al. [39], at a University in a Csa climate, highlight the need for hybrid strategies that prioritise ventilation without thermal treatment at moderate outdoor temperatures and use active systems as support in extreme conditions. Their results reveal that in naturally ventilated classrooms, when outdoor temperatures exceed 28 °C, thermal discomfort increases (which is the case from 25 °C in the case study of this paper). In contrast, air-conditioned classrooms maintain stable and comfortable conditions,

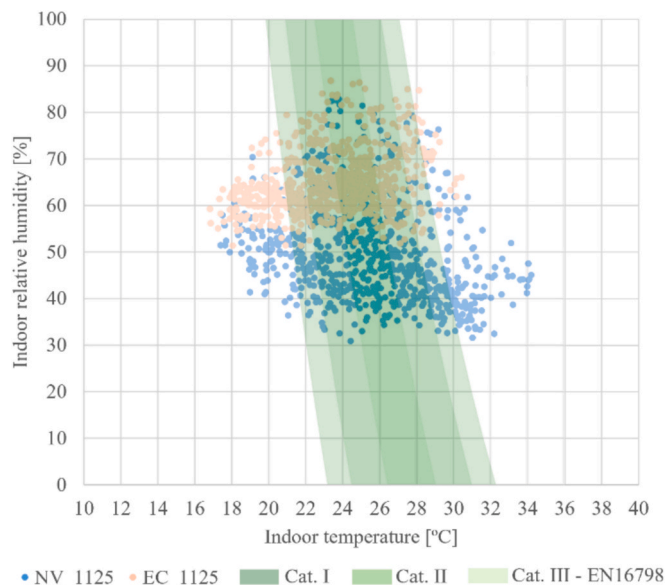


Fig. 11. Evaluation of indoor relative humidity and thermal comfort.

with average indoor temperatures 2.5 °C below the values measured with natural ventilation (a value very similar to that obtained in the simulations of this work). The importance of balancing thermal comfort and energy efficiency is also underlined in that study.

Therefore, it is necessary to explore and test the capacity of energy-efficient active systems, such as the DEC, to mitigate the problem of overheating. Heracleous and Michael [56], after argued that passive strategies as night ventilation and cross-ventilation alone are insufficient to ensure indoor comfort (with maximum differences between indoor and outdoor temperatures under 5 °C), claimed that DEC systems can achieve temperature decreases of up to 10 °C with outdoor temperatures below 35 °C. They do not have measured data from hotter days or heatwave episodes, but other studies [57,58] suggested that the difference could be as much as 8 °C with outdoor temperatures above 35 °C. In the case study simulated in this paper, with outdoor conditions of around 35 °C, the indoor temperature drops by up to 7 °C compared to the outdoor temperature ('EC_3600', with an air renewal rate of 26 ACH). This finding highlights the effectiveness of the DEC system under severe summer climatic conditions.

Similarly, Spentzou et al. [59] achieved a temperature reduction of 4.1 °C (i.e. the indoor value relative to the outdoor value) by numerical methods in a residential building on a summer day in Athens (Greece), reaching an air renewal rate of 12 ACH. Bouchahm et al. [60] reported a temperature reduction of up to 18.6 °C in Ouargla (Algeria), with outdoor conditions of 33–48 °C, which may be comparable to those detected in the 2050 climate projection used in this study. The novelty of this work lies in the fact that it explicitly validates the DEC system in future climate scenarios, reducing the percentage of overheating hours in the case study to 0.56% by increasing the air renewal rate, with outdoor temperatures of up to 39 °C.

Regarding the limits of thermal comfort, Sadrizadeh et al. [61] stated that children are more sensitive to high temperatures and need cooler environments than adults. Along the same line, Haddad et al. [62] concluded that the thermal neutrality of children in hot climates must be considered lower than that of adults under the same conditions, and Kim and de Dear [63] estimated that the preferred temperature would be 2–3 °C lower than that of adults.

In the Mediterranean region, Dorizas et al. [28] proposed an optimal comfort temperature of 22.3 °C and stated that indoor temperatures above 25 °C generate dissatisfaction. Similar values are indicated in the studies by Trebilcock et al. [30] in Chile in spring and by Miao et al. [36] in schools with natural ventilation in northern Spain, setting neutrality

between 21 and 25 °C. In the case study of the present work, the static criterion used sets the thermal comfort band between 23 and 25 °C, whereas the adaptive criterion considers indoor comfort temperatures up to 30 °C.

4.4. Limitations and future research

Despite the results obtained, which demonstrate the potential of the DEC system ensuring IAQ and mitigating the risks of overheating in the Mediterranean context, several limitations of both the system itself and the present study must be outlined.

One significant limitation of this system lies in its reduced performance under humid climatic conditions, where evaporative cooling capacity is limited and increasing indoor humidity may not be desirable. In addition, the system requires careful maintenance to prevent the proliferation of Legionella bacteria. This necessitates the continuous circulation of water and the implementation of a dedicated maintenance protocol, potentially increasing operational complexity and associated costs.

Regarding the current study limitations, it is intended as an initial step for validating the DEC system and its simulation model, as well as a first evaluation of its performance in a representative case study. But the cost assessment of the system and the evaluation of its energy and water consumption is out of the scope of this work. Future research steps will address these issues, also analysing the implications of increasing air change rates during extreme climatic periods, which could affect resource use. A comparative study with other common systems (such as the vapour compression cycle one) will be carried out in order to evaluate the feasibility and competitiveness of the DEC system from an energetic and financial standpoint.

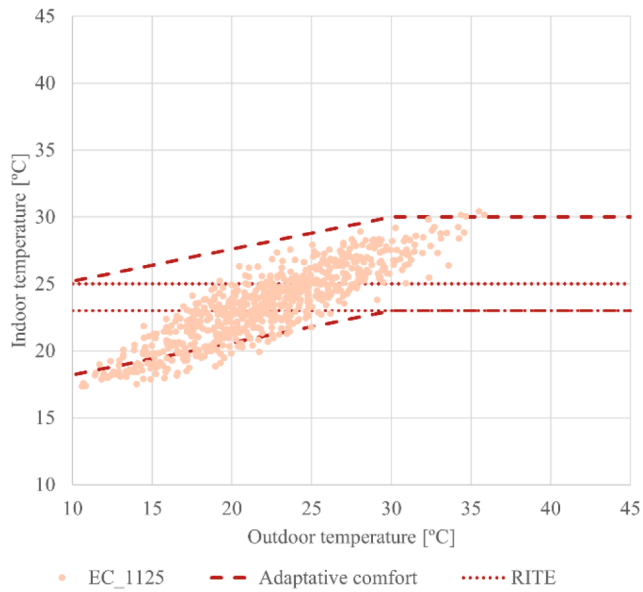
In addition, future research should explore the effectiveness of the DEC system in other specific climates, carry out continuous measurement campaigns over time, and establish optimised operational protocols for using this system. In winter, the application of the DEC systems as controlled mechanical ventilation systems will be also studied, offering an alternative to conventional natural ventilation systems, which often rely on uncontrolled air change rates.

5. Conclusions

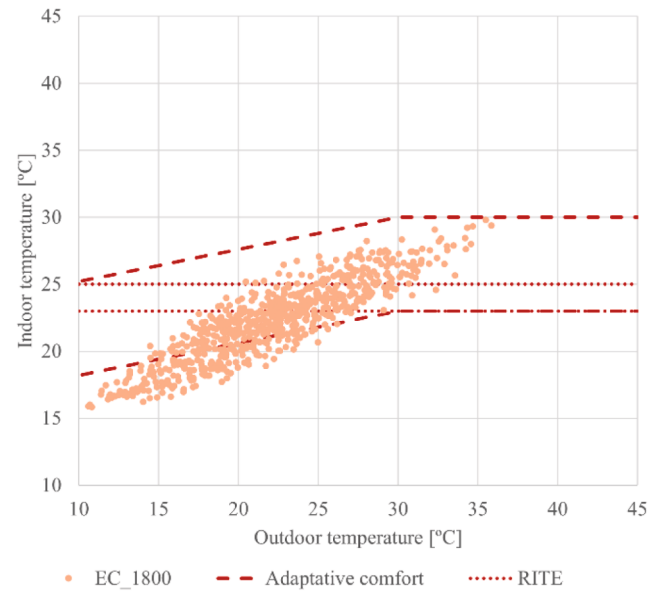
This study aims to address the lack of research on energy-efficient solutions for reducing overheating in Mediterranean school buildings while also ensuring indoor air quality. For this purpose, a simulation model of a representative case study was developed and validated with on-site measurements, including a direct evaporative cooling (DEC) system. The key contribution of this work lies in the practical evaluation of the effectiveness of this system in the hot and dry climate of southern Spain, highlighting its potential as a feasible solution for maintaining both IAQ and thermal comfort, even in extreme climate conditions (considering future climate scenarios).

The main key insights drawn from this analysis are summarised below:

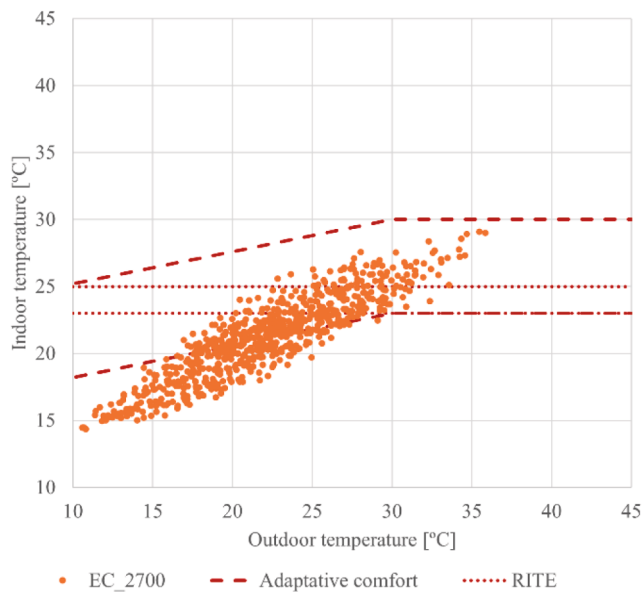
- By only considering natural ventilation, it is impossible to avoid overheating when outdoor temperatures exceed 25 °C.
- The use of the DEC system is clearly effective when outdoor temperatures exceed 20–25 °C, achieving a reduction in the percentage of overheating of up to 26% compared to natural ventilation.
- According to the adaptive standard, the DEC system with the minimum ventilation rate maintains comfort conditions for more than 99% of the occupied hours.
- The increase in DEC ventilation rates leads to a significant reduction in indoor temperatures, which improves comfort conditions during extreme periods (as the future climate scenario evaluated, where an air renewal rate of at least 30 l/s per person will be necessary to maintain comfort conditions for 99% of the occupied hours).



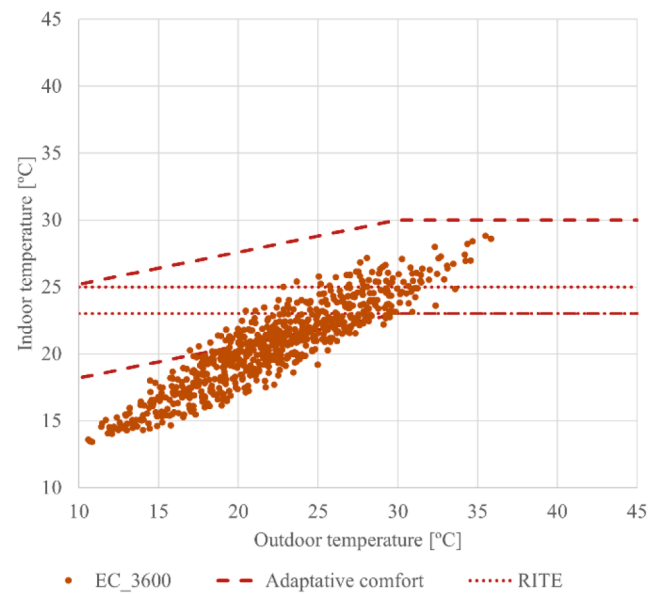
(a)



(b)



(c)



(d)

Fig. 12. Influence of the ventilation rate of the DEC system on thermal comfort: (a) 1125 m³/h; (b) 1800 m³/h; (c) 2700 m³/h; (d) 3600 m³/h.

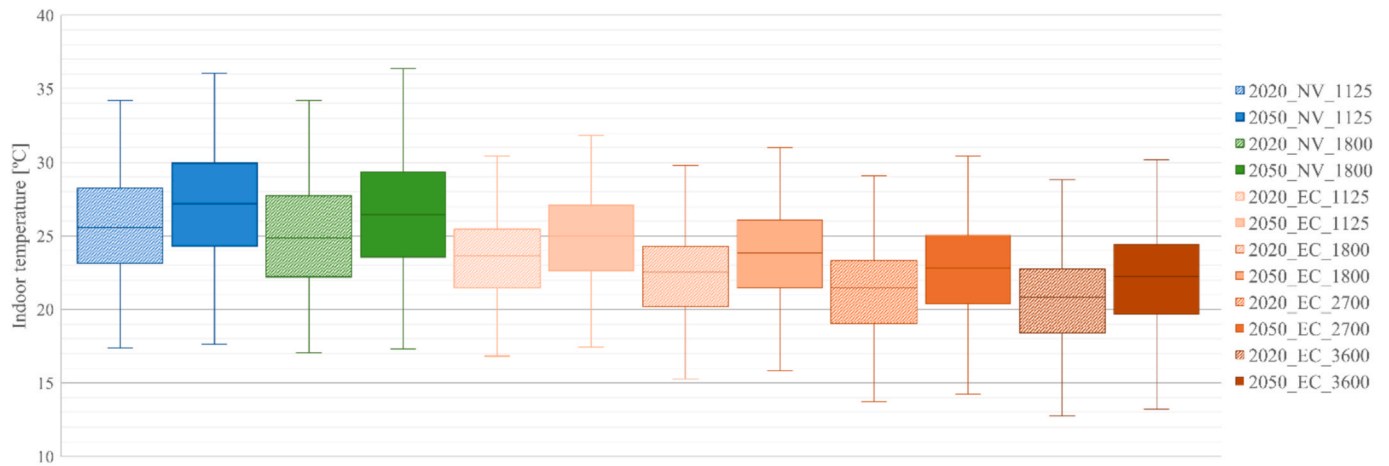


Fig. 13. Indoor temperature evaluation under diverse ventilation and climate scenarios.

Table 6

Results of the comfort analysis: percentage of overheating hours.

	Ventilation scenarios					
	NV_1125	NV_1800	EC_1125	EC_1800	EC_2700	EC_3600
Comfort standard						
RITE [49]	56.72%	48.32%	30.11%	18.35%	11.06%	8.26%
Barbadilla et al. [50]	22.83%	18.91%	0.84%	0.28%	0.00%	0.00%
2050						
RITE [49]	69.05%	63.73%	50.00%	35.99%	25.07%	19.61%
Barbadilla et al. [50]	33.89%	28.57%	4.62%	1.82%	0.84%	0.56%

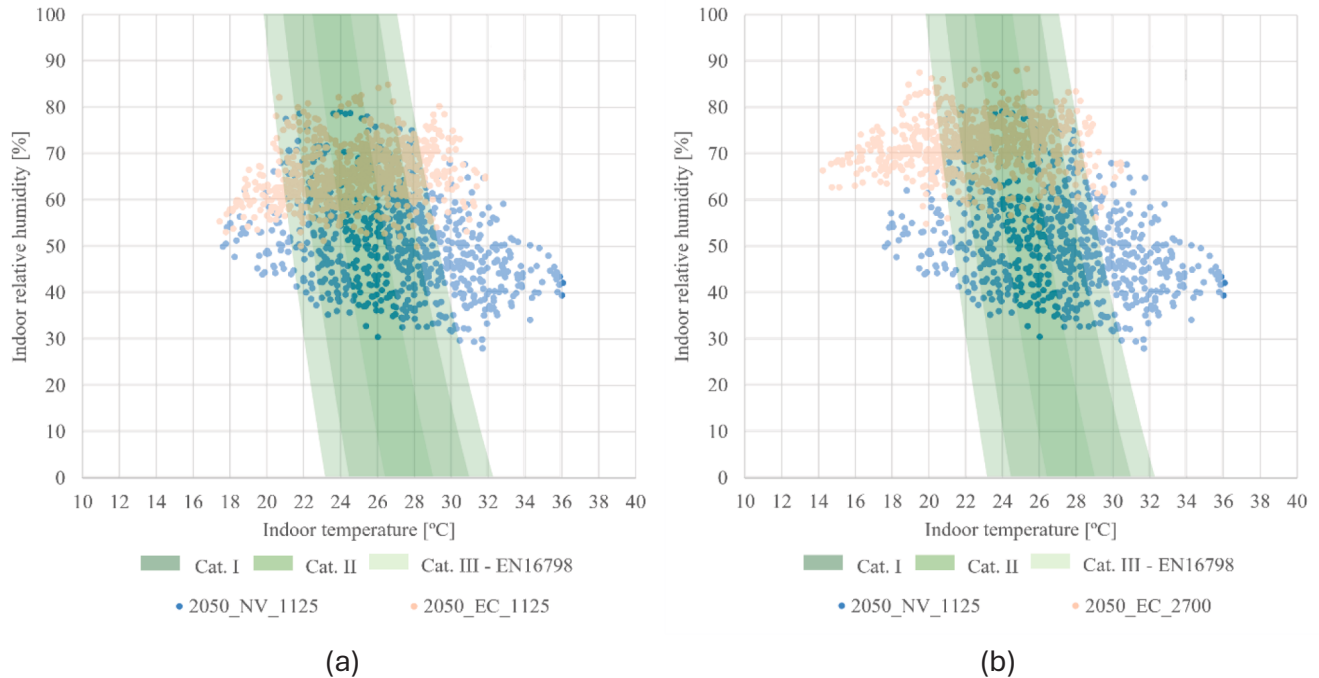


Fig. 14. Evaluation of indoor relative humidity and thermal comfort in 2050 climate scenario: (a) 2050_NV_1125 vs 2050_EC_1125; (b) 2050_NV_1125 vs 2050_EC_2700.

However, this may also result in excessively low indoor temperatures when outdoor temperatures fall below 20 °C.

These findings are intended to serve as a practical guide for the design and management of DEC systems installed in schools, taking as a reference the outdoor temperatures at which it is advisable to activate the system rather than relying solely on natural ventilation, as well as the recommended air renewal rates to avoid discomfort and excessive consumption.

CRedit authorship contribution statement

Giuseppe Aruta: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rocío Escandón:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Carmen María Calama-González:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fabrizio Ascione:** Writing –

review & editing, Supervision, Methodology, Conceptualization. **Rafael Suárez:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Funding

This research was funded by Grant (PID2020-117722RB-I00) “Retrofit ventilation strategies for healthy and comfortable schools within a nearly zero-energy building horizon”, funded by MICIU/AEI/10.13039/501100011033. Escandón also acknowledges the financing of the VI PPIT-US through the 2020 Call for Contracts for Access to the Spanish Science. Technology and Innovation System for the Development of the US's Own R&D&I Program.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

This appendix outlines the main potentialities of evaporative cooling as an effective and energy-efficient thermal management approach. Leveraging the latent heat of water evaporation, this technique enables significant heat removal with minimal energy input, offering advantages in terms of sustainability, scalability, and integration into different systems. The following overview highlights key operational principles, performance metrics, and prospective developments relevant to advanced applications.

Compared to traditional air conditioning systems, direct evaporative cooling (DEC) consumes significantly less energy because it does not rely on a vapour compression cycle. Instead, it operates using only fans and pumps to circulate water.

The efficiency of this process is directly linked to the air's ability to absorb moisture, making it particularly effective in regions with low relative humidity (*RH*). Under such conditions, DEC systems can provide substantial temperature reductions while maintaining a highly energy-efficient operation.

The cooling mechanism itself is a natural process: warm outside air is drawn through a porous medium, typically a water-saturated pad. As the air passes through the pad, a portion of the water evaporates, absorbing latent heat from the air, thereby lowering its temperature. This cooled, humidified air is then distributed into the indoor space.

Fig. 3 of the manuscript illustrates a conceptual representation of the process, showing how the air enters the system at an initial temperature (T_e) and relative humidity (φ_e) and exits at a lower temperature (T_{in}) and higher humidity level (φ_{in}), ready to be introduced into the environment.

This technology, i.e., the direct evaporative cooler, does not require chemical refrigerants, making it a more environmentally-friendly cooling solution with minimal impact on environmental conditions. Beyond cooling, DEC also increases the relative humidity of the air, which can be beneficial in extremely dry climates. However, in already humid environments, its effectiveness decreases, and it may make conditions less comfortable.

To illustrate its potential, Fig. A.1 presents an example demonstrating the efficiency of this technology in hot and dry climates. The figure considers an external temperature (T_e) of 35 °C and two different relative humidity levels, i.e., 30 and 40%, representing a typical minimum and maximum range of *RH* in such conditions.

From these two starting points (35 °C, 30% *RH* and 35 °C, 40% *RH*), two isoenthalpic lines were drawn on the psychrometric chart to describe the transformations the air undergoes during the evaporative cooling process (see Fig. A.1). As the air cools, its relative humidity increases. However, it is nearly impossible for the air to reach full saturation. Instead, a key performance indicator known as saturation efficiency (η_{sat}) is used to quantify how close the air gets to the wet-bulb temperature during the process. Saturation efficiency expresses the extent to which the cooled air approaches the wet-bulb temperature relative to its initial conditions. The higher the efficiency, the closer the cooled air will be to the wet-bulb temperature, thus maximising the cooling effect.

The temperature of the cooled air (T_{in}) is calculated with Eq. (A.1):

$$T_{in} = T_{dry} - \eta_{sat}(T_{dry} - T_{wet}) \quad (A1)$$

where T_{dry} represents the initial temperature of dry air, T_{wet} represents the corresponding wet-bulb temperature, and η_{sat} represents the effectiveness or efficiency of the evaporative cooling (typically around 80–90 %).

Looking at the psychrometric chart, shown in Fig. A.1:

- For 35 °C with 30% *RH*, the wet bulb temperature is approximately 21.7 °C.
- For 35 °C with 40% *RH*, the wet bulb temperature is approximately 24.0 °C.

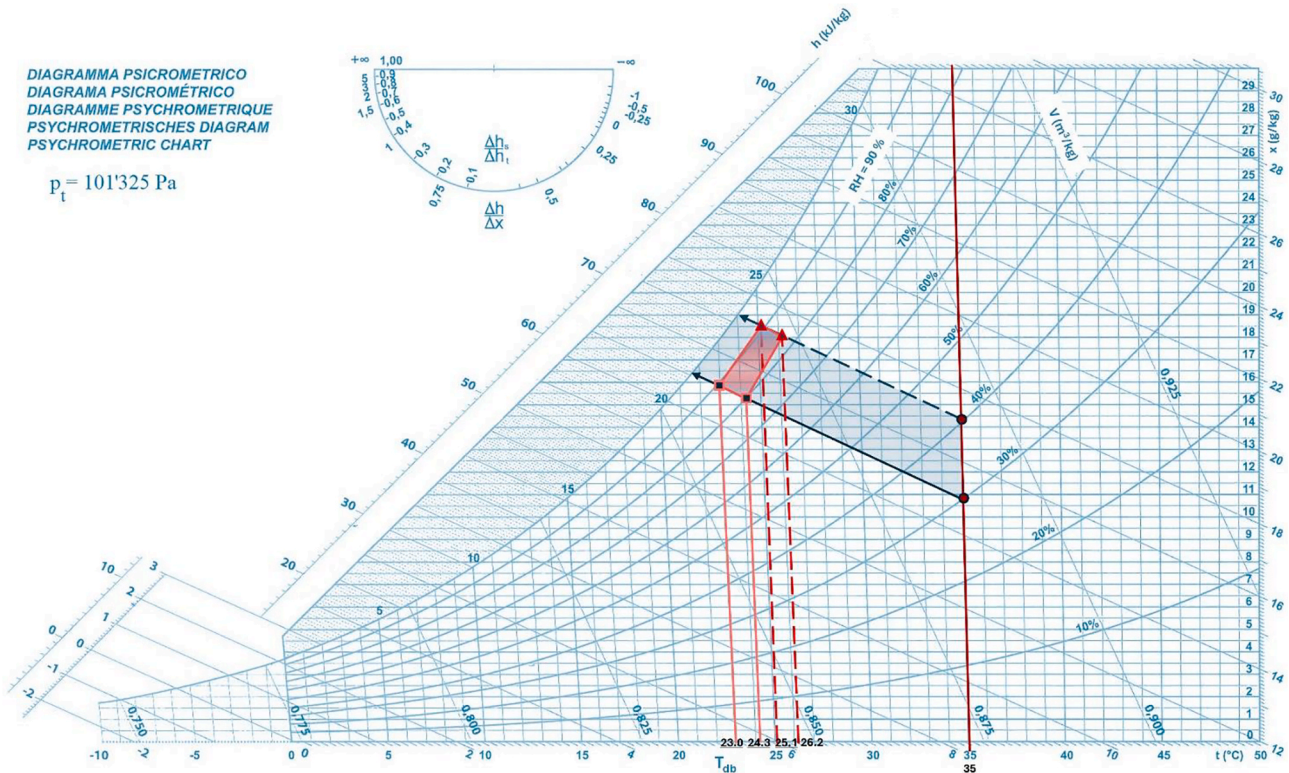


Fig. A.1. Psychrometric chart showing the possible injection point of the evaporative cooler with a temperature of 35 °C and a between 30% and 40%.

With a η_{sat} between 80% and 90%, the final temperature of the cooled air will be between 24.3 °C and 23 °C when the initial RH is 30%, and between 26.2 °C and 25.1 °C when the initial RH is 40%:

- For RH = 30% à $T(\eta = 80\%) \approx 24.3$ °C - $T(\eta = 90\%) \approx 23.0$ °C;
- For RH = 40% à $T(\eta = 80\%) \approx 26.2$ °C - $T(\eta = 90\%) \approx 25.1$ °C.

Therefore, it is possible to define an air intake zone, where the lower boundary is formed by points with 30% RH and the upper boundary by points with 40% RH.

In conclusion, with a saturation efficiency of 80–90%, the air exiting the evaporative cooler could experience a temperature drop of approximately 9–12 °C, reducing it to approximately 23–26 °C. This represents a significant cooling effect while consuming far less energy than a traditional air conditioning system. The only energy used is for powering the fan, which drives the cooled air into the environment, and the pump required to keep the porous medium moist.

Appendix B

This appendix details the calibration procedure adopted to align the simulation model with the actual performance of the evaporative cooler, thereby improving the reliability and predictive accuracy of subsequent EnergyPlus simulations. The calibration process was carried out following the criteria established by ASHRAE Guideline 14, which defines acceptable thresholds for the Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) depending on the analysis time step. The methodology, metrics, and validation steps described here provide a comprehensive framework for assessing and refining the model's accuracy.

For monthly analyses, acceptable values are:

1. MBE: $\pm 5\%$ for energy consumption
2. CV(RMSE): $< 15\%$ for energy consumption

For hourly or daily analyses:

1. MBE: $\pm 10\%$
2. CV(RMSE): $< 30\%$

These threshold values, if met, indicate that the model is considered sufficiently accurate for use in analyses and decisions regarding energy savings and post-efficiency performance evaluations.

For a model to be considered “calibrated” according to ASHRAE Guideline 14, both MBE and CV(RMSE) requirements must be met simultaneously. These two metrics provide complementary insights into model quality:

- MBE measures the model's overall accuracy by indicating whether it consistently overestimates or underestimates energy consumption compared to actual data.
- CV(RMSE) assesses the degree of variation between the model's estimated values and the actual data, regardless of the direction of the error.

Using both criteria ensures that the model is not only accurate (lacking systematic bias) but also reliable in terms of precision. Using only one metric could lead to an incomplete or misleading assessment. For instance, a low MBE might mask large variations (which CV(RMSE) would reveal) or vice versa.

Therefore, meeting both the MBE and CV(RMSE) thresholds is essential to confirm a valid calibration. Eqs. (B.1) and (B.2) explain how MBE and CV(RMSE) are calculated, respectively:

$$MBE = \frac{\sum_{period} (M - S)_{ts}}{\sum_{period} M_{ts}} \quad (B1)$$

$$CV(RMSE_{month}) = \frac{RMSE_{period}}{Average_{period}} \quad (B2)$$

where M represents the measured data, S represents the simulated one, and ts represents the time step. ASHRAE Guideline 14's criteria for MBE and CV(RMSE) can theoretically be adapted for evaluating whether an HVAC system simulation accurately predicts internal temperatures. When adapting these metrics to internal temperature calibration:

- MBE could indicate whether there is a consistent bias in the temperature simulation, such as consistent over- or underestimation of the indoor temperature.
- CV(RMSE) would assess the overall variability of the simulated temperature compared to the actual measurements, providing insight into how closely the model's temperature predictions follow real internal conditions.

Using these thresholds specifically for temperature calibration requires careful consideration. Indoor temperature is influenced by numerous dynamic factors (e.g., occupant behaviour, variable weather, and equipment operation cycles), which can introduce more variability than energy consumption predictions. Thus, while $\pm 10\%$ MBE and $< 30\%$ CV(RMSE) could serve as initial benchmarks, they may need adjustment based on the specific accuracy requirements of temperature control simulations in buildings.

Data availability

Data will be made available on request.

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