Title: Holistic overview of natural ventilation and mixed mode in built environment of warm climate zones and hot seasons

Authors:

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Abstract:
The climate change leads to periods of extreme events (i.e. reduction of cold seasons, heat waves, overheating, urban heat island among others) that affect the performance of residential and tertiary buildings with high occupancy (i.e. hospitals, schools, commercial centres, offices etc). However, most of low-carbon policies do not consider the ventilation as a mitigation measure. In fact, a lack of studies on natural ventilation (NV) and mixed-mode (MM) strategies was detected, especially for warm regions or areas with hot and humid climates. This paper aims to carry out a bibliometric analysis from 1928 to 2023, to observe the evolution of the topic. After identifying the main research clusters (thermal comfort, energy efficiency, indoor air quality and simulation tools) by science mapping, the most relevant publications of the last 20 years were assessed (2003 – 2023). The results of this study revealed that only 1.51% of the scientific documents in 95 years corresponded to an extensive literature review, although epidemic or disease outbreaks led to peaks of production in this topic. This emphasizes the importance of observing what was done and how was implemented over the years. Regarding the clusters, some relevant aspects can be highlighted: (i) non-homogeneity of studies on NV or MM related to building type; (ii) interregional projects should be drawn up to check the effectiveness of NV and MM, especially when other architectural techniques are adopted (i.e. solar chimneys, window wall ratio –WWR-, thermally activated building structures –TABS- etc); (iii) the optimization of simulation tools should be based on the incorporation of BIM and generative design for NV and MM.

Keywords:
natural ventilation; mixed mode; thermal comfort; energy efficiency; built environment; IAQ; software; simulation

Highlights:

- Only 1.51% of scientific production on ventilation corresponds to review journal papers.
- Four clusters were identified: thermal comfort, IAQ, energy efficiency and simulation.
- Heterogeneity of studies related to building type.
- NV and MM strategies are effective in achieving reductions in energy consumption.
- An holistic analysis of NV and MM with several energy saving measures is required.
- Seasonal variations on IAQ have been scarcely assessed in the scientific literature.
- BIM and generative design for NV and MM should be adopted to optimize simulation tools.

1. Introduction

The planet Earth is suffering a process of warming due to climate change [1,2]. This causes effects as varied as the extension of summers, desertification and the reduction of cold seasons [3]. This increase in temperatures constitutes a challenge for survival. In the case of buildings, the majority of low-carbon policies propose two mitigation measure domains: (i) the reduction of environmental impact (minimizing energy consumption), and (ii) the adaptation of users to guarantee adequate conditions of thermal comfort [4]. For this reason, the policies are mainly based on the technological improvement of buildings [5]. However, energy saving and thermal adaptability techniques used in the past are often forgotten.

In this sense, a measure that can have a positive impact on both mentioned aspects is ventilation. Ventilation is a measure traditionally applied to enhance indoor air quality (IAQ). Nevertheless, the importance of ventilation to reduce energy-cooling demand has only been highlighted in the recent years [6]. Natural ventilation (NV) is characterized by depending on the external conditions, since it usually occurs due to pressure gradient and stack effect. Given the variability of cases, the following classification of NV can be established [7]: (i) unilateral ventilation; (ii) cross ventilation; and (iii) stack ventilation. Figure 1 schematically shows the principles of these classes of NV.

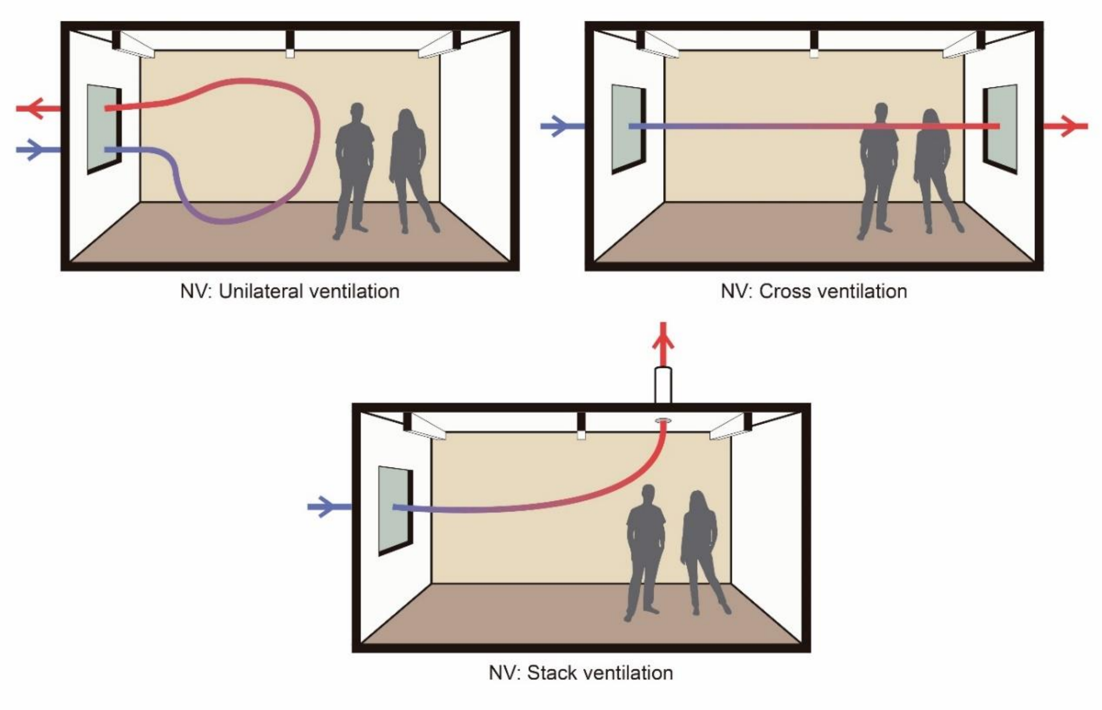

Figure 1. Natural ventilation schemes.

Despite of being a cost-effective measure [8,9], NV has several limitations. For example, it can be difficult to ensure users' thermal comfort [10]. Given this circumstance, mixed-mode (MM) could be an alternative. MM controls the temperature of the indoor air with NV and air conditioning. The use of one system or another depends on the outside temperature conditions [11]: when the outside temperature has adequate conditions for thermal comfort, the windows are opened; otherwise, the air conditioning will be used. MM makes it possible to ensure a balance between maintaining thermal comfort and adequate use of air conditioning.

1.1. Aim of this study

Thus, both NV and MM can be effective measures to improve the situation of buildings in the face of climate change. As a result, a wide variety of studies have been developed in the scientific literature. However, no previous review studies were detected to comprehensively address the application of NV and MM in warm regions (i.e. analysis of the influence on energy, thermal comfort, indoor air quality, control strategies, etc.). Most of the existing reviews have carried out partial analyses of these aspects and, in some cases, without specifying the climatic zone: (i) Kim and de Dear [12] analysed the state of the art in relation to MM and its influence on thermal comfort and energy saving; (ii) Mateus et al. [13] reviewed previous researches focused on the characterization of the ventilation of large air masses; (iii) Zhong et al. [14] evaluated single-sided natural ventilation, highlighting aspects such as methodologies, classifications, and influence factors; (iv) Ferrari et al. [15] reported past studies of classroom ventilation to reduce virus transmission; (v) Izadyar and Miller [16] carried out an extensive literature review about the influence of ventilation typologies on the risk of contagion; (vi) Ahmed et al. [17] analysed prior studies that combine natural ventilation and solar chimneys in hot areas, considering the domain of thermal comfort; and (vii) recently, Jiang et al. [18] reviewed the methods for modelling cross ventilation. As observed, it is necessary to know the current state of the art about the influence of cost-effective ventilation strategies as a measure against climate change. Based on this, the aim of this work was to provide a detailed framework on the applicability of NV or MM in areas with warm climates, as well as regions under singular effects such as urban heat islands (UHI) or heat waves (HW).

For this holistic overview, the manuscript was structured in five sections. Section 2 describes the methodology used in the research. Section 3 reports the bibliometric analysis related to the topic. Section 4 presents the assessment of the research clusters detected in the scientific literature (thermal comfort, energy efficiency, indoor air quality and simulation tools). Finally, Section 5 reports the discussions and conclusions of the study.

2. Methodology

The research methodology was divided into two steps, as shown in Figure 2.

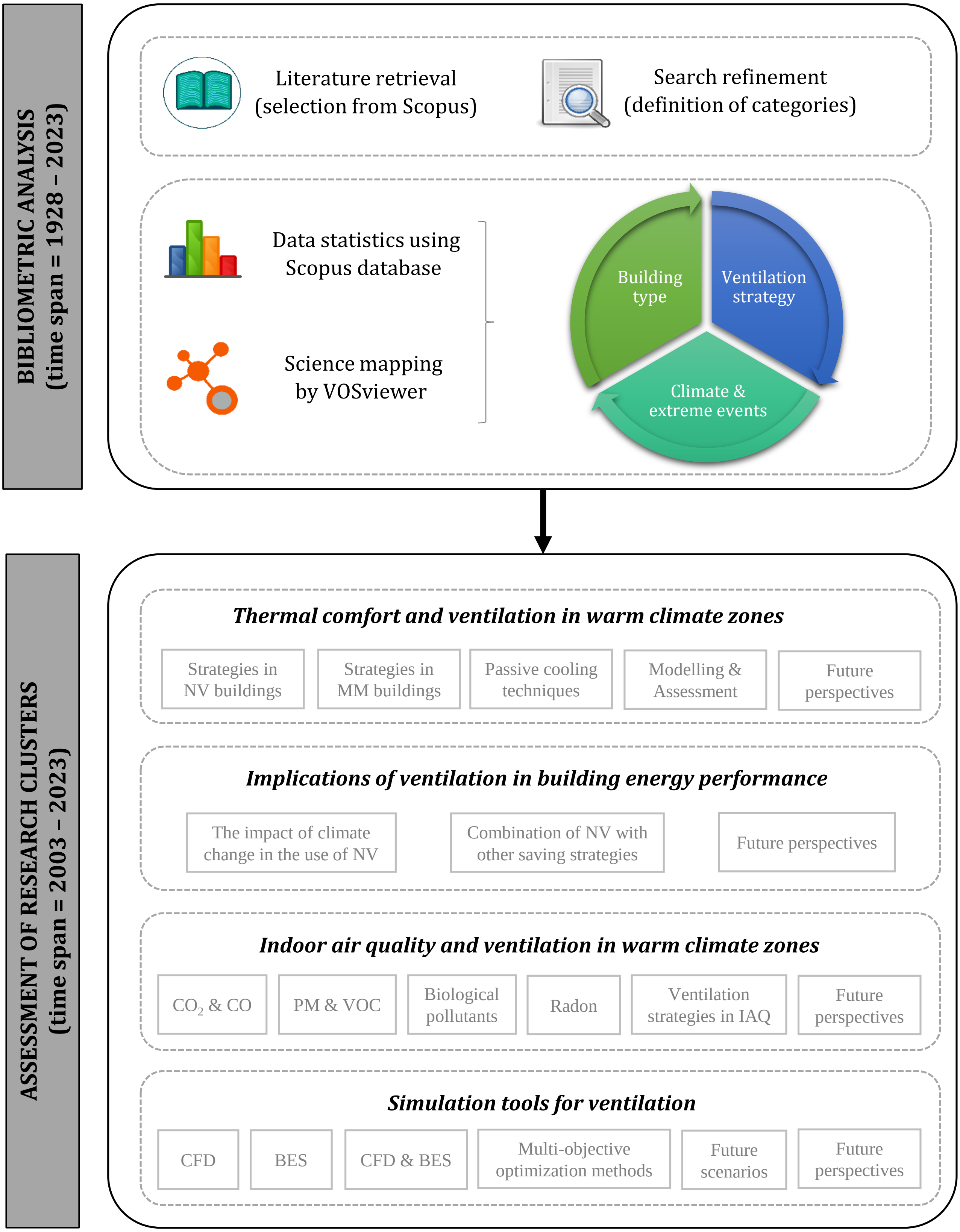

Figure 2. Flowchart of the research methodology (Source: Elaborated by the authors).

Firstly, the bibliometric analysis was conducted, considering a time span of 95 years (from 1928 to 2023) and adopting Scopus database as reference. Several authors stated that Scopus has an expanded spectrum of scientific publications, covering up 20% more than Web of Science [19–21]. In addition, the data statistics from Scopus offers the possibility to know the geographic distribution of the publications, the type of document and the analysis of the authors. Subsequently, science mapping was applied to identify hot topics and trends, since it is a quantitative approach which allows to classify and to evaluate bibliographic networks in a specific research field [22,23]. For this purpose, the most widely used open-source software (VOSviewer) was executed [20,24,25]. Secondly, taking into account the results of the first step of the methodology, an evaluation of research clusters was carried out for the last 20 years (from 2003 to 2023). This implied the review of the most relevant studies on: (i) thermal comfort and ventilation in warm climate zones; (ii) implications of the ventilation in the energy performance of buildings; (iii) indoor air quality and ventilation in warm climate zones; (iv) simulation tools for ventilation.

3. Bibliometric analysis

3.1. Data statistics from Scopus database

According to Section 2, it was needed to develop a literature retrieval and a search refinement. As shown in Table 1, the combination of keywords was computed among three categories: (i) ventilation strategy; (ii) climate and extreme thermal events; (iii) type of buildings. Considering that the first article on this research field corresponds to 1928, 1856 scientific publications were found for a period of 95 years. Indeed, it can be reported that 61.6% of documents corresponded to journal papers (Figure 3), while 38.4% were attributed to grey literature (i.e. book chapters, conference papers and so on). However, only 1.5% referred to review articles (28 documents in 95 years). Concerning the geographic distribution (Figure 4), the ten countries with a higher number of publications were China (260), UK (260), USA (180), Japan (120), India (109), Italy (91), Spain (80), Australia (78), Malaysia (74) and Germany (69). All of them represents the 71.2% of the analysed sample. It should be noted that the common peaks of research production were given when an epidemic or disease outbreak had occurred: (i) the avian and swine influenza (2000 – 2009) [26]; (ii) the West African Ebola epidemic (2013 – 2016) [27]; and (iii) the Covid-19 pandemic (2019 – present) [28].

Table 1. Queries used for categories 1 to 3.

	Category	Query
1	Ventilation strategy	TITLE-ABS-KEY("natural ventilation" OR "naturally ventilated" OR “NV” OR "mixed-mode" OR “MM” OR "free running" OR “FR” OR "unilateral ventilation" OR "cross ventilation" OR "stack ventilation")
2	Climate & extreme events	TITLE-ABS-KEY(“summer” OR “warm” OR “hot” OR “Mediterranean” OR "humid climate" OR "climate change" OR "urban heat island" OR "UHI" OR "heat wave" OR “HW” OR "cooling systems" OR "passive cooling" OR "free cooling")
3	Building type	TITLE-ABS-KEY(“dwelling” OR “house” OR "residential building" OR "historic building" OR "heritage building" OR “office” OR "shopping center" OR "shopping mall" OR "commercial building" OR "educational building" OR “schools” OR “universities” OR “hospital” OR “clinic” OR “hospice” OR "nursing homes" OR “elderly care centers” OR “ECC”)

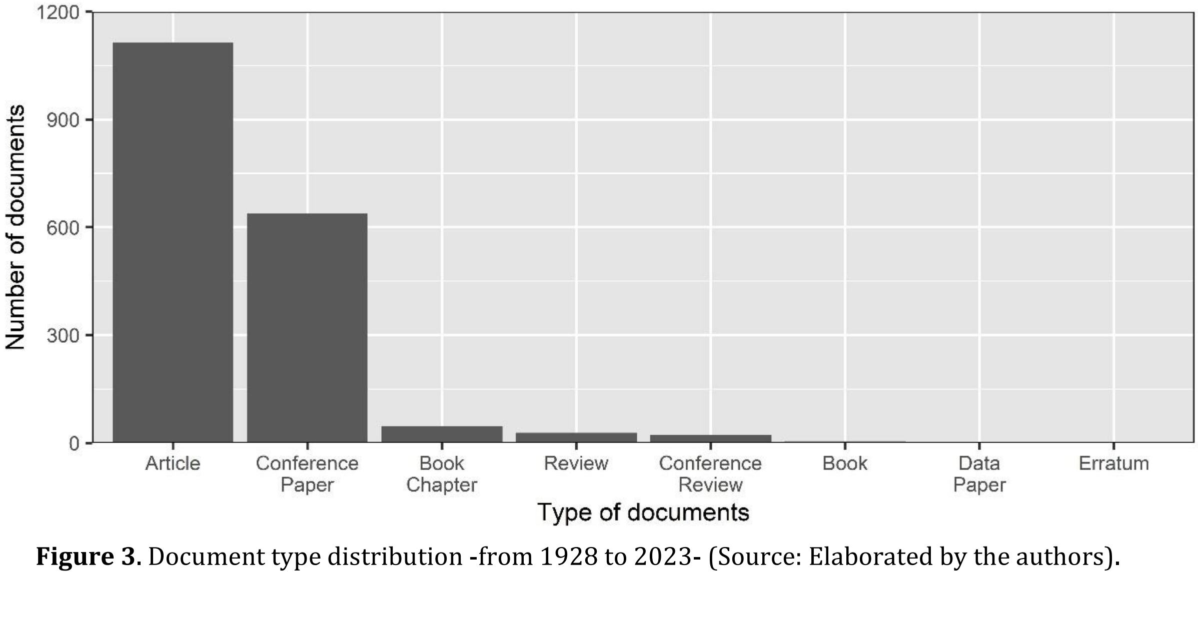

Figure 3. Document type distribution -from 1928 to 2023- (Source: Elaborated by the authors).

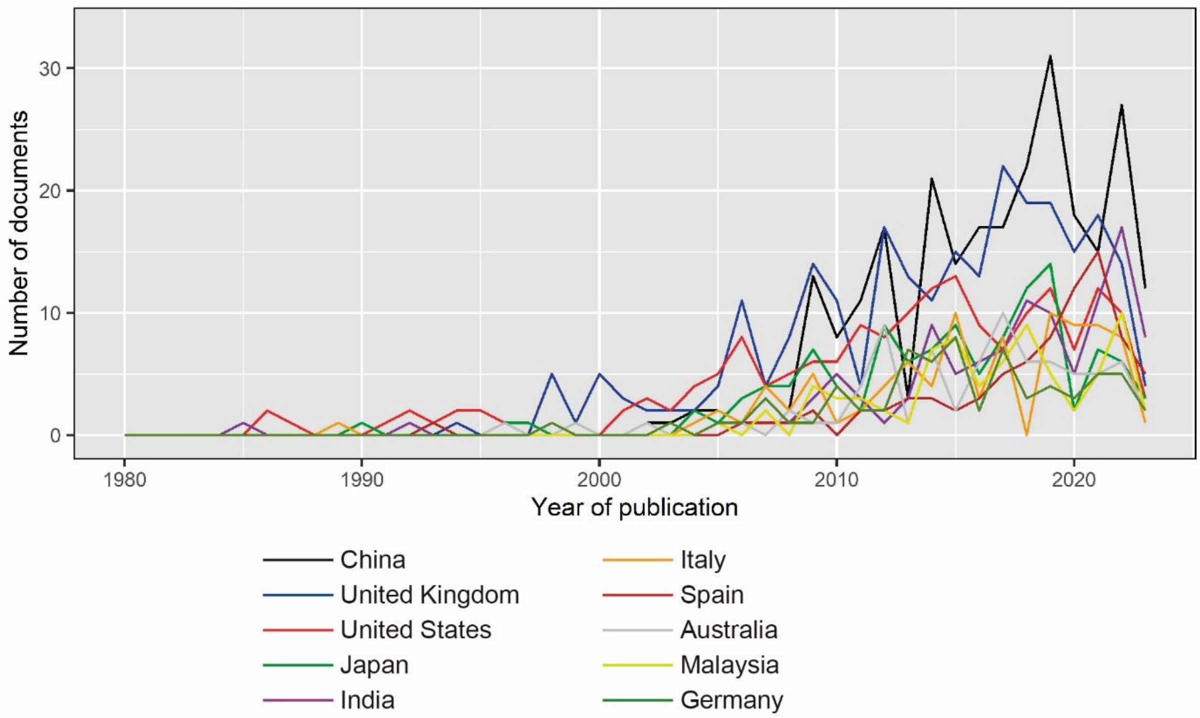

Figure 4. Publications for the top 10 countries -from 1928 to 2023- (Source: Elaborated by the authors).

Regarding the ten researchers with more influence on this topic, these are listed in Table 2. However, most of them did not collaborate together.

Table 2. The ten researchers with more influence on this topic.

Researcher	Number of documents	University (Country)	h-index
Dr. Tetsu Kubota	21	Hiroshima University (Japan)	14
Dr. Hom B. Rijal	19	Tokyo City University (Japan)	30
Dr. Roberto Lamberts	12	Federal University of Santa Catarina (Brazil)	34
Dr. Kevin J. Lomas	12	Loughborough University (UK)	37
Dr. Richard De Dear	12	University of Sydney (Australia)	63
Dr. Madhavi Indraganti	10	Qatar University (Qatar)	19
Dr. Maria Kolokotroni	10	Brunel University London Uxbridge (UK)	30
Dr. Anna Mavrogianni	10	University College London (UK)	31
Dr. Andreas Wagner	10	Karlsruhe Institute of Technology (Germany)	29
Dr. Runming Yao	10	Chongqing University (China)	38

3.2. Science mapping: overview of the research field

After conducting science mapping with VOSviewer, the co-occurrence network of keywords for a time span of 95 years (1928 – 2023) and the overlay visualization were plotted (Figures 5 and 6). As a result, a total of 288 items and 18952 links were obtained. From 1856 scientific publications, and applying a minimum occurrence of 15 times, 5 macro research areas were detected (Figure 5). Cluster 1 (energy efficiency; red colour) covers 99 items related to: building codes, architectural design (passive and active strategies), building energy performance in front of climatic conditions, energy management, intelligent buildings, retrofitting (i.e. improvement of thermal insulation of envelopes), building life cycle, and investments. Cluster 2 (indoor air quality - green colour) with 63 items emphasizes the air pollution and how this can be monitored and controlled (i.e. airflow, ventilation rates, type of pollutants –CO_2, PM-, urbans areas, risk assessment), especially in educational buildings. Cluster 3 (indoor thermal comfort - blue colour) covers 59 items that mainly refer to users' behaviour and adaptive comfort models, considering the data gathered from field surveys. Cluster 4 (simulation tools for ventilation - yellow colour) with 55 items involves existing computational simulation tools to develop numerical models. This allows evaluating wind effects, ventilation performance (during the day and the night), stack effect, thermal buoyancy, heat fluxes, cooling loads, solar chimneys and so on. Cluster 5 (hybrid ventilation systems - purple colour), with only 12 items, is more focused on the use of hybrid ventilation systems. In particular, those facilities designed for hospitals or neonatal spaces.

Furthermore, the findings revealed a strong relationship among Cluster 1, 2 and 4. By way of example, the implementation of ventilation models (cluster 4) could help to achieve a better use of energy (cluster 1) and to reduce carbon dioxide levels (cluster 2) inside buildings.

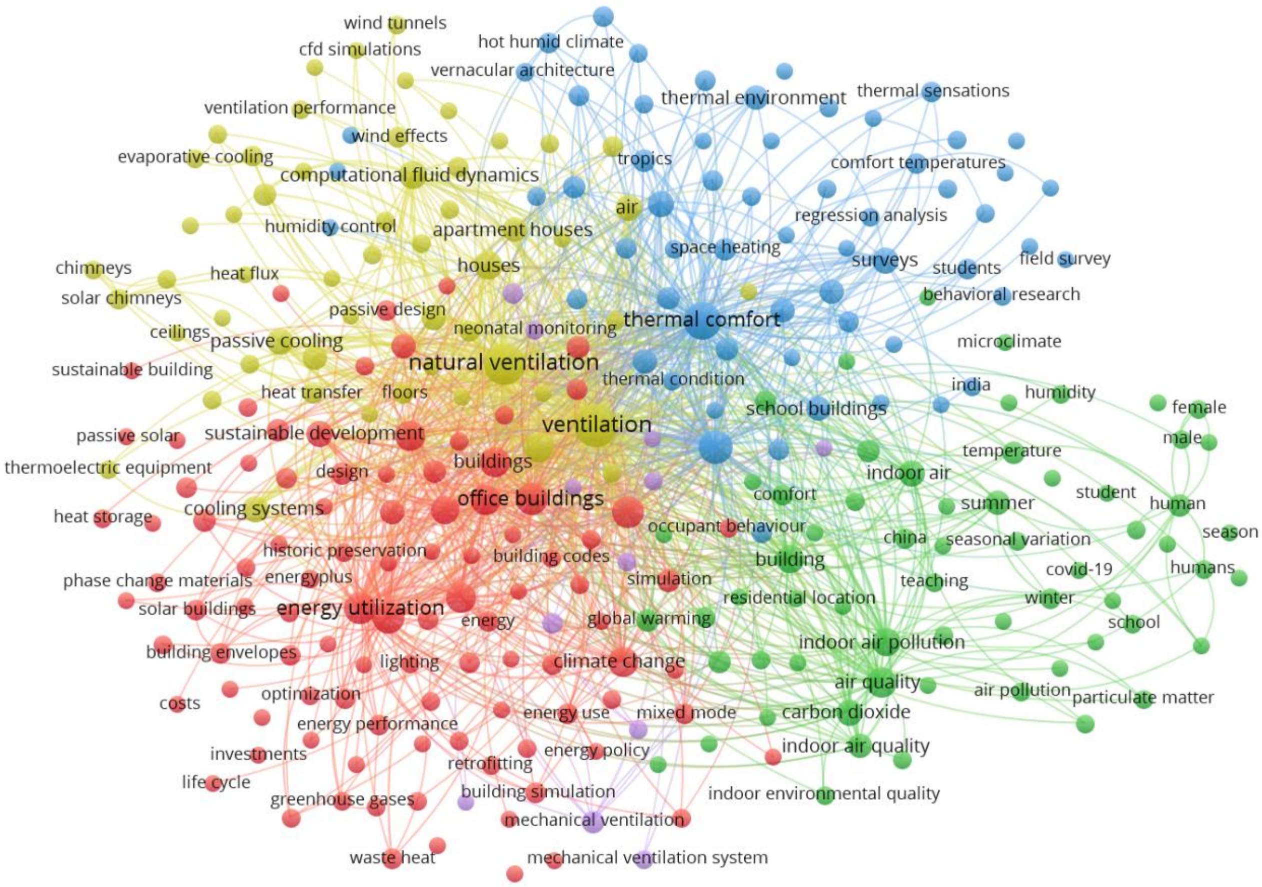

Figure 5. Co-occurrence network of keywords (Source: Created by the authors using VOSviewer and Scopus data).

Concerning the overlay visualization (Figure 6), it can be extrapolated that the first studies (before 2013) were associated to the application of computational fluid dynamics (CFD) simulations to assess air pollution of offices or to evaluate the building envelope of houses. The different scenarios were defined by season (summer / winter), building characteristics (i.e. heat transfer of construction materials) and gender population (male / female). From 2013 to 2016, the researchers concentrated their efforts on analysing the indoor air quality and thermal comfort, without connection between these two domains. Nevertheless, the first on-site experimental campaigns with microclimate stations and surveys about thermal sensation were carried out in this period, taking hospitals or schools as case studies. Regarding data processing, regression analysis was chosen as calculation method. In addition, several passive strategies like solar chimneys, vernacular architecture (use of local materials) or heat storage systems were tested as a solution related to natural ventilation. From 2016 to the present, with the effects of climate change and covid-19, the interest on zero energy buildings or smart buildings and ventilation systems increased. According to the Scopus database, it is estimated that 53.6~~1~~% of the total scientific documents were published in the last 7 years. The current trends are: the influence of indoor air pollutants in humans; the use of phase change materials for greater sustainability; historic preservation of patrimonial assets when opting for NV; the impact of overheating periods and seasonal variations on the performance of ventilation systems; investments and energy savings associated to ventilation systems; and the implementation of adaptive models to achieve both operative and comfort temperatures. Actually, simulations tools to unify thermal comfort and ventilation domains are still on going.

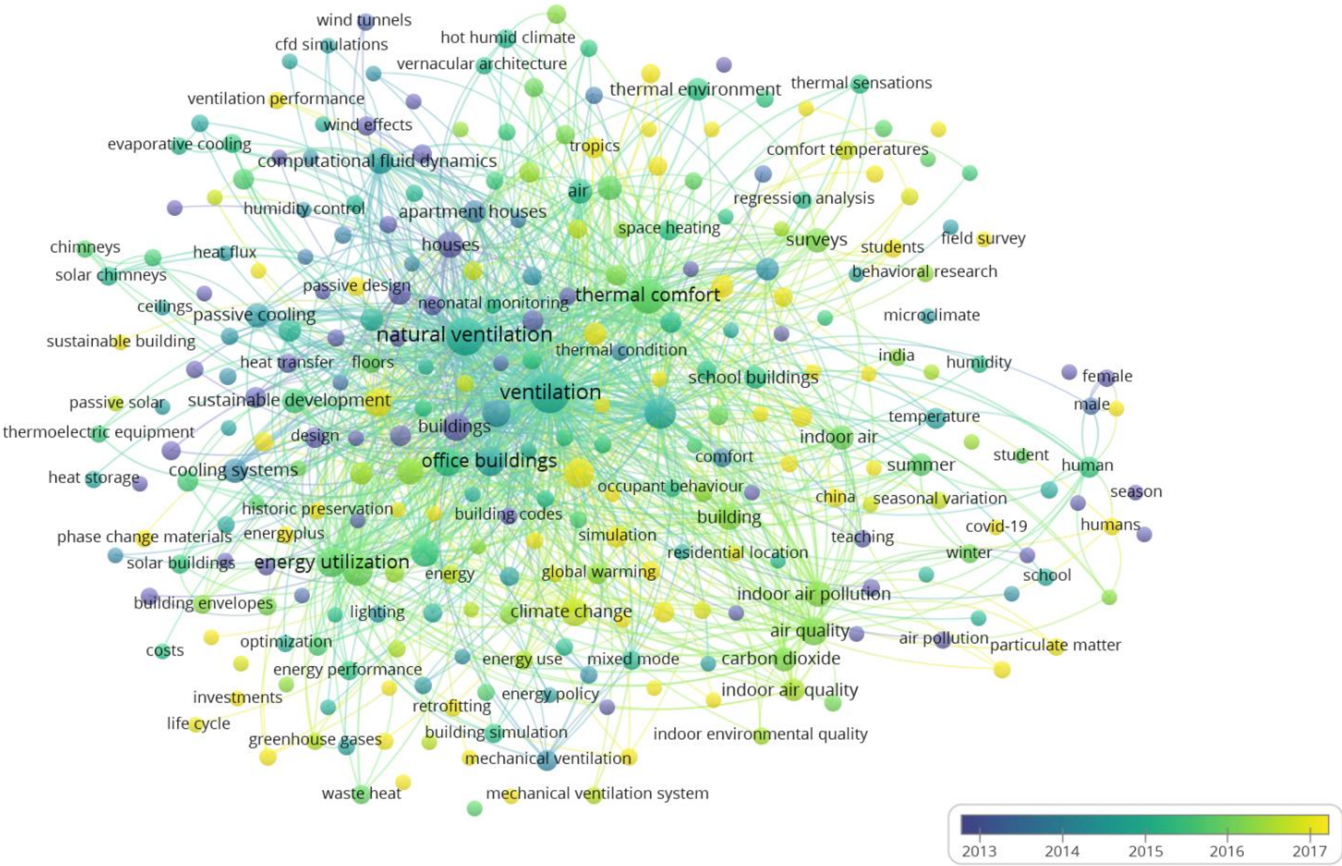

Figure 6. Overlay visualization (Source: Created by the authors using VOSviewer and Scopus data).

4. Assessment of research clusters

4.1. Thermal comfort and ventilation in warm climate zones

Thermal comfort is defined as the condition that expresses satisfaction with the surroundings and is assessed by subjective evaluation [29]. Thermal sensation is mainly related to the thermal balance of the human-body as a whole. This balance is influenced by physical factors (i.e. activity and clothing) and environmental parameters (i.e. air temperature, mean radiant temperature, air velocity and air humidity) [30]. Most of the studies on thermal comfort are mainly based on static models (i.e. PMV-PPD [30], SET [29], etc.) or adaptive models (ASHRAE-55, EN 16798-1:2019) (Figure 7). Static thermal comfort models usually consider steady-state heat transfer conditions between the human body and the environment, assigning a comfort vote (e.g. PMV). In contrast, adaptive models take into account the human responses and relative changes to the indoor environment. In this sense, physiological acclimatisation, psychological expectation and behavioural factors can influence the human thermal perception [31].

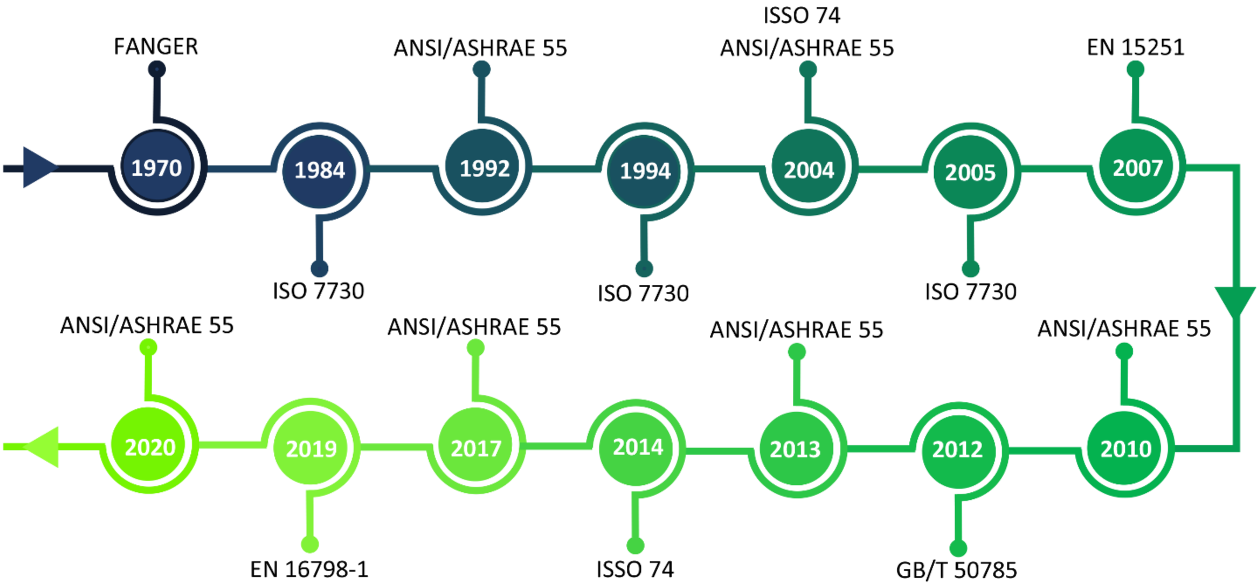

Figure 7. Timeline of thermal comfort models (Source: elaborated by the authors).

ASHRAE-55 and EN 16798-1 standards establish the use of adaptive models in occupant-controlled naturally conditioned spaces. These models tend to have a wider comfort temperature band, which could lead to significant energy savings in naturally ventilated (NV), air-conditioned (AC) and mixed mode (MM) buildings [32].

Current thermal comfort standards still differentiate between NV and AC buildings, while buildings that alternate between AC and NV (i.e. MM) are often left in an undefined range [33,34]. Several studies analysed how NV strategies influence thermal comfort in buildings. A summary of these works is shown in Table 3, regardless building type (most studies do not indicate whether the NV strategy is single-side or cross-ventilation). Along this line, Figure 8 shows a summary of the neutral temperature distribution of the studies reviewed in the scientific literature. The values show that the occupants of residential and offices NV buildings have a higher tolerance to thermal environment at higher temperatures, while the values show lower neutral temperature for the NV+F, MM and FR buildings. In contrast, a higher tolerance to thermal environment is observed in educational buildings with NV+F and MM systems. It should be noted that the occupants' density, mode of operation, dress code and space characteristics of rooms in educational buildings may vary from that of residential or office buildings, and therefore, influence occupants' thermal preference. Regarding nursing buildings, Figure 8 shows the lowest neutral temperature. This difference may be due to the fact that the residents of such buildings are older people and have different characteristics (lower metabolic rates, wear more insulated clothing, etc.) than a young adults. In addition, in this type of building, users often have disabilities and pathologies that can significantly affect thermal comfort. Finally, a wider range of neutral temperatures is observed in the different building types for the NV systems compared to the others.

Table 3. Summary of the main field research on thermal comfort and NV and MM building (2003 – 2023).

Year	Country	Climate	Ventilation system	Type of building	Equation	Acceptability/ Comfort limits	Reference
2023	India	Aw	NV + CF	Educational	$TSV = 0.37\ T_{op} - 10.94$	27.0 – 32.4 °C	[35]
2023	India	Cwa	NV + CF	Residential	$TSV = 0.09T_g - 2.10$ $T_{comf} = 0.54T_{out} + 12.32$	12.2 – 34.4 °C [-1 +1]	[36]
2022	Zanzibar	Aw	NV	Residential	$TSV = 0.65\ T_{op} - 17.74$	26.0 – 28.9 °C [-1 +1]	[37]
2022	India	Aw	NV + CF	Educational	$MTSV=0.41*T_{op} - 11.81$	25.0 – 32.5°C	[38]
2022	India	BSh – Aw – Cwa – Cwb	MM	Residential		18.2 – 38.3 °C	[39]
2022	Spain Portugal	Csa – Csb	NV	Nursing home	$MTSV = 0.0997T_{op} - 1.8058$ $MTSV = 0.1235T_{op} - 1.7371$	8.1 – 28.1 °C 6.0 – 22.2 °C	[40]
2022	Ghana	BSh-Aw	NV + F	Office		23.4 – 28.4 °C 23.1 – 28.1 °C	[41]
2021	Cyprus	BSh	NV	Educational		24.3 - 30.3 °C	[42]
2021	Spain	Csa	NV	Nursing home	$MTSV = 0.12T_{op} - 2.8$ $MTSV = 0.32\ T_{op} - 6.95$		[43]
2021	South Algeria	BWh	NV	Residential	$TSV = 0.216\ T_{op} - 6.8133$ $T_{comf} = 0.33\ T_{out} + 20.15$		[44]
2021	China	Cfa	NV	Educational	$TSV = 0.289T_{op} - 7.569$	~29.6 (upper limit)	[45]
2021	Japan	Cfa	NV	Educational	$TSV = 0.38\ T_{op} - 9.93$	23.3–28.5	[46]
2021	Ecuador	Cfb – Aw – Af	FR MM	Educational	$TSV = 0.2933\ T_{op} - 6.4074$ $TSV = 0.4985\ T_{op} - 12.972$	±1.7 °C (90%) ±3.4 °C (80%) ±1.2 °C (90%) ±2.4 °C (80%)	[47]
2021	Nigeria	Am	NV	Educational	$TSV = 0.24T_{op} - 6.90$	25.2 –32.3 °C	[48]
2020	Bangladesh	Aw	NV	Educational	$TSV = 0.14T_{op} - 2.7084$ $T_{comf} = 0.38T_{rm} + 16.10$	21.6 – 34 °C	[49]
2020	UK	Cfb	NV	Educational		23.0 – 25.0 °C	[50]
2019	Australia	Csa	NV	Residential	$T_{comf} = 0.27\ T_{rm} + 19.2$		[51]
2019	California	Csb	NV + CF	Office		18 – 27 °C	[52]
2019	India	BSh - Cwa	NV + F	Educational	$TSV=0.17T_{op}-4.95$	16 – 33.7 °C	[53]
2019	China	Cwa	MM	Office	$TSV = 0.18T_{op} - 4.86$	24 - 30 °C (80%)	[54]
2019	Australia	Cfa	MM	Office	AC(B1) - $TSV= 0.15T_{op} -4.27$ NV(B1) - $TSV= 0.16T_{op} -4.49$ $T_{comf} = 0.16\ T_{pma(out)} + 22.58$ AC(B2) - $TSV= 0.28T_{op} -7.15$ NV(B2) - $TSV= 0.25T_{op} -6.53$ $T_{comf} = 0.48\ T_{pma(out)} + 15.86$ AC(B3) - $TSV= 0.24T_{op} -7.22$ NV(B3) - $TSV= 0.18T_{op} -4.79$ $T_{comf} = 0.23\ T_{pma(out)} + 20.75$		[55]
2019	China	Cfa	NV + Fan	Residential	$TSV = 0.33T_{op}-8.61$		[56]
2019	Mexico	Aw	NV	Educational	$TSV = 0.324T_{op} - 8.30$ $T_{comf} = 0.32T_{rm} + 18.45$	22.5 – 28.7 °C	[57]
2019	Singapore	Af	NV + AC NV	Educational	$TSV = 0.20\ T_{op} - 5.92$ $TSV = 0.18\ T_{op} - 4.92$	25.2 – 33.7 °C (80%) 27.0 – 31.9 °C (90%) 23.0 – 32.6 °C (80%)	[58]

						24.9 – 30.6 °C (90%)	
2018	India	BSh	NV	Educational	TSV=0.19 T_a-5.04	21.8–31.8 °C	[59]
2018	China	Cfa	NV	Residential	TSV = 0.2347T_{op} – 6.5646	22.0 °C – 30.1 °C (80%)	[60]
2018	Indonesia	Am	NV	Educational	TSV = 0.175T_{op} – 5.074		[61]
2018	India	BSh	NV + CF	Educational	TSV = 0.19T_a – 5.04 T_{comf} = 0.49T_{rm} +13.8		[62]
2017	China	Cfa – Cwa	FR	Residential	TSV = 0.155 T_a – 3.76 $T_{n,d}$ = 0.29 T_{rm} – 19.90 $T_{n,d}$ = 0.709 T_{rm} + 8.25		[63]
2016	Indonesia Japan	Am - Cfa	FR, MM	Office		(Indonesia) FR = 26.7 °C MM = 27.4 °C (Japan) FR = 26.6 °C	[64]
2016	Japan	Cfa	FR	Educational	TSV = 0.491T_{op} – 13.1		[65]
2016	India	BSh – Aw – Cwa – Cwb	NV MM	Office	TSV = 0.19T_{op} – 4.82 TSV = 0.15T_{op} – 4.02		[66]
2015	India	BSh	NV + F	Institutes, offices, and hostels	TSV = 0.299T_a – 8.788		[67]
2014	Japan	Cfa	NV	Residential	TSV = 0.192T_a – 0.872 TSV = 0.189T_g – 0.809		[68]
2014	India	Aw	NV	Office	TSV = 0.26T_g-7.09 T_{comf} = 0.26 T_{rm} + 21.4		[69]
2013	India	Aw	NV	Office	TSV = 0.326 T_g - 8.489 TSV = 0.173 T_g – 4.099		[70]
2013	Venezuela	BSh	NV + PC	Residential	TSV = 0.1155T_a – 3.1715 TSV = 0.6445T_a – 18.523		[71]
2012	Australia	Cfa	MM	Office	TSV = 0.0735T_{op} -1.31		[34]
2011	India	Aw	NV	Residential		31.38 – 32.9 °C	[72]
2010	India	BSh	NV	Residential	TSV = 0.31T_g – 9.06	26.0 °C – 32.5 °C (−1 to +1)	[73–76]
2008	China	Cfa	NV	Office	TSV = 0.32T_{op} – 9.12	25.0 – 31.6 °C	[77]
2003	China	Af	NV	Educational		27.1 – 29.3 °C	[78]

CF: Ceiling fans; F: fans; PC: passive cooling; MTSV: mean thermal sensation vote; T_a: air temperature; T_{comf}: comfort temperature; T_g: globe temperature; $T_{n,d}$: daily neutral temperature; T_{op}: operative temperature; T_{out}: outdoor temperature; $T_{pma(out)}$: prevailing mean outdoor temperature; T_{rm}: running mean temperature; TSV: thermal sensation vote; B1: Building 1; B2: Building 2; B3: Building 3; FR: free-running;

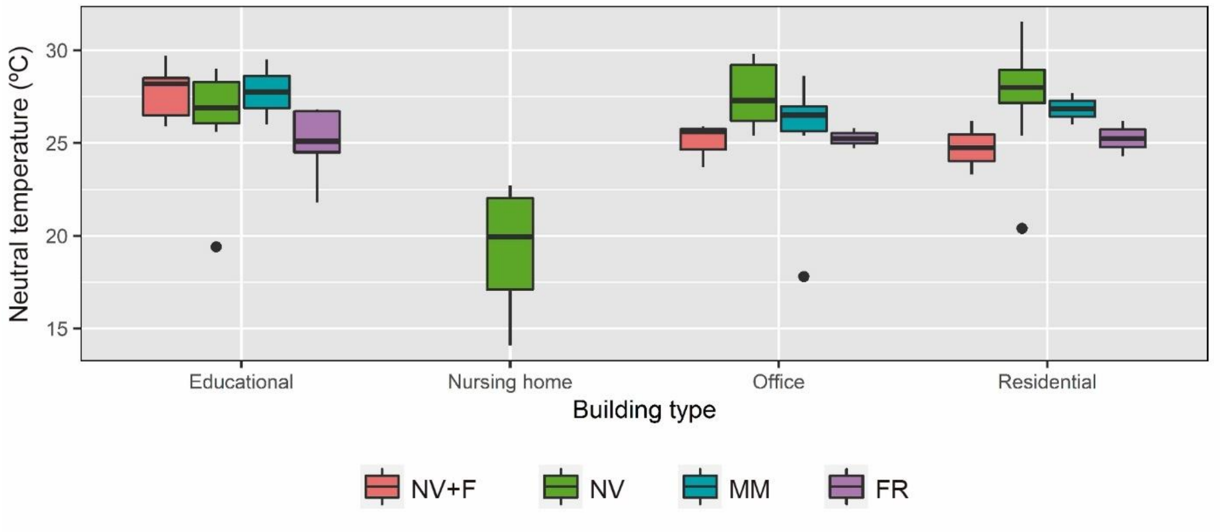

Figure 8. Summary of neutral temperature in NV and MM buildings in scientific literature (Source: Elaborated by the authors).

4.1.1. Strategies in NV buildings

Numerous studies evaluated the effect of NV strategies in different types of buildings (e.g. hospitals, schools, offices, dwellings or commercial buildings) to check if indoor thermal comfort could be acceptable in warm climates or during summer season. Regarding NV residential buildings, Zepeda-Gil and Natarajan [79] evaluated thermal comfort in NV dwellings in the central Mexican plateau and found that 83% of the comfortable votes were obtained during spring and summer compared to 47.5% in winter.

The study conducted by Ramos et al. [80] in Brazilian residential buildings showed a massive preference for NV environment in all climates zones. In fact, the most common method of adaptation on hot days was opening windows and doors. Morey et al. [81] investigated overheating risk in FR social housing properties located in central England (UK). Among their major findings, it was detected that a higher proportion of bedrooms exceeded static overheating thresholds, while very few houses exceeded the criteria for thermal comfort adaptive methods. The results reported by Morey suggest that English Midlands housing stock might be expected to overheat significantly in future years, according to static criteria. The results reported in studies conducted in NV nursing homes in Mediterranean climate (SPAIN) supports the use of NV at broader setpoint temperatures without compromising occupants' comfort and well-being [40,43].

Regarding educational buildings, ventilation strategies and indoor thermal conditions should be especially considered given the potential impact on students' performance and health. The study carried out by Wang et al. [45] in China revealed that special attention shall be paid in NV classrooms to avoid summer overheating. In this line, Buonocore et al. [82] also highlighted that thermal discomfort due to heat is an important issue in NV classrooms under hot and humid conditions in Brazil (indoor temperatures above 29 °C). Heracleous et al. [42] pointed out that most educational buildings in Cyprus are NV and consequently, cannot perform in a thermally comfortable manner (neither in the present or future climatic conditions). Similar conclusions were reported by Dhalluin et al. [83], who highlighted that NV strategies could be problematic in hot and humid climates due to the risk of overheating in NV buildings. Previous studies also investigated the use of fans in NV classrooms. Bhandari et al. [35] analysed the influence of ceiling fan-induced non-uniform thermal environment on thermal comfort in NV lecture halls in Tamil Nadu. They found a significant difference in thermal comfort conditions between different zones. Students seated farther from the fan experienced less air velocity, which impacted in thermal sensation, air velocity sensation, sweating sensation, air velocity preference, thermal comfort vote and productivity. Due to higher air velocity of fan, a slightly higher neutral temperature of 29.7 °C was determined in comparison with other studies conducted in similar climate zone. Other studies carried out in warm humid climate (Kumasi, Ghana) Koranteng et al. [84] concluded that opening windows and the use of fans could keep students comfortable.

These aspects are also relevant in NV offices buildings, as the intensity of fatigue and headache have been pointed out as one of the consequences of air temperature over the comfortable zone [85]. Kyritsi and Michael [86] carried out field measurement in office buildings, in the dry climate of Cyprus, and found that NV can have a positive contribution to the passive cooling of these buildings. He et al. [87] highlighted that office occupants in China place a great value on natural ventilation, especially in summer and winter.

It is also remarkable that in buildings where ventilation through doors and windows is the main way to control thermal comfort, occupant adaptation is particularly relevant. A considerable diversity in occupants' adaptation measures in NV buildings have been analysed in numerous studies. Indraganti et al. [73–76] found that occupants of apartments in Hyderabad (India) adapted through clothing and metabolism as the temperature increased in summer (although clothing adjustments in women were limited due to socially and culturally practices). At high temperature, occupants used fans and other electrical controls for air movement and windows/doors/curtains were closed to contain heat gain, glare and hot breezes. Kumar et al. [59] concluded that the proportion of 'open window' has a growing trend with an increase in indoor and outdoor air temperature values up to 34 °C. Dhaka et al. [67] reported similar conclusions in NV buildings in the region of India. In China, Lai et al. [88,89] analysed occupants' behaviour in residential buildings and the authors also concluded that NV duration increased as the climate became warmer. The study on thermal comfort in a family condominium conducted by KC et al. [90] in Shinagawa (Japan) found that opening the windows increased the thermal comfort of the occupants even though the indoor air temperature was quite high. Other adaptive measures were used, such as changing the insulation of clothing or using fans to adjust the thermal environment. Similar conclusions were found by Rijal [68] in Japanese houses during the hot and humid season. These adaptive behaviours in response to warm and hot conditions were also employed by households living in NV houses in hot humid climates in Australia, including adjusting the arrangement of clothing, operation of the dwelling and use of external measures (e.g. lowering body temperature by swimming), with an almost continuous natural ventilation strategy [91]. In contrast, previous studies identified barriers to use NV and adaptive measure in residential buildings in India [36,73]. Among the identified causes, it can be noted the lack of privacy when the windows opened into the public realm [73] or the heat outside [36] in dwellings.

Other studies have looked at the particular case of students' adaptive behaviour in NV educational buildings as thermal perception of children and teenagers can vary significantly from that of the adults [92]. Jindal [53] pointed out that students in this age range demonstrated considerable adaptability to indoor temperature variations by taking adaptive measures such as switching fans on/off or opening windows. These both measures were also identified by Khambadkone et al. [38], along with the wearing lighter clothing, partly closing curtain blinds and drinking cold water, as the main adaptive measures of students in NV classrooms in the warm-to-moderate climate of India. Aparicio-Ruiz et al. [93] observed that the preference towards opening windows and doors as adaptive strategy decreased along with the outdoor temperature in Spanish primary classrooms during summer season. Talukdar et al. [49] evaluated student thermal comfort and adaptation measures in NV university classrooms with ceiling fans in Mymensingh (Bangladesh) and concluded that high air velocity minimized the discomfort due to high humidity. These findings highlight the importance of occupant adaptation in NV buildings in warm climatic zones.

4.1.2. Strategies in MM buildings

Concerning MM buildings, they operate in both NV and AC. The measures of adaptive behaviour found in NV buildings are also employed by occupants in MM buildings. Additionally, occupants in MM buildings can also switch on and off the air-conditioning systems to control the indoor thermal environment [54,94]. The adaptive comfort behaviours in MM residential buildings in Tianjin (China) by Hou, J. [95] and they found that the most common adaptive strategies adopted by occupants to reach thermal comfort was opening windows and doors. Ke Zhong et al. [96] pointed out that occupants usually make full use of the ventilating facilities or low energy-consumption methods to control and adapt the indoor thermal environment in NV and AC equipped rooms of residential buildings. Chen et al. [97] evaluated thermal comfort in a MM school building in Taiwan and also found that the most commonly used systems were open the windows and run the fans (64 %), which was followed by opening the windows alone (25 %) and the joint use of the fans and AC (11 %).

Regarding MM offices, Sun et al. [94] found that NV and cooling equipment (fans and AC) were commonly used in summer, indicating a MM adaptive behaviour. Indraganti et al. [70] found a low satisfaction in office buildings in Chennai and Hyderabad (India) when these buildings operated in NV mode. They observed that 80% of air velocity was around of 0.0–0.2 m/s, a range much lower than the allowable limits set in ASHRAE-55. This resulted in more than half the occupants demanded increased air speeds. Among the causes limiting the opening of windows, the authors identified the following: mosquitoes, noise, vandalism, jamming, user lethargy etc.

It should be remarked that the ventilation system influences the occupants' thermal perception. The comparison of several types of ventilation systems showed that the subjective thermal response of NV mode was significant different from that of AC mode. Lau et al. [58] conducted a study in educational buildings with AC, MM and NV systems in Singapore. A wider range of temperature acceptance was found in MM and NV spaces than in AC spaces. Despite this, the respondents of AC spaces had a cooler thermal sensation than MM and NV spaces, compared to NV spaces where the users presented a warmer sensation. This suggests that the occupants of these spaces have a higher tolerance to indoor thermal conditions. It allows the implementation of more adaptive measures in these spaces. Similar results were found in educational buildings in China [98], in Mexico [57] and in Australia [99,100].

In the case of offices, the comparative analysis among occupants' thermal perception led to locations around the world. Mustapa et al. [65] found that in FR-mode office buildings in Japan, many of the occupants would prefer slightly cooler conditions, while 50% of the occupants did not want to change the thermal environment in AC mode. The users of FR mode adopted an adaptive behaviour, such as taking drinks, switching on fans and opening doors and windows. Wu et al. [54] concluded that office occupants could benefit from split air-conditioned, since they could freely adjust indoor temperature and control windows, compared to the AC and NV buildings. This issue is also evident in the results reported by Rup et al. [101]. Lower prevalence of 'cold' discomfort response among the occupants of MM buildings was demonstrated, comparing those offices with centralized HVAC and under the equivalent thermal conditions in Brazil. In contrast, De Vecchi et al. [102] observed non-significant difference in terms of thermal acceptability between MM and fully-air-conditioned office buildings under humid subtropical conditions.

4.1.3. Passive cooling techniques

Numerous studies explored the use of other passive cooling techniques to improve the indoor thermal environment. For example, several studies analysed the used of night ventilation to control the indoor temperature in buildings [42,86,103–108]. Heracleous et al. [42] concluded that the night ventilation strategy in Cyprus has a positive contribution to the cooling effect of indoor spaces during the hot summer period [105]. Similar results were found in office buildings [86] and vernacular architecture [106,107] in this region. Kubota and Chyee [104] found that night ventilation is better than daytime ventilation in modern houses in Malaysia, while full-day ventilation and no ventilation were optimal in terms of air temperature reductions during the day and night. However, additional measures are necessary to improve diurnal thermal conditions in the room such as dehumidification (to reduce indoor humidity) or increasing the indoor air speed (using fans).

Other passive techniques, such as thermal stack flue, cross ventilation and water wall are also analysed in the research literature. Moosavi et al. [109] investigated the use these techniques in order to minimize the overheating inside an atrium lobby of office building in Putrajaya, Malaysia. From the comparison, they conclude that cross ventilation and water wall reduce the temperature inside the atrium when the stack flue has its highest performance. Nevertheless, the effect of stack flue is more effective on the reduction of the humidity. Elmualim [110] evaluated the use of wind catcher (tower natural ventilation system) in a seminar room in the University of Reading in the UK. This system, in conjunction with openable windows, can achieve a higher night and daytime cooling effect in the particular area where the system was installed. Furthermore, occupants expressed their overall satisfaction with the system and comfort conditions. Psomas et al. [111] analysed automated roof window control system to address overheating on renovated houses (Cfb climate) and found that automated window system reduces overheating risk in houses of temperate climates. Nevertheless, Ortiz et al. [112] analysed passive measures for the energy refurbishment of residential buildings in Catalonia (Spain) and pointed out that the behaviour of the passive measures is not always possible during the warm season, especially if the hours of overheating are analysed. Nevertheless, buildings may be constrained to operate naturally ventilated and cause thermal dissatisfaction for occupants

4.1.4. Modelling and assessment

It should be also highlighted the application of the several thermal assessment methods in warm-hot climates. Significant differences were detected between the assessment obtained from the static models and the adaptive models in NV buildings. Several studies pointed out that PMV method showed lower accuracy and occupants' thermal perception is often overestimated or underestimated [38,46,53,67,70,113–116]. Rangaswamy and Ramamurthy [113] analysed different thermal comfort indexes (i.e. PMV, e-PMV, a-PMV, Tropical Summer Index -TSI-, standard effective temperature -SET-, predicted thermal sensation -PTS-, ASHRAE–adaptive, and Indian model for adaptive comfort -IMAC-) in NV apartment buildings in Chennai (Hot–Humid Climate, India). Their results showed that PMV, SET and IMAC had lower accuracy compared to the other indices applied in this climate and building type, while the TSI is consistent in accurately predicting occupants' actual vote. The results reported by Wagner et al. [117] from a field study on thermal comfort in a NV office building in Karlsruhe (Germany) showed that models with a fixed limit o indoor temperature predict the thermal sensation and thermal comfort of occupants worse than adaptive comfort models, if periods with transient indoor (and outdoor) climate conditions are considered. Lau et al. [58] conducted a study in educational buildings with AC, MM and NV systems in Singapore. They determined that the percentage of responses from respondents in MM and NV spaces (within the acceptable region according to the adaptive model) were consistently higher than those derived to the PMV/PPD model for all respondents. Similar conclusions were obtained by numerous researches in other climate zones [34,43,52,70,100].

In addition, previous studies concluded that the adaptive model provides a more accurate assessment than static models such as the PMV [34,39,54,55,95,118] in MM buildings. This is due to the possibility of using adaptive measures by the occupants, as they can switch between AC mode (switching on/off the air conditioning system) or NV mode (opening/closing doors and windows). The acceptable region of thermal comfort is wider in this type of buildings [66]. Deuble and de Dear [34] pointed out that adaptive comfort model was applicable to the MM building, especially during times of NV. One of the challenges of creating NV or MM buildings used by many occupants is not only to provide and ensure adaptive options, but also to foster a social context that encourages successful communication and implementation of adaptive adjustments among the occupants [119].

In summary, the models defined in ASHRAE-55 and EN 16798-1 were the most widely applied. Nevertheless, they resulted inaccurate in some climatic regions for assessing the thermal comfort of building occupants. To solve this drawback, several studies have proposed new adaptive models more suited to the climate of these regions. For example, Daghigh et al. [116] obtained that the neutrality temperatures in office rooms at University Putra Malaysia for both scenarios (NV and AC) were higher than those given in the ASHRAE Standard 55-1992 and suggested a wider thermal comfort band for Malaysians. Zhai et al. [52] analysed the use of adaptive control and its effect on human comfort in a NV office in California. They concluded that the adaptive model is generally effective in predicting thermal comfort, but its comfort zone could be wider for occupants in mild climates like in north California. Aparicio-Ruiz et al. [93] observed a widening in the thermal comfort range for children compared with EN 16798–1 and the ASHRAE-55 Standard in Spain. Bassoud et al. [44] discussed the thermal behaviour of NV buildings constructed in adobe in hot arid Sahara regions during summer and proposed a comfort model for this zone which is within the acceptability range of the ASHRAE model with a difference of order 4 °C, and an 8% difference between the slopes of the comfort temperature equations. Munonye and Ji [48] concluded that children schools are less sensitive to temperature changes than adults in NV primary schools of warm and humid environment in Nigeriaand that the comfort ranges. From this study, the upper limit of ASHRAE-55 comfortable temperature was extended. López-Pérez et al. [57] evaluated an adaptive thermal comfort field study in educational buildings in Tuxtla Gutiérrez (México) during warm season. The authors reported that respondents expressed thermal satisfaction at comfort temperatures above current international standards. Rawal et al. [39] also proposed an adaptive model for MM and NV residences in Indian climate.

4.1.5. Future perspectives

Finally, although advances in knowledge have been made so far, further studies are needed to explore the following aspects:

- Field thermal comfort studies in a wider variety of different climates. The literature review highlighted that many studies have been carried out in the regions of China, India and Australia. However, other warm climate regions, such as the Mediterranean basin and South America, are underrepresented in terms of the number of publications. Future field studies should be conducted in these areas to better understand the influence of climate on thermal perception and occupants' behaviour, as well as to generate a regional database, complete the ASHRAE global thermal database II and help to develop regional thermal comfort models applicable to NV and MM buildings in these locations.
- Analysis of different occupant activity types. Main studies focused on the analysis of thermal comfort in sedentary or near-sedentary physical activities (i.e. office work, teaching activities, domestic activities, etc.) Nevertheless, human thermal perception is influenced by metabolic rate, which in turn depends on the type of physical activity performed. It is necessary to extend studies to other types of activities, considering different metabolic rates and assessing the impact of building performance on the thermal comfort of users in these scenarios.
- Elderly building occupants. More research is needed to understand the impact of thermal conditions in NV or MM buildings on older occupants. Society in developed countries is facing demographic change due to an ageing population. In Europe, 29.1% of the population is expected to be over 65 by 2080 [120]. Given that the thermal perception in this age range is different from that of an adolescent or adult, and that global warming may lead to more heat waves in the coming years, analysing this segment of the population is essential because of their special vulnerability to the risk of overheating.
- Further analysis of adaptive measures. Numerous studies reported that adaptive measures, such as the use of electrical appliances like fans, can improve the thermal satisfaction of building occupants [35,121]. However, these measures may also cause local discomfort (due to the relative position of the occupant inside the room and that the air velocity may be higher/lower) and influence other domains of indoor conditions (e.g. noise). In this respect, further research is required to study the influence of this equipment in the overall occupants' satisfaction.
- Previous studies suggest that subjects' physiological adaptation may not be influenced by short-term indoor thermal history. However, further studies are required to confirm that there is no effect [98]. This aspect should be analysed to identify its impact in the behavioural adaptation aspect (adjusting clothing and using fans, doors, windows and AC).
- Different types of occupants can be in a building simultaneously. Research focused on the study of adaptive measures among office workers or occupants of residential buildings has been extensively evaluated. Nevertheless, other scenarios where different types of occupants come together (i.e. students and professors, workers and

users/costumers, etc.) should be evaluated and adaptive measures for each category and type of activity should be assessed.

- Analysis of the passive cooling strategies' usage in contemporary buildings. Previous studies highlighted that some buildings cannot perform thermally comfortably under future climate conditions [42] and a risk of overheating might be expected in future years [81]. It needs future research efforts to analyse passive cooling strategies to effectively limit the overheating risk in contemporary buildings.

4.2. Implications of ventilation in the energy performance of buildings

4.2.1. The impact of climate change in the use of NV

The use of NV to improve the energy efficiency of buildings has focused much of the research in recent years. The possibility of using NV is simple: if the outside temperature is within the user's thermal comfort conditions, the interior can be ventilated. This makes possible to achieve reductions in cooling energy demand. Although the premise is simple, there are many factors that affect the possibility of applying NV effectively, such as the urban environment [122] or the shape of the building [123,124].

NV is understood as an effective measure to reduce energy consumption in the warm months. In this sense, its use during the summer stands out [125]. This aspect may be an advantage in the context of climate change, since summers are expected to be longer. However, a significant increase in outside temperature is also estimated, which could limit the use of this strategy. In relation to this, the studies carried out by Bienvenido-Huertas et al. [126,127] have reflected the expected variation with the use of NV. Figure 9 shows the trends of change in the use of NV in Europe with RCP scenarios. As seen, the northern areas will increase the use of NV throughout the year, while the southern areas will see a decrease in the possibility of use.

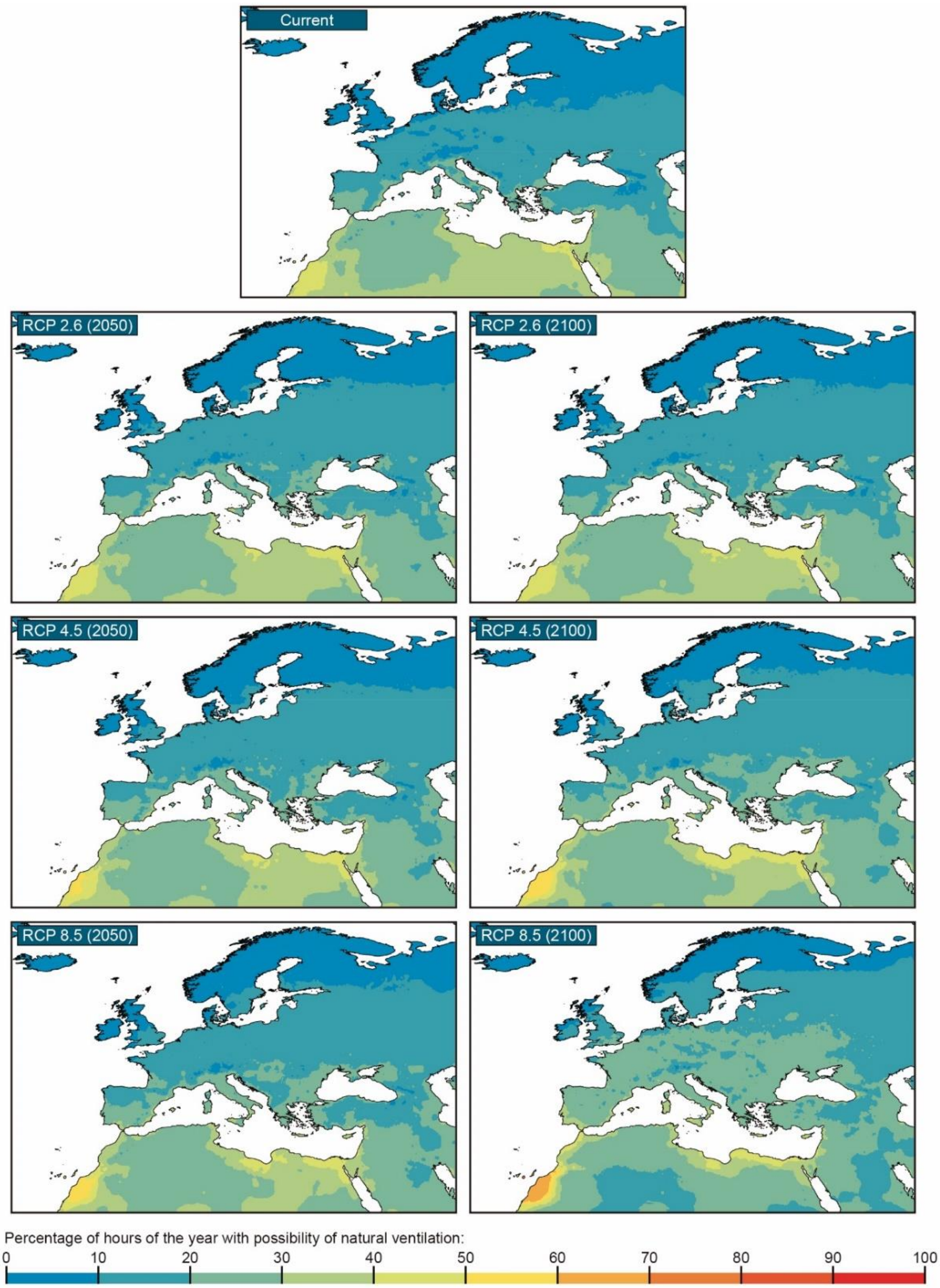

Figure 9. Maps of Europe and the Mediterranean area with the yearly use of NV (Source: Elaborated by the authors). Data and methodology used according to the study by Bienvenido-Huertas et al. [128,129].

In any case, climate change will mean a variation in the possibility of using NV to save cooling energy consumption. This aspect has already been reported by several studies: (i) Kaudeer et al. [130] determined that climate change will increase the hours of thermal discomfort in naturally ventilated buildings in Mauritius by up to 15%; (ii) Rysanek et al. [131] evaluated the impact of climate change on naturally ventilated office buildings in Vancouver. The analysis was carried out for the summer months using the adaptive thermal comfort model of ASHRAE 55-2017. The authors found that the RCP 8.5 scenario may increase by up to 33 days per year in 2050 and up to 55 days per year in 2080; and (iii) Pajek et al. [132] determined that the most effective measures for energy saving in the residential environment in Montenegro were roof insulation, shading and NV. Thus, the use of NV has an expected variability in the future, which implies increases or decreases in its effectiveness as an energy measure. The results based on the current scenario have shown interesting energy savings, but that are far from zero energy consumption. Li et al. [133] determined that night ventilation in Shenyang University buildings (China) allowed cooling energy savings of up to 45% in summer. Sun et al. [134] focused their efforts on finding effective passive measures for disadvantaged neighbourhoods in California. The results showed how NV allowed to achieve reductions of up to 26% in hours of thermal discomfort. Thus, these studies did not show 100% effectiveness of NV. For this purpose, it is necessary to combine NV with other measures. In this sense, Sun et al. [134] highlighted that in their study the use of NV with other passive measures and air-conditioning to achieve 100% of the hours of thermal comfort.

4.2.2. Combination of NV with other saving strategies

Given this circumstance, much of the efforts of researches have focused on the optimal combination of ventilation strategies with other measures [135]. The analysis of NV energy savings with other measures is very varied (Figure 10). Analysis with variables such as: building shape [136–138], shadows [139], Windows to Wall Ratio (WWR) [136–138], orientation [136–138], cold roof and walls [136–138], thermal transmittance [140], solar heat gain [141], courtyards [142,143], and Thermally Activated Building Structures (TABS) [144].

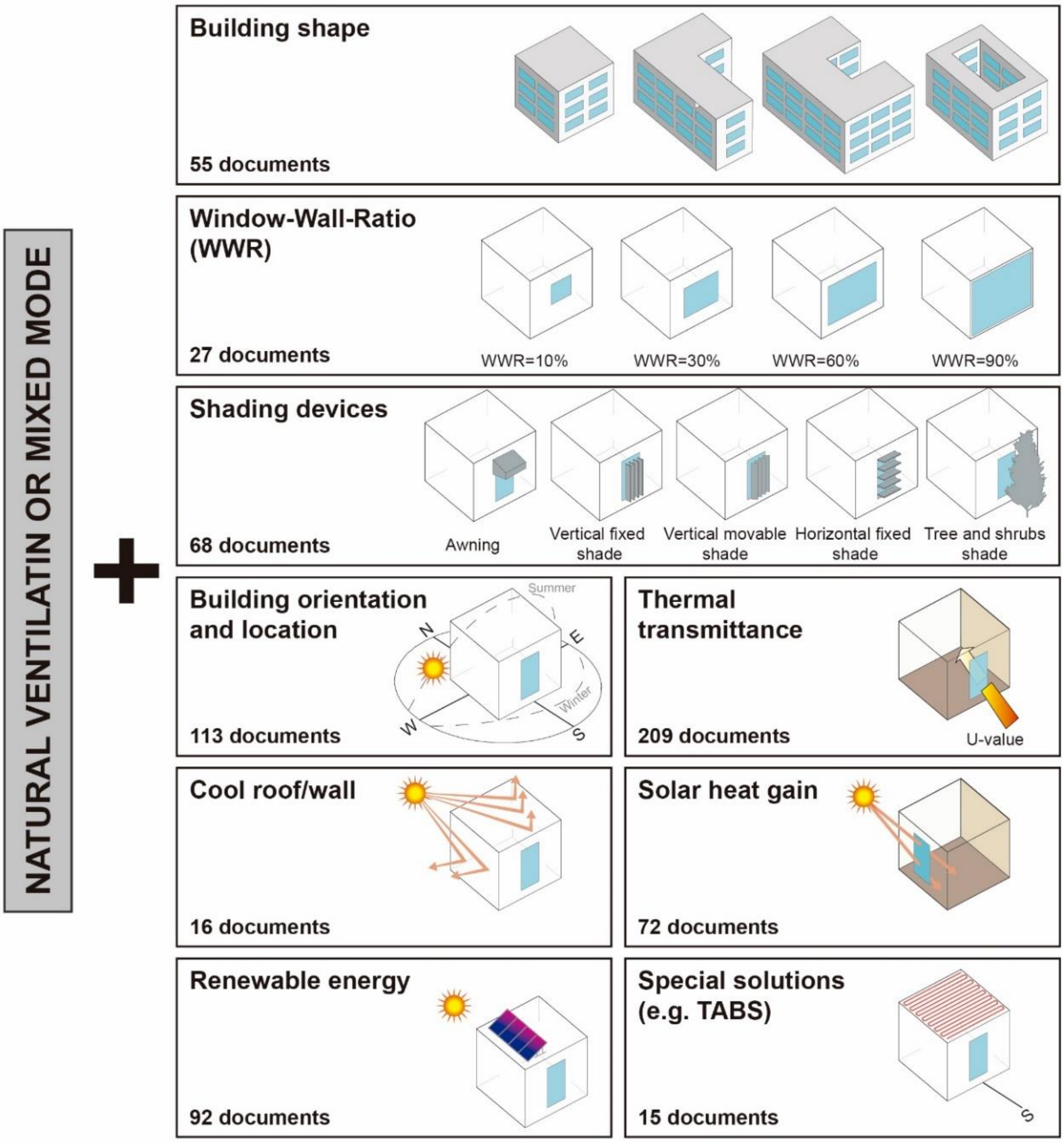

Figure 10. Combinations of NV with other measures analysed in the scientific literature. The number of studies associated with each combination is also indicated (Source: Elaborated by the authors)

In these studies, it is possible to highlight those that have been oriented in climatic environments of desert areas, traditionally hot. The construction and ventilation techniques of these countries can be followed to propose measures that are useful throughout the world. In this sense, Zoure and Genovese [136,137] and Elshafei et al. [138] analysed the effectiveness of NV with other factors (building shape, glazing, shading and WWR) in buildings with an arid climate, such as Burkina Faso or Egypt. The results showed that the use of NV together with north-south orientations and WWR of 30% allowed to achieve reductions in yearly energy demand of up to 15%. The results also reflected the need to avoid large window dimensions to reduce solar radiation. A simpler analysis than the previous ones was carried out by Elhassan [141] in an arid climate. In his research, Elhassan determined that the unique use of NV allowed energy savings of up to 70%. Likewise, Elshafei et al. [145] observed that modifications in window design (window location and size, as well as the incorporation of windows) in residential buildings in Egypt allow decreases in indoor air temperature which implies a minor air-conditioning consumption. Khalid et al. [139] analysed the possibilities of efficient cooling of buildings located in Pakistan. Cross natural ventilation led to achieve reductions in energy consumption, although its combination with External Thermal Insulation Composite Systems (ETICS), shading blinds and low emissivity glass allowed to achieve an optimal reduction in energy consumption.

Likewise, the use of NV together with front green wall can also be an effective measure in climates such as Pakistan [146], with reductions in cooling energy consumption of up to 27%. Finally, El-Bichri et al. [147] evaluated how natural night ventilation and shading techniques reduced the energy demand up to 51% for cooling rammed earth houses in arid climates. Along this line, Albatayneh [148] performed a parametric analysis of building design optimization. Through the sensitivity analysis with the results obtained for Jordan, 2 clusters of measures were detected based on their importance. The most important variables were NV together with WWR, shadows, infiltrations, and type of glazing. These variables had more relevance with respect to others, such as orientation or the type of shading element. Akhozheya et al. [149] evaluated the application of high thermal mass measurements and night ventilation in an educational building in Minneapolis (United States). Up to 3ºC could be decreased of the maximum temperature values in the classroom and with delays of 4 hours with respect to the designs of average thermal mass.

The combination of bioclimatic designs with NV was also relevant. Bevilacqua et al. [150] analysed the possibility of applying NV and Trombe walls in buildings located in the Mediterranean climate. The results obtained decreases in the cooling energy demand, in such a way that the systems were activated during less than 10% of summer hours. The effect of inner courtyards can also have a significant impact on energy savings with NV. Gunasagaran et al. [142] determined that the combination of semi-enclosed courtyards with shades could reduce the use of air-conditioning systems in warm climates. However, the effectiveness of NV may have rebound effects on other types of energy consumption. Likewise, Sun et al. [143] determined 7 courtyard design guidelines to achieve an adequate decrease in cooling energy demand. These guidelines included everything from courtyard height to stepped designs. In any case, the analysis was limited to the climatic and architectural characteristics of Vietnam. Likewise, other case studies have been evaluated for special buildings. For example, in high-rise office buildings, the large number of windows can increase cooling energy demand from solar gains in summer. The use of NV can compensate part of this energy demand, although the support with other solutions is necessary [151]. In this sense, transom window is also an interesting measure to improve the energy performance of this type of building. Liu et al. [152] concluded that the mentioned measure presented cooling energy savings of up to 22.7% in high-rise buildings. Hence, NV in combination with passive cooling measures can achieve significant decreases in energy consumption in the warm months. Despite this, passive and NV measures cannot prevent thermal discomfort in many of the studies in the scientific literature [134,146]. To avoid this, it will be necessary to use MM to be able to compensate for the hours of high temperatures [153].

The potential of MM for energy savings is clear. Indeed, several studies have highlighted the following aspects. Cook et al. [154] analysed the impact of NV and MM on the air-conditioning hours in Indian residential buildings. The use of MM led to reductions of up to 55% in energy consumption. Ran et al. [155] managed to reduce the number of air-conditioning hours in Chinese residential buildings by 50% with the use of MM. Sánchez-García et al. [156] evaluated the use of MM in office buildings in southern Spain, obtaining a decrease in cooling energy demand of up to 74%. Bienvenido-Huertas et al. [125] evaluated the use of MM in social dwellings in coastal areas of southern Spain. The use of MM based on EN 16798-1:2019 made it possible to achieve reductions of up to 100% in cooling energy consumption, as well as the risk of energy poverty in families [160]. Thus, MM could guarantee 100% hours of thermal comfort in warm months with moderate energy consumption. The greater or lesser effectiveness in energy saving depends on the operational pattern considered for NV. Approaches based on adaptive thermal comfort models such as ASHRAE 55-2017 and EN 16798-1:2019 have shown great effectiveness in previous studies [125,156]. However, these approaches can have very wide ranges of temperatures and limitations in certain buildings, such as elderly care centres [157].

Likewise, the use of a more efficient MM has also been assessed with modern equipment and passive measures similar to those analysed in the NV studies. Shakya et al. [158] evaluated the potential of using MM with radiant ceiling cooling systems and dehumidifiers in hot climates such as Singapore. Up to 77% less of energy consumption was obtained in comparison with classic cooling systems. MM based on the combination of NV wind collectors and evaporative cooling is also an opportunity in hot climates. It is expected that the cooling system will reduce its consumption by 52% in school buildings in Kuwait [159]. The use of Earth-to-air heat exchanger can also be an alternative in summers of warm climates, with inlet air temperature reductions of up to 9.9 ºC [160]. MM can be improved by incorporating ceiling or manual fans [161] (because air speed increases convection around users [162]). These systems could achieve a greater reduction in cooling energy consumption in hot seasons, as reported below. Bamdad et al. [163] found that the use of MM with ceiling fans led to savings in Australian buildings of up to 23% today and 15% in the future. André et al. [164] analysed the use of MM with desk fans in office buildings in Brazil. The results showed that energy consumption could be reduced by up to 40%. Bienvenido-Huertas et al. [165] evaluated the application of the tolerances of the upper limit that admits the standards of adaptive thermal comfort with the increase of the speed of the air in interiors. Up to 600 hours less of air-conditioning could be achieved by fans that generate air speeds greater than 0.6 m/s. Furthermore, MM can be optimized for future scenarios by using modern installations. In this sense, Martins and Bourne-Webb [166] determined that the use of NV together with ground–source heat pump system can be an effective measure to reduce the cooling energy consumption of office buildings in Spain in the future.

It is also convenient to highlight the great potential that MM (or NV) has in the event of possible power outages or overheating, especially in heat waves [167]. Borghero et al. [168] stated that, although the use of active systems would allow more hours of thermal comfort to be achieved in future heat waves, the high peaks of energy consumption in these periods could imply to cuts in the electricity supply. The use of NV with the adaptive approaches of EN 16798-1:2019 could lead to reductions in energy consumption of up to 15% in future heat waves. In any case, overheating can also be avoided with NV or MM [169]. For this purpose, it uses the experience of countries with desert climates (such as western sub-Saharan Africa [170]) in which NV together with other passive measures decrease the risk of overheating. Thus, NV is essential to improve the performance of passive measures, since even without NV passive measures can have negative effects. In this sense, Bo et al. [140] determined that the insulation of rooms without NV could lead to an increase in superheated hours of up to 22.5% compared to rooms without insulation. Likewise, Baba et al. [171] determined that high energy efficiency buildings have risks of overheating if they do not have adequate ventilation. Thus, building energy improvement strategies should consider ventilation to avoid the risks of overheating. Despite the aforementioned aspects, there is the effect of incorrect applications of MM. Du et al. [172] evaluated 10 households in Chongqing (China) for one year. The results showed that up to 68% of the users left small areas of the windows open when they had the air conditioning system activated. This caused an increase in the cooling energy demand.

4.2.3. Future perspectives

As seen, there are a series of knowledge gaps about NV and MM that have been detected and that should be analysed in future works of the theme:

- Climate and effectiveness of NV and MM. Many studies report the climate as one of the main limitations. The results obtained could vary in other climates [136–138]. Likewise, the characteristics of the built environment may also vary. It is necessary to deepen the differences between energy saving solutions. For this, interregional studies should be carried out where the effectiveness of the holistic strategies considered (NV or MM with other measures) is known in various climates at the same time.
- Holistic analysis of NV and MM with other energy saving measures. In the state-of-the-art, many studies have addressed the use of NV (or MM) with other passive measures to reduce energy consumption and improve the thermal comfort of users. The existing results in the literature have shown that the combination of measures is useful to achieve significant reductions in energy consumption. However, the combinations used in the studies do not usually consider all possible measures. To eliminate this knowledge gap, the authors should perform holistic analyses where the different variables indicated in Figure 4 are combined.
- Influence of the use of NV or MM. Few studies have addressed the joint influence of various factors on the implementation of NV or MM. These factors may be different from the indoor temperature. In this sense, the work carried out by Belias and Licina [173] reflected how outdoor air pollution (mainly due to PM2.5 and PM10) limited the energy savings obtained with NV. Thus, the location of the building in the urban environment is essential to assess the effectiveness of ventilation, since areas with high contamination will have a low potential for cooling savings. In any case, the scope of the study was limited without considering other potential environmental factors that may affect energy-saving potential, such as outside noise [174,175]. Future work should address the limitations associated with the environment of cities in the use of NV.
- Energy saving and thermal comfort with night ventilation. Several studies report the advantages of night ventilation for energy savings and thermal comfort hours [176,177]. They achieve this both in office buildings and residential buildings. However, these studies do not consider the effect that nocturnal ventilation has on sleep quality [178]. The consideration that the thermal comfort conditions during sleep hours are the same as sedentary activities can generate errors in the assessment of the thermal quality of the indoor environment. Thus, users may not endure the use of NV at night. This would mean that the current results could overestimate the potential for energy savings in residential buildings. Future studies should address the existing limitation in energy savings with night ventilation in residential buildings.
- User participation and energy saving. The effectiveness of NV in achieving energy savings depends to a large extent on the participation of the occupants. Most of the studies tend to consider that NV is regulated by controlling the environmental temperature (indoor or outdoor) [125]. However, this may be unrealistic if users do not have the means to perform a check. Thus, future work should address the possible limitations associated with the effective operation of windows to achieve energy savings. Likewise, knowledge of other measures that the user can adopt to reduce the energy demand for cooling should be expanded, such as manual fans or the use of light clothing.
- Application in different case studies. Most NV studies have focused efforts on residential buildings [168,179], office buildings [136,137] or educational buildings [153]. Figure 11 summarizes the studies published by type of building case. As observed, there is a significant difference with other types of buildings. It is necessary to extend the analysis to other case studies where NV may have more limitations. An example may be the elderly care centres. The main limitation is the adaptability that older people have, especially in hot seasons. Faced with this circumstance, many studies opt for other type of measures, such as the energy improvement of the building and the moderate use of air conditioning [157].

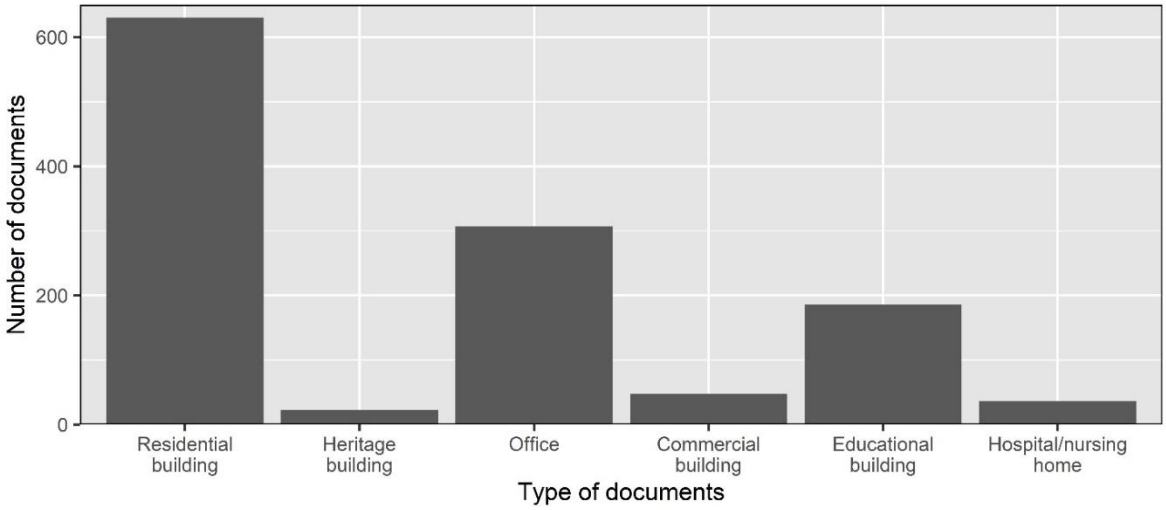

Figure 11. NV or MM studies by type of building (Source: Elaborated by the authors).

4.3. Indoor air quality and ventilation in warm climate zones

The quality of the air inside and around buildings and structures is refers as Indoor Air Quality (IAQ). The application of minimum ventilation rates and other measures to avoid poor IAQ is essential to minimize adverse health effects [180]. Several air pollutants, such as gases (e.g. carbon dioxide, radon, or volatile organic compounds), particles (e.g. PM10 or PM2.5) and bioaerosol (e.g. mold or virus) may deteriorate the IAQ and affect occupants' health and well-being. Figure 12 summarises the published studies by pollutant type. The Environmental Protection Agency noted that inadequate ventilation can result in indoor pollutants becoming more concentrated by not letting in enough outdoor air to reduce emissions from indoor sources and by not removing pollutants from the area. Therefore, maintaining safe concentrations of air pollutants for building occupants requires sufficient air exchange through ventilation. NV can be used to supply fresh outdoor air to indoor spaces and to reduce indoor generated pollutants.

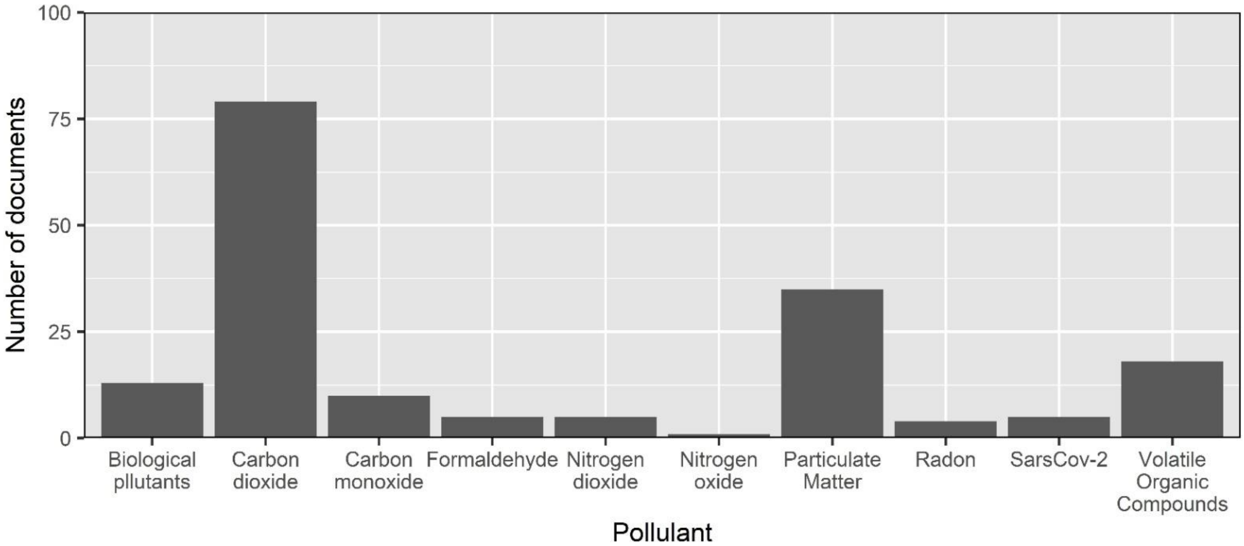

Figure 12. Number of documents by type of air pollutant (Source: Elaborated by the authors).

4.3.1. Carbon dioxide and carbon monoxide

Great attention was paid in scientific literature to carbon dioxide (CO_2) concentration because, although it is not classified as a pollutant by the World Health Organization, high concentrations may cause negative effects in occupants and international standards used this parameter as an indicator of IAQ (ASHRAE, RHEVA). Several studies monitored CO_2 concentration in NV buildings during warm season. Shrestha et al. [181] found that indoor CO_2 concentrations were significantly lower than the acceptable limit in NV school buildings in the temperate climate of Nepal during summer season and that most students perceived the IAQ as acceptable under such conditions. Habil and Taneja [182] highlighted that the CO_2 concentration values were lower in summer than winter due to the lower ventilation rates observed in densely populated classrooms during cold season. A higher correlation between CO_2 and ventilation was obtained in summer season, which explains the decay of CO_2 levels when exchange takes place through open windows and when classrooms are unoccupied, showing the ability to building ventilation. Campano-Laborda et al. [183] stressed that the use of CO_2 as a stand-alone indicator of environmental quality may be insufficient and lead to situations of increased discomfort for occupants. Student' environmental sensation votes, perception and indoor-related symptoms (i.e. tiredness) have a direct influence in windows' operation during lessons in Southern Europe. In fact, effective controlled ventilation systems are required to guarantee a real renewal of the indoor environment and a supply of clean air in NV classrooms. Similar results were reported in studies conducted in residential buildings [184], offices buildings [185] and kindergartens [186]. In contrast, the results reported by Yang et al. [187] from a field study conducted in Korean schools suggested that air exchange rate was too low in classrooms during summer season since the mean CO_2 concentration was above 1000 ppm.

In any case, NV supposes a challenge to stop outdoor pollutants from entering the building. Given window opening time increases as temperature rises in NV buildings, ventilation rate also increases in summer and indoor levels of air pollutants are strongly dependent on outdoor ambient levels [188,189]. Thus, numerous studies monitored other air pollutants generated both indoors and outdoors. A pollutant that can be generated both indoors and outdoors is carbon monoxide (CO). Indoors, the generation of CO is mainly due to the malfunctioning of gas installations such as a faulty gas furnace with a blocked exhaust pipe. In this context, a proper NV method together with optimal placement of the header in the household minimize the risk of CO poisoning [190]. However, this situation is extraordinary and previous studies pointed out that indoor CO concentration were lower than those of outdoors, suggesting that the mains CO source was outside the building (e.g. traffic) [187,191] . Chithra and Nagendra [191] found low concentrations of CO in school buildings, although there were higher concentration values during peak traffic hours. Abdel-Salam [188] monitored CO in residential buildings in Alexandria (Egypt) and found a season variation in CO levels which could be due to different ventilation practice in winter and summer.

4.3.2. Particulate matter and volatile organic compounds

The particulate matter (PM) is a complex mixture of solid and/or liquid particles suspended in air that can be found indoors and outdoors [192]. This parameter is also commonly monitored in NV buildings and, depending on the location of the buildings, the outdoor concentration may be higher or lower than the indoor concentration. Habil and Taneja [182] analysed the PM 10, PM 2.5 and PM 1.0 levels inside and outside NV school classrooms, and [188] the mean indoor concentrations lowered from 3 to 2 times in summer compared to winter. Chithra and Nagendra [193] carried out a measurement campaign in a NV school building located near an urban roadway in Chennai (India). The authors found a strong seasonal influence with minimum PM values during summer and maximum values during winter and monsoon seasons. The indoor PM 10 and PM 2.5 levels were often exceeding the National Ambient Air Quality Standards. Similar results were found by Mentese et al. [194] for PM2.5 in different type of buildings (house, office, kindergarten and primary school). In contrast, other studies found opposite trends in the ratio of PM levels in winter and summer. Oroji et al. [195] evaluated the PM concentration in NV classrooms at Shahid Beheshti University (Tehran) and found that the lowest concentration occurred in spring and winter, while the highest concentration in summer. The trend of variation of concentration inside the classroom was similar to the outside due to the NV in spring and summer seasons. Sahu et al. [196] assessed spatial and seasonal variations of IAQ among different indoor microenvironments of a technical university in India and concluded that PM level with open windows (NV) showed higher seasonal variation compared to AC mode. Furthermore, Belias and Licina [197] performed simulations to assess the use of NV in residential buildings in 26 European cities and pointed out that both PM2.5 and PM10 significantly restricts the use of NV in all types of locations evaluated. In order to minimize PM pollutants concentration, previous study analysed the effect of air purifiers on the reduction of indoor PM2.5 in NV buildings and found that air purifiers are effective for indoor PM2.5 control. Li et al. [198] concluded that air purifiers can reduce population health damage by 43.47% to 86.46%.

As for Volatile Organic Compound (VOC), Mentese et al. [194] found that VOC levels were higher in winter than summer. They observed that, among the VOCs, toluene was the most predominant, whereas elevated n-hexane levels were also observed in the kindergarten and the primary school, probably due to the frequent wet cleaning during school days. Stamp et al. [199] found that indoor generated VOC pollutants (d-limonene and alpha-pinene) in offices were reduced by up to half with increasing summer NV.

4.3.3. Biological pollutants

Regarding biological pollutants, its control is essential to ensure suitable IAQ and prevent the transmission of airborne viruses. Particularly, an adequate management of IAQ in healthcare units and hospitals has relevant impact on patient safety and occupational health. The microbiological loads of indoor air in healthcare units are of utmost importance since the airborne spread of pathogens is one of the main causes of nosocomial infections. Fonseca et al. [200] found an increase in microbiological in units care during summer caused by higher values of indoor air temperature and RH. Núñez and García [201] found that opening a window in a hospital for 2 h has little effect on the composition of bioaerosols in the room (any season). Mendes et al. [202] assessed elderly care centers and found low levels of bacteria concentration, but indoor levels were twofold higher than levels outdoors. NV can be a useful addition to mechanical ventilation systems in healthcare facilities for IAQ management. It is important to keep the indoor air relative humidity and CO_2 concentration at appropriate levels to lower the chance of infection through the air [200]. Moreover, due to the COVID-19 outbreak, recent research has analysed different NV strategies in relation to whether they provide sufficient ventilation rate to minimize airborne virus transmission in offices [203,204], educational buildings [205–207] and residential buildings [208,209].

4.3.4. Radon

Along this line, ventilation has also proven to be an effective measure for other pollutant gases such as radon. In the case of this gas pollutant, the combination of ventilation together with high temperatures favours low levels of indoor contamination in summer [210]. The results reported by Al-Azmi et al. [211] suggested that the lack of ventilation in the basements may result in higher concentrations of radon levels compared with other rooms on the ground and first floors of dwellings. NV reduces radon levels both by dilution and by decreasing basement depressurization and thus the radon entry rate.

4.3.5. Impact of ventilation strategies in IAQ

Within this context, the scientific literature shows that NV can be an effective measure to dilute indoor pollutants to levels that are not detrimental to the health and well-being of occupants. However, the opening behaviour of windows by occupants is a key factor affecting IAQ conditions, as it is de only way of air exchange between indoor and outdoor in NV buildings [212]. As a result, IAQ may be compromised on occasions when external conditions are not favourable (e.g. hot calm days) [213]. Therefore, the occupants' behaviour is a key factor in the analysis of NV and IAQ that has been analysed in previous studies. For example, the stimuli for the use of windows in offices in South Korea were analysed by Yun et al. [214]. They found large seasonal effects on window use patterns and drivers for the use of windows would differ with season. During summer, the use of a window is influenced by CO_2 concentration when the window is already open, but it is not related to thermal factors. In addition, the probability of a window being opened increased as the CO_2 concentration rise. This fact suggest that perceive IAQ is a non-thermal stimulus affecting the applicability of windows. In contrast, if the window is closed in summer, the use of a window is explained by thermal stimuli while the CO_2 concentration level is irrelevant. The transition probability of a window state from closed to open rises with an increase in indoor temperature and RH but falls with an increase in outdoor temperature and RH. Yun et al. [214] inferred that, when the outdoor temperature is high, the occupants would realize that opening a window would increase indoor temperature from their past thermal experiences of hot summer. In this scenario, occupants would prioritize thermal satisfaction over IAQ, and may therefore be exposed to poor IAQ. This aspect was also highlighted by Deng T. et al. [212], who identified that the tree main drivers for occupants' window-opening behaviour in the temperate zone in China were: indoor CO_2 concentration, indoor temperature and outdoor PM10 concentration. The effect of unhealthy IAQ conditions in indoor spaces with AC mode was noted by Graudenz et al. [215], who highlighted that a group of individuals working in an office building under AC systems has a higher prevalence of nasal, sinusitis symptoms, naso-ocular, persistent cough and building relation of the symptoms, than individuals under NV.

Similar results were found by Lai et al. [88,89] in MM residential buildings, where the researchers found that as climate became warmer, natural ventilation increased and mechanical ventilation decreased. However, the open-window duration starts to decrease when an outdoor temperature is reached. Above this 'cut-off' temperature, occupants tend to use AC systems and close windows. Lai et al. [89] stated that the 'cut off' temperature ranged from 24 to 29 °C in different regions of China, indicating that building occupants in southern regions were more prone to use AC than those in northern warm climates. Du et al. [216] added that although the probability of opening windows increases with increasing indoor/outdoor temperatures, the monitored daily durations for opening windows reduced when the indoor temperature exceeded 30 °C. In fact, they observed that the ratio of duration of the day for windows opened is higher than 0.8 when the outdoor temperatures ranged between 15 and 25 °C, while this proportion decreases to <0.6 when the outdoor temperature is outside this range. During periods in which windows are closed and AC is on, indoor air may cause uncomfortable feelings like stuffy air and poor air quality in residents 'subjective perception since enhanced airtightness in rooms would increase the CO_2 concentration. These results showed the importance of understanding the occupants' window-opening behaviour. It is essential to analyse ventilation performance and design the required outdoor air supply rate in rooms for comfort and health. Nevertheless, previous studies have already pointed out that there is a disconnection between observed window opening practices and typical design principles, assuming adjustment to a given ventilation system or changing weather conditions [217].

It is also worth noting that, although cross ventilation is a more effective ventilation strategy than unilateral ventilation, there are spaces where this ventilation strategy cannot be applied (e.g. studios and one-bedroom flats). In these cases, proper design of balconies and openings can significantly improve indoor ventilation performance, and thus improve both IAQ and thermal comfort [218]. Furthermore, the use of mixed ventilation (i.e. fans + NV) in classrooms proved to provide higher ventilation rate values compared to the exclusive use of NV [219]. Several studies also assessed the stack ventilation effectiveness in term of IAQ [220–223]. The wind catcher systems are considered an efficient way channel fresh air into the indoor spaces and can be used to reach sufficient ventilation rates in public buildings [224]. Elmualim [110] evaluated the effectiveness of a wind catcher and found that the CO_2 concentration was within standards and rarely exceeded 500 ppm. Jones and Kirby [225] analysed the IAQ in UK school classrooms ventilated by natural ventilation wind catchers and concluded that the ventilator is capable of significantly improving ventilation rates as well as reducing CO_2 levels during summer months, especially when used in combination with open windows. Kolokotroni et al. [213] investigated the performance in use of ventilation stacks in classrooms of a school during the summer period and found that the measured classroom air exchange rates did not differ between rooms with stack and without stacks during one measured period. This fact reflects that occupants would adjust flow paths to increase ventilation in the classroom (by opening the windows fully or opening internal doors).

4.3.6. Futures perspectives

In this section has been identified several research gaps that need to be addressed in future research, such as:

- IAQ field studies in different locations. Several studies analysed the effect of NV on IAQ in different locations in the urban environment [182,193,194]. However, further research involving a wider variety of locations (urban environments, industrial, dense road traffic, etc.) is still needed to analyse the effect of NV or MM on occupants. The growth of urban areas and the densification of cities may lead to an increase in air pollution and therefore affect IAQ inside buildings. Hence, studies that evaluate and provide control strategies to avoid poor IAQ in NV and MM buildings in these scenarios are needed.
- Analysis of the potential of passive ventilation systems in different regions. Numerous scientific studies have highlighted the use of solar chimneys, wind towers and other passive ventilation systems [17]. The implementation

of these systems could contribute to improving IAQ inside buildings in hot regions. Future studies should be developed to assess their implementation in current and future scenarios. Furthermore, it is necessary to assess their impact not only on-air quality or thermal conditions, but the effect on indoor environmental quality as a whole should be assessed including other factors such as noise and lighting.

- Seasonal variations on IAQ have been scarcely analysed in the scientific literature [188,196]. Future research is needed to analyse this issue in detail in different warm locations. In fact, many studies are limited in demographic, geographic or temporal scope [195]. Wider research is required to analyse adverse health effects derived from IAQ conditions on occupants of NV and MM buildings.
- Impact of IAQ on MM Buildings. Numerous studies have evaluated the impact of IAQ in NV buildings, but few have focused this evaluation on MM buildings. The use of AC mode can lead to decreased ventilation rate and increased concentration of indoor pollutants [216,217]. In fact, studies found a higher prevalence of nasal symptoms in office buildings under AC system [215]. It is necessary to deepen the analysis and evaluation of IAQ in these spaces under different modes of operation.
- Analysis of the combination of air filters with solar chimneys and windcatchers. Although both systems have shown their potential application in buildings, no studies have been found that combine them with air filters [17].
- More studies on the relationship between thermal comfort and IAQ are needed to better understand human behaviour and NV strategies [202]. Few studies analysed the effect of thermal comfort and IAQ on human behaviour as a whole, but a holistic analysis that takes into account different variables such as indoor temperature and pollutant concentration is essential [88,89,216,217]. This approach will allow a better understanding of window-opening behaviour or mode switching between NV and MM.

4.4. Simulation tools for ventilation

Several computational simulation methods have been identified for NV studies in areas or regions with hot climates: (i) simulation based on CFD, (ii) Building Energy Simulation (BES) and (iii) combination of CFD with BES tools. These approaches were mainly executed to evaluate NV performance, energy/thermal building performance or a combination of both. Figure 13 shows a summary of the simulation process used in the reviewed studies.

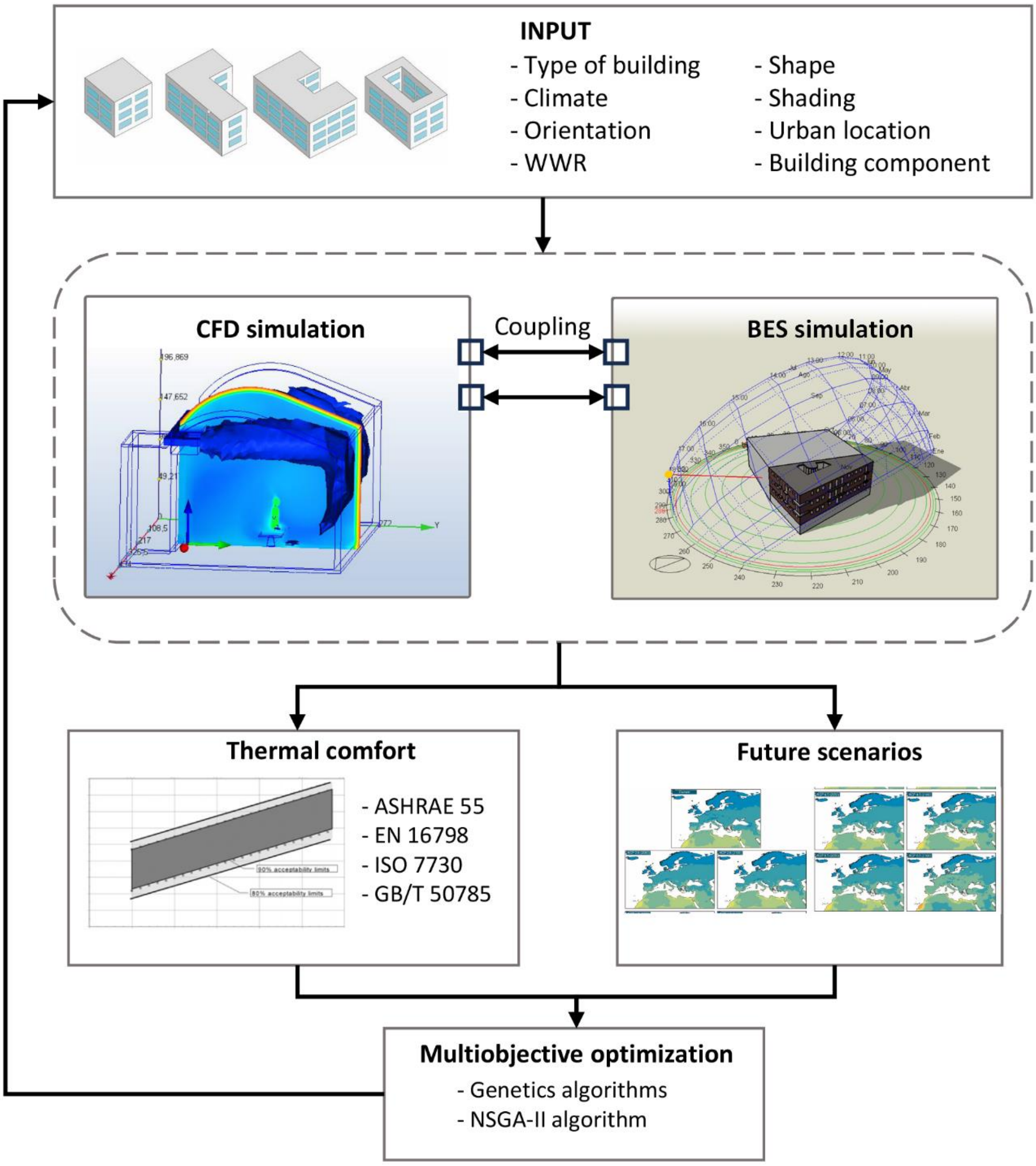

Figure 13. Simulation process used in NV and MM buildings (Source: Elaborated by the authors).

4.4.1. Simulations based on CFD

CFD is a method used to evaluate indoor environments by analysing airflow and physical environmental parameter distribution (air velocity, pressure, temperature and particle concentration) in indoor spaces. CFD uses numerical analysis and turbulence models to solve problems that involve fluid flows. The principles of the Navier-Stokes equations are employed in these models [226]. Previous research that has carried out CFD simulations includes the use of software such as ANSYS Fluent [227–229], TRNSYS [230–232], OPENFOAM [233], PHOENICS [234–236], Design Builder [237,238], CONTAM [190,239], STAR-CCM+ [240], Solidworks [241], CFX [242], AirPak (Y. Hou et al., 2022), ANSYS ICEM CFD [244,245], Comsol [246], Gambit [247,248], FloVent [249]. CFD has been extensively applied for airflow analysis. For example, numerous studies used CFD to assess the configuration of courtyard space to enhance environmental conditions, since it is essential to mitigate outdoor climate fluctuation in buildings in hot-humid climate [227,228,250–254]. The reported results showed that the use of courtyard along with NV strategies can provide effective building heat dissipation. Similar studies computed CFD to assess NV mechanisms in vernacular buildings [233,243,255] and residential buildings [229,249]. Along this line, CFD has been also implemented to simulate ventilation patterns with different ventilation systems, such as windtower/windcatcher [234,244,256,257], solar chimney system [241], naturally ventilated roofs [235,248,258] or night ventilation [259]. Previous studies also employed CFD to simulate the combination of different passive cooling system: solar chimney and radiant cooling cavity [260], windcatcher, earth-to-air heat exchanger and direct evaporative cooling system [261], natural ventilation and passive wall system (evaporative cooling) [245] or solar chimney and windcatcher [262], as well as migration of pollutants inside buildings [190].

4.4.2. Simulations based on BES

Regarding BES tools, they are mainly developed for the calculation of the thermal loads of HVAC systems and building energy performance. BES systems usually adopt multi-zone approach based on airflow network model [226], and each room is considered a separate zone [231,263–266]. The accuracy of the multi-zone modelling increases compared to unizone, although it increases model complexity and computation time. For this reason, previous research also includes other software such as EnergyPlus [267–269], Design-Builder [270], IESVE [271–273], IDA-ICE [274,275], BSim [276], DOE-2 [277], TRNSYS [231,278], ESP-r [279], Modelica [209], WinEtana [280], TAS software [281–284], CAPSOL [285], ECOTECT [286–288], H-AIR [289], COMETh [290], CitySim [291], DIAL+ [292,293], Dest [294,295], EQUEST [296]. For those studies that considered a single-zone model to represent the building system for being simpler and faster, such as type building [267,268,273,297–300], it was extrapolated that the heat transfer between different spaces was not adequate.

Concerning the simulation of NV buildings' performance with different characteristics and configurations, El-Bichri et al. [278] evaluated the impact of different construction materials on building's thermal behaviour and indoor thermal comfort in a hot and semi-arid climate. Ben-Alon and Rempel [297] investigated different earthen and conventional wall assemblies to provide adaptive thermal comfort in different climates (US), with and without passive heating and cooling systems. Other studies also investigated the use of phase change materials in conjunction with the use of NV strategies to improve the energy efficiency of buildings [263,267,270,301]. The literature review also noted the applicability of BES for the assessment and simulation of passive cooling strategies in different types of buildings, such as: natural ventilation, wall absorptance, shading effect of the semi-outdoor space as perimeter buffers (e.g. balconies), solar heat gain coefficient of windows, wall U-value, WWR, building orientation or passive direct evaporative cooling systems [268,269,298]. In addition, building retrofit measures and their impact on energy savings and thermal comfort was studied. BES allowed the life-cycle cost of different building solutions to be assessed, enabling the selection of optimal retrofitting strategies based on long-term costs and benefits [264,299,302,303]. Another approach investigated in previous studies is the analysis of human behaviour in NV buildings. For example, Schünemann et al. [274] demonstrated how the window ventilation behaviour affects the heat resilience in multi-residential buildings, or the study conducted by Scheuring and Weller [300] where they analysed the impact of different control strategies on the energy efficiency of an operable louver window. Other researches focused on the use of MM in residential buildings [266,304] or office buildings [265,305].

4.4.3. Coupled simulations between BES and CFD

The use of coupled simulations between BES and CFD can provide a more accurate prediction in NV buildings. Indeed, there are numerous combinations of both types of programmes in the scientific literature. For example, the BES software ESP-r and the CFD software Fluent can make possible to estimate the impact of various ventilation strategies and façade designs on the indoor thermal environment of NV residential buildings [279]. This process was used to assess various façade designs according to the orientation, WWR and shading device dimensions. The combination of both software provided a quicker and more accurate method of assessing the NV performance of the building and detailed thermal environmental information. Liping and Hien [279] developed a coupling program that fed the indoor CFD simulation with the boundary conditions previously calculated with ESP-r. The DesignBuilder's CFD and EnergyPlus programmes have also been used together by Prajongsan and Sharlples [306] to assess thermal comfort and energy saving in high-rise residential buildings using ventilation shafts in Bangkok. The parameters included in the built model were the location, building' components, opening sizes and operation schedule, internal heat-gain and weather data. The boundary conditions were first calculate using EnergyPlus and subsequently used for the CFD simulation. The same software combination has been applied for other purpose in NV buildings, such us to assess NV strategies during summer in high-rise buildings [307], to assess the impact of window parameters on indoor NV [308] or to assess the impact of different strategies such us orientation, WWR and coating colour on NV [309]. The coupled simulations between IESVE software with MicroFlo extension (CFD simulator) was carried out by Bay et al., [310], to assess thermal and energy performance in different ventilation scenarios (i.e. no NV; fully open windows and doors; night ventilation) in a Church. A triple combination was developed by Abbas and Gursel Dino [311], to analyse the effectiveness of NV in preventing infection risk for COVID-19 through the indoor air of a NV room. With this goal, the authors execute Open Foam to perform CFD simulation, EnergyPlus to carry out energy modelling and simulations, and NIST CONTAM to compute contamination analyses. The Analysis System ANSYS Fluent and EnergyPlus programs were used by Liu et al. [312] to evaluate the effectiveness of transom window in reducing cooling energy use in high-rise residential buildings. In this study, CFD simulation allow to obtain an accurate prediction of achievable ventilation rates and indoor air velocities, while energy simulation predicted the hour-by-hour indoor air temperatures and potential cooling energy saving. The indoor thermal comfort was evaluated based on adaptive comfort models and using the predicted parameters (air velocities and temperatures). The combination of Fluent and EnergyPlus was led by Albuquerque et al. [313], to analyse night-time NV of a large atrium in no-residential buildings. The coupling program between Integrated Environmental Solutions Virtual Environment (IESVE) for natural ventilation and daylight simulations and Design-Builder for thermal comfort and energy consumption simulations was used by Zoure and Genovese [238]. The results obtained facilitated the investigation of NV and daylighting improvements in office buildings in order to maximize thermal comfort and energy efficiency. Carrilho da Graça et al, [314] used PHOENICS and Design Builder to analyse NV in shopping mall and identify thermal problems.

4.4.4. Simulations tools combined with multi-objective optimization methods (MOM)

It should be also noted that multi-objective optimization methods combined with simulation tools, such as CFD or BES, has been investigated to find optimal configurations of NV. Indeed, these tools have also been applied in the process of optimising the design of buildings with passive cooling measures. For example, the Non-dominant Sorting Genetic Algorithm II (NSGA-II) and EnergyPlus were developed by Baba et al. ([315]) to identify those school building characteristics that minimise overheating hours, heating energy and artificial lighting energy through a multi-objective optimisation process (the selected optimisation variables were thermal properties of building envelope components, exterior and interior shading options, WWR, Window Opening Ratio (WOR), night cooling and cool roof). This combination was also used in previous studies to investigate the optimization of passive cooling in vernacular houses in order to minimize CO_2 emissions and cooling load (the optimization parameters were WWR, site orientation, infiltration level, local shading type, external wall construction type, roof type, ground floor construction, glazing type) [316] or to investigate how buildings characteristics (i.e. different glazing types, windows area, building orientation, insulation, etc.) influence NV in a single-family house [317]. Liu et al. [237] also proposed a multi-objective optimization approach based on NSGA-II algorithm to reduce lighting and AC energy consumption by using NV, cool roofs and solar shading in residential buildings in China. Energy simulations were conducted using DesignBuilder and the parameters tested according to energy consumption were: orientation, roof albedo, roof insulation thickness, exterior wall insulation thickness, WWR, window heat transfer coefficient, window solar heat gain coefficient, ratio of window height to balcony depth, thermal mass and infiltration air mass flow coefficient. Harkouss et al. [318] implemented a methodology for passive design optimization of low energy buildings and evaluated different ventilation strategies in different climates using the NSGA-II algorithm. The impact of various ventilation strategies on heating demand, thermal comfort and CO_2 concentration was analysed by Grygierek and Ferdyn-Grygierek [239] based on a multi-objective process using Contam and EnergyPlus software in conjunction with the Python programming language. The opening and closing of windows as a function of temperature and CO_2 concentration were considered for the optimization of the NV in Single-Family House. Song et al. [319] investigated window-opening behaviour and simulated the optimal window opening time in residential houses located in 13 typical climate cities in Xinjiang (China) using aPMV index and EnergyPlus. The genetic algorithm included in the Galapagos module of the Grasshopper platform was executed for the optimization process.

4.4.5. Simulation of future scenarios

The scientific literature has also focused on the analysis of future scenarios that pose a challenge to society as consequence of climate change. Previous studies assessed temperature projections and subsequently, simulated the energy consumption using BES. For example, Pérez -Andreu et al. [320] explored a range of energy improvements measures applied to typical Mediterranean residential buildings under various climate-change scenario. They used the used the Global Circulation Models (CNRM-CM5 and MPI-ESM-LR), under two emission scenarios (RCP4.5 and RCP8.5) to predict temperature projections and used TRNSYS tools to carry out energy simulations. Bienvenido-Huertas et al. [321] evaluated adaptive strategies in NV social dwellings. They analysed the current scenario (2015, 2016, and 2017) and a climate change scenario (2030, 2040, 2050, 2060, 2070, 2080, 2090, and 2100) in 10 Spanish cities and subsequently assessed the thermal comfort hours based on the ASHRAE 55-2017 and EN 16798-1:2019 standards. The EPW files for future scenario were generated with METEONORM and incorporated into EnergyPlus for the simulation process. Fiorito et al. [322] put their efforts on the adaptation of users in a historic building, assuming five weather scenarios: typical meteorological year, current extreme weather year (2018) and future meteorological conditions (period 2011–2040 (Average 2020), period2041–2070 (Average 2050), and period 2071–2100 (Average 2080)). Future meteorological conditions were derived using the statistical downscaling method in EnergyPlus. Thapa [323] investigated the risk of overheating in low-rise NV residential buildings in northeast India. Thapa used EnergyPlus software to simulate indoor thermal comfort in future climatic condition and the CCWorldWeatherGen tool to generate TMY files for the years 2050 and 2080 by morphing the present-TMY weather file. Pajek and Košir [324] took advantage from this same set of tools to simulate long-term energy performance in single-family residential buildings under representative European climates for the periods "2020″ (2011-2040), "2050″ (2041-2070) and "2080″ (2071-2100). Similar investigations were carried out in conjunction with the same tools in MM office buildings in different locations, such as United States and Canada [325,326] or residential MM buildings in Argentina [327].

Although NV can contribute significantly to improving indoor thermal comfort conditions, previous studies showed that its effectiveness may be limited in future scenarios as a result of climate change. In fact, several authors claim that the increase in temperature in warm climatic regions will lead to longer hours of thermal discomfort in the summer months [321]. The analysis of future scenarios shows that the use of NV can improve the indoor thermal conditions during mid-seasons (spring and autumn), while this ventilation strategy should be complemented with other passive techniques or with the use of AC system during the summer months [327]. Therefore, the development of new techniques and the use of renewable energies to replace conventional energy is crucial to ensure the sustainability of the building stock in warm climate zones, while guaranteeing the thermal comfort of the building occupants.

4.4.6. Future perspectives

Finally, future research should focus on the following issues:

- Few studies use CFD to study IAQ during hot periods. Most of the reviewed studies employ simulation software for the analysis of energy or thermal comfort in different types of buildings or in the use of different passive cooling strategies. More studies are needed to understand in detail the ventilation strategies and IAQ in this scenario in hot/warm regions [196].
- Future research could examine the applicability of using BIM to address ventilation and energy performance in NV and MM buildings. BIM tools provide detailed information on the construction geometry and materials that can be exported to feed the generation of computational domains in CFD and BES models. Studies focused on interoperability and file sharing are needed.
- Generative design and BES/CFD systems. Technological evolution in the construction sector has led to the emergence of new tools such as the use of multi-objective optimization or generative design. Generative design and BES or CFD are tools that can be used to improve the ventilation and energy efficiency of buildings. Generative design is a computer-aided design process that uses algorithms to generate optimal design solutions. Future

research should study the use of these tools combined with BES and CFD tools to obtain better results, as well as improve the time consumption in the simulation process.

5. Discussion and Conclusions

The main contribution of this review article was the development of a detailed framework on the use of NV and MM in hot climate zones. The review carried out a bibliometric analysis from 1928 to 2023, to identify the main clusters that define the research area. Subsequently, publications of the last 20 years (2000-2023) were analysed, distinguishing among: (i) thermal comfort; (ii) energy efficiency; (iii) IAQ; and (iv) simulation. The main results of the review are reported below:

- The use of NV and MM is effective in achieving reductions in energy consumption, especially those based on night ventilation. Although this strategy significantly decreases the interior temperature, it can compromise the quality of sleep-in residential buildings due to the noise. In addition, NV and MM may have limited use due to outside contamination. Finally, the combination of NV and MM with other technical measures (i.e. thermal properties of windows) should be addressed to know in detail the most appropriate energy improvement strategies.
- No homogenization of the studies in building types. Currently, most of the studies have been carried out in residential and office buildings. It is necessary to expand knowledge in other typologies (i.e. nursing homes). Likewise, it is also required to evaluate more climatic zones in order to ensure the reproducibility of the methods and the respective results. In this sense, many studies were developed in Australia, China and India. However, there are few studies conducted in southern Europe and South America.
- The physiological adaptation should be evaluated in-depth. Previous studies have shown that the adaptation may not be influenced by short-term thermal history. However, the impact of user's behaviour on the potential effectiveness of NV and MM should be assessed.
- Effect of climate change and urban heat islands. Few studies have been detected related to the effects of climate change and heat islands in NV and MM. Hence, further research should be developed in this topic. In addition, improvement strategies (such as passive cooling to avoid overheating of buildings) should be tested.
- Ventilation strategies and IAQ need to be further explored. Despite a wide variety of studies (especially after the Covid-19 lockdown), most of them have an IAQ enhancement approach with basic ventilation strategies. Nevertheless, some aspects require an in-depth analysis in warm climate zones, such as: the implementation of special systems (i.e. air filters with solar chimneys and wind catchers); the effectiveness of MM in improving IAQ; the seasonal variability of the IAQ and the relationship with thermal comfort.
- For simulation and analysis purposes, it is detected that few studies use CFD to evaluate IAQ in warm months. Most of these researches focus on energy or thermal domains. Likewise, the use of BIM and generative design for NV and MM analyses should be promoted to optimize the results of the simulations.

To conclude, the review has shown the need of a holistic analysis about the potential of NV and MM in hot areas. Partial analysis are common in the state of the art, but they do not consider other dimensions of the topic that may affect the effectiveness of the strategies. Likewise, the studies are limited to certain regions, so the replicability of the methods can lead to variable results. Therefore, it is necessary to broaden the perspective of the analysis of NV and MM in warm areas. The use of these techniques can play a prominent role in the face of climate change and compliance with the Sustainable Development Goals. The reported information may be used by architects, engineers, researchers, and authorities related to the built environment in hot climate zones.

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