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Advancing hybrid ventilation in hot climates: a review of current research and limitations

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Introduction: Hybrid ventilation systems present a promising solution for reducing cooling energy consumption in buildings, particularly in hot climates. However, while existing research highlights their potential, variability in reported cooling energy reductions underscores the need for standardized performance evaluation methods.

Methods: This review synthesizes findings from 84 research articles published between 2010 and the first quarter of 2024. The studies include simulation-based analyses, experimental investigations, and real-world case studies sourced from prominent academic databases.

Results: The review identifies substantial potential for cooling energy reductions through hybrid ventilation systems. However, it also reveals significant variability in energy savings across studies, suggesting that further work is needed to standardize reporting methods for accurate performance comparisons.

Discussion: To address these challenges, this paper proposes a framework integrating Industry 4.0 technologies. The framework emphasizes standardized research methodologies, context-specific design considerations, and robust knowledge dissemination strategies. Artificial Intelligence (AI) is positioned as a critical enabler of innovation, driving design optimization and smart control systems. The proposed framework aims to improve performance assessments, tailor system designs to specific building types and climates, and enable real-time control for enhanced energy efficiency and occupant comfort. This approach has the potential to support the wider adoption and optimized implementation of hybrid ventilation systems, contributing to a more sustainable and energy-efficient built environment, particularly in hot climates.

KEYWORDS

hybrid ventilation, hot climate, indoor thermal comfort, energy efficiency, industry 4.0 - advantages and challenges

1 Introduction

Globally, buildings account for approximately 40% of annual energy consumption, driven by population growth, an increase in housing, and rising standards of living. This energy is predominantly used for lighting, heating, cooling, and air conditioning (AC), with global energy demand rising by 2.3% in 2018, the highest increase in the past decade (International Energy Agency, 2019). The extensive energy use in buildings, coupled with its quality, places immense pressure on the environment, leading to significant carbon emissions from the construction sector. This contributes to increased pollution levels indoors and outdoors, threatening health, energy security, and exacerbating climate change. Countries in arid climates face heightened challenges, such as elevated cooling demands and a higher incidence of heat-related health risks like heat stress (Harlan et al., 2006). For instance, the United Arab Emirates (UAE) consumes significantly more energy than other nations in the region (IRENA, Renewable Energy Market Analysis, 2019). Similar to global trends, rapid urbanization, population growth, and energy-intensive industries drive the UAE's high *per capita* energy consumption. Its hot, arid climate necessitates frequent use of cooling systems, which dominate energy consumption in buildings (IRENA, Renewable Energy Market Analysis, 2019). AC units account for 60%–65% of a building's electricity use, contributing significantly to carbon emissions and the release of heat-trapping gases (Mardiana and Riffat, 2015; UN Environment and International Energy Agency, 2017; Elnabawi, 2021). Rising annual temperatures further increase dependence on mechanical cooling, thereby intensifying climate change.

To mitigate these impacts, there has been a shift toward passive energy conservation strategies, such as natural and hybrid ventilation systems, as alternatives to traditional AC (Pfafferott et al., 2004; Pollock et al., 2009; Bianco et al., 2009; Elnabawi and Saber, 2021; Abdulla Kutty et al., 2024). These systems aim to enhance indoor comfort while minimizing energy consumption and environmental impact. Natural ventilation is a widely used method for regulating indoor climates and achieving air quality standards without excessive energy use (Pfafferott et al., 2004; Annan et al., 2014). Research shows natural ventilation is effective for about 52% of the year in the Middle East (Annan et al., 2014). Another study in the UAE reported energy savings of 10%–40% when natural ventilation was utilized during moderate temperatures (Taleb, 2015). However, natural ventilation alone is insufficient for maintaining year-round thermal comfort, particularly in extreme climates where productivity can be compromised (Fiorentini et al., 2019; Ledo Gomis et al., 2021). Its efficiency also depends on local climatic conditions, making it unsuitable for certain regions (Gomis et al., 2020). Hybrid ventilation systems address these limitations by prioritizing natural ventilation during mild conditions and switching to mechanical systems during extreme heat (Griffiths and Eftekhari, 2008; Bianco et al., 2009; Ezzeldin and Rees, 2013; Elnabawi and Saber, 2021). This approach ensures indoor comfort while significantly reducing the energy consumption associated with mechanical cooling.

The hybrid ventilation approach optimizes energy efficiency and occupant comfort by adapting ventilation modes to seasonal and ambient conditions (Alves et al., 2015). While natural ventilation is employed for extended periods, the hybrid mode maintains acceptable comfort levels (Humphreys M. A. and Nicol J. F., 1998; Alves et al., 2015; Wang and Greenberg, 2015). Despite its potential, most research on hybrid systems has focused on temperate climates in North America and Europe, with limited application to the Middle East (Ezzeldin and Rees, 2013; Daaboul et al., 2018; Gomis et al., 2020; Elnabawi and Saber, 2022). For example, a review found only four studies on hybrid ventilation in the Middle East over the past decade (Gomis et al., 2020), while another analysis of 174 publications found just nine focused on hot, arid climates (Peng et al., 2018). Soebiyan (2021) reported that hybrid systems save 50% of energy in hot, arid climates, compared to 60%–70% in temperate regions and 28% in warm, humid areas. The limited research on hybrid ventilation in hot climates reflects challenges, such as regulating natural ventilation under high-temperature conditions. Effective cooling in such climates requires external air conditions to surpass indoor temperature and humidity levels, necessitating careful consideration of wind speed, direction, and air quality.

Ensuring thermal comfort in hybrid systems presents unique challenges. While factors such as indoor air quality, visual comfort, and acoustics are important, thermal comfort is often considered the most critical (Frontczak and Wargocki, 2011). Establishing universal comfort standards for hybrid buildings is difficult, as occupants of naturally ventilated buildings tend to tolerate broader temperature ranges than those in mechanically conditioned spaces. This tolerance varies significantly based on climate and location (Humphreys et al., 2015; Elnabawi and Hamza, 2020). Promoting natural ventilation over mechanical cooling could enhance occupants' thermal adaptability (Carrilho da Graça and Linden, 2016). Adaptive comfort models, such as ASHRAE 55 and CIBSE TM52, are more suitable for evaluating naturally ventilated buildings compared to traditional PMV models. Further research is needed to explore adaptive comfort, especially in hot, arid climates, to accurately assess the benefits of natural over mechanical cooling. By directly exposing occupants to external air, natural ventilation fosters thermal equilibrium, which is often unattainable with mechanical systems.

Smart ventilation systems, leveraging advanced technologies like artificial intelligence (AI) and the Internet of Things (IoT), offer a promising solution to enhance energy efficiency and occupant comfort (Liu et al., 2020; Goli et al., 2020; Elnabawi and Hamza, 2024; Gholami et al., 2022). These systems dynamically adjust ventilation rates using real-time data from sensors, weather forecasts, and occupant preferences, optimizing energy use and indoor air quality (Elnabawi and Hamza, 2024; Gholami et al., 2022). AI-powered algorithms predict future ventilation needs and proactively adjust systems, while IoT-enabled sensors facilitate data-driven decision-making and remote monitoring. Integrating smart ventilation with HVAC and lighting systems enables holistic optimization of the built environment, resulting in significant energy savings and improved occupant wellbeing. Despite these advancements, research on the long-term performance and scalability of smart ventilation systems across various climates and building types remains limited, underscoring the need for comprehensive field studies and standardized testing procedures. Existing literature often emphasizes theoretical models over empirical data, limiting the understanding of real-world performance and user interactions (Ghahramani et al., 2020; Petrie et al., 2018). Moreover, a disconnect exists between precise thermal comfort modeling in hybrid ventilation buildings and general studies on thermal comfort improvements through machine learning and IoT. This fragmented approach, as highlighted by Kariminia et al. (2016) and Jeong et al. (2022), hinders the development of holistic solutions. Further research is necessary to explore hybrid ventilation implementation in hot climates, establish consistent thermal comfort standards, and manage systems reliant on fluctuating external microclimates.

To address these challenges, this review advocates for a paradigm shift, integrating traditional approaches with Industry

4.0 technologies in order to develop a robust, region-specific hybrid/mixed ventilation design guide through "Knowledge Translation." While Industry 4.0 encompasses a broad spectrum of advancements, this paper focuses on its potential to foster human-machine interaction. This entails seamless integration and collaboration between humans and intelligent machines, leveraging the unique capabilities of AI, IoT, and VR/AR for enhanced efficiency. Table 1 summarises key Industry 4.0 applications that can optimise hybrid/mixed ventilation implementation, addressing system management, thermal comfort, and energy efficiency. By assimilating information from digital twins, GIS, ML, VR, MR, and IoT, Industry 4.0 can pave the way for hybrid/mixed ventilation buildings with high prediction accuracy, ensuring both comfort and sustainability in challenging climates.

1.1 Advancing previous reviews: unresolved issues

While numerous literature reviews have explored natural and hybrid ventilation systems, a critical gap remains in addressing the unique challenges posed by hot, arid climates, particularly in regions like the Middle East. Existing reviews offer valuable insights into various aspects of hybrid ventilation. For example, Nomura and Hiyama (2017) analyzed the design-phase performance of naturally ventilated office buildings, while Saber et al. (2021) investigated control systems for similar climates. Sakiyama et al. (2020) reviewed studies focusing on thermal comfort and energy savings, and Solgi et al. (2018) explored strategies for night ventilation. Other researchers, such as Kim and de Dear, (2021) examined thermal comfort in mixed-mode buildings, while Kojok et al. (2016) investigated mechanical systems for hybrid cooling. Roetzel et al. (2010) reviewed occupant behaviour related to natural ventilation, and Fabi et al. (2012) investigated behaviours in window-opening. Salcido et al. (2016) reviewed hybrid ventilation through simulation and monitoring case studies, and Li and Heiselberg (2003) analysed methods for both natural and hybrid ventilation. Peng et al. (2018) focused on automated building envelope control in hybrid systems, while Ledo Gomis et al. (2021) reviewed control methods, highlighting the importance of system coordination and the potential of predictive control.

A thorough search of the relevant literature did not yield a comprehensive review that focused on a particular region to provide a specific framework which can really work. These reviews frequently concentrate on climates prevalent in North America and Europe, thereby limiting their applicability to the unique conditions of the Middle East region. (Ezzeldin and Rees, 2013; Daaboul et al., 2018; Gomis et al., 2020; Elnabawi and Saber, 2022). This geographical bias is evident in the limited number of studies dedicated to hot, arid climates (Gomis et al., 2020; Peng et al., 2018). This gap is significant because, as Soebiyan (2021) notes, hybrid ventilation systems can achieve energy savings of up to 50% in hot, arid climates. Moreover, the hot arid climate, such as the Middle East, contributes to significantly higher carbon emissions compared to more temperate regions (Chen et al., 2023). There is a pressing need for context-specific research in the Middle East to evaluate hybrid ventilation systems in its unique climate, develop tailored design and control strategies for hot, arid environments and explore advanced technologies, such as artificial intelligence to optimise system performance and improve thermal comfort predictions (Elnabawi and Hamza, 2024). These AI-based methods, particularly machine learning models such as Artificial Neural Networks and Random Forest have demonstrated high prediction accuracy and energy-efficient control performance in building environments (Ji and Moon, 2022). For example, ANNs and Random Forest can be utilised to enhance the accuracy of hybrid ventilation systems in achieving indoor thermal comfort. Further innovative applications include using Internet of Things (IoT) devices for real-time thermal comfort estimation and leveraging digital twins coupled with Geographic Information Systems to assess the feasibility of hybrid ventilation in specific locations.

This paper critically assesses the current research approaches related to the thermal management of hybrid/mixed ventilation buildings in hot climates, similar to the Middle East including hot arid and hot humid, to address critical gaps in understanding and optimising their effectiveness. The analyses includes geographical and temporal distribution of existing studies, the types of buildings examined, and climate context, assumptions made regarding building characteristics, internal gains, and set-points, the comfort standards used for evaluating indoor thermal conditions, coordination between natural and mechanical systems, and control strategies employed. Furthermore, the paper examines the minimum and maximum energy savings reported in both simulated and experimental studies, offering insights into the actual effectiveness of hybrid ventilation systems in hot climate zones. Building upon these findings, the paper explores how integrating Industry 4.0 principles can guide the development and implementation of more effective hybrid ventilation systems in hot, arid regions. The paper's originality lies in its identification of a key methodological challenge in hybrid ventilation research, its suggestion for a novel Industry 4.0-driven framework to address this challenge, and its emphasis on AI-powered optimization and context-specific design for maximizing energy efficiency and occupant comfort in hot climates. Ultimately serving as a valuable application guide for the hybrid ventilation mode and assisting with strategic decisions on cooling strategies for such buildings.

2 Methodology

This study presents a comprehensive review of the effectiveness of hybrid ventilation systems in achieving thermal comfort located within hot, arid climates zones similar to the Middle East. Guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines (PRISMA), the review adopted a rigorous four-step methodology for a study selection, mirroring the approach outlined by Umar (2020), Liberati et al. (2009) and Carlucci et al. (2020): identification, screening, eligibility assessment, and final inclusion (as illustrated in Figure 1). This systematic process ensured the inclusion of only the most relevant research. The selection criteria prioritised studies that: investigated mixed-mode ventilation systems (specifically combining natural and mechanical ventilation) in buildings; focused on arid climate regions; evaluated the impact of hybrid ventilation on occupant

TABLE 1 Key Industry 4.0 applications that can optimize hybrid/mixed ventilation implementation.

Tools	Depiction
Deep learning techniques	Deep learning, a powerful subset of machine learning, seeks to emulate human learning processes by training computational systems on vast datasets. This data-driven approach has illustrated promise in various fields, including thermal comfort modelling. Common deep learning architectures, such as Convolutional Neural Networks, Long Short-Term Memory Networks, and Recurrent Neural Networks, can be employed independently or integrated with existing models to enhance accuracy. For instance, researchers have successfully used deep learning to incorporate psychological and behavioural factors into thermal comfort predictions, leading to more robust and personalised models
Brain–Computer Interface	Neurotechnology, particularly brain-computer interfaces, offers a unique approach to understanding thermal comfort by directly measuring brain activity associated with thermal perception and preference (Banaei et al. (2017). This real-time monitoring of cognitive processes, such as attention, emotions, and preferences towards the environment, provides valuable insights into the subjective experience of thermal comfort (Banaei et al. (2017). Integrating EEG measurements with other sensory modalities, such as physiological or behavioural monitoring, enables a comprehensive understanding of embodied cognition through mobile brain/body imaging. This approach allows researchers to evaluate specific cognitive metrics relevant to their study objectives (Gramann et al., 2014). For example, Scanlon et al. (2019) investigated attention-related metrics during various physical activities, while Banaei et al. (2017) explored emotional responses to different virtual architectural spaces This neuro-adaptive technology holds immense potential for thermal comfort research, particularly in simulating and evaluating human responses to diverse environmental stimuli, beyond traditional audio-visual or motor-related stimuli
Multi-sensory and multi-mediated reality	Artificial realities, encompassing a spectrum of computer-generated simulations, offer innovative ways to experience and interact with environments beyond the physical world (Mann et al., 2018). These technologies, ranging from virtual reality to multi-sensory mixed reality, differ in their level of immersion and integration with the real world (Chiamulera et al., 2017) VR provides a completely immersive experience, replacing the real world with a virtual one, as exemplified by Google Street View with Earth VR (Carmigniani and Furht, 2011). Conversely, augmented reality overlays virtual elements onto the real world, enhancing rather than replacing the user's perception. Mixed reality further blurs the lines by seamlessly blending real and virtual elements, allowing for dynamic interactions along a virtuality continuum. Multi-sensory MR extends this concept by incorporating multiple sensory inputs, creating highly realistic simulations that can even mimic weather and climatic variations (Carmigniani and Furht, 2011) The effectiveness of these simulated realities stems from the human brain's inability to fully distinguish between real and imagined experiences, as confirmed by neuroscientific studies (Pascual-Leone et al., 1995). This characteristic allows researchers to leverage these technologies to create controlled environments for studying human responses to various stimuli, including thermal comfort. By monitoring neural activity, researchers can gain insights into users' emotional and even unconscious responses to simulated environments, providing valuable data for designing more comfortable and engaging spaces (Hamann and Ivtzan, 2017)
Geo-spatial digital twins	Digital twins, particularly in the context of buildings and cities, represent a powerful convergence of Building Information Modeling, Internet of Things technologies, and geospatial data. These dynamic, data-rich representations of physical assets enable real-time monitoring, analysis, and optimisation of complex systems (Elnabawi and Hamza, 2024). By integrating data from various sources, including sensors, BIM models, and Geographic Information Systems, digital twins create a bridge between the physical and virtual worlds. This interconnectedness allows for real-time feedback loops, enabling a more efficient operation, in addition to informed decision-making, and enhanced quality of life for occupants (Opoku et al., 2021)
Internet of Things	The Internet of Things, a term coined by Kevin Ashton in 1999, has ushered in a new era of interconnectedness, exceeding the scope of traditional computing devices. This vast network of internet-enabled objects, ranging from household appliances to industrial sensors, forms the backbone of smart technologies, enabling seamless communication and data exchange between the physical and virtual realms Notwithstanding, IoT plays a crucial role in realising the concept of smart buildings and cities. By continuously gathering data through embedded sensors, IoT devices provide the raw material for big advanced data analytics. This data, processed and analysed via cloud computing, enables real-time monitoring, control, and optimisation of building systems, ultimately enhancing efficiency, comfort, and sustainability Essentially, the IoT acts as the sensory system of digital twins, providing the continuous data flow necessary for informed decision-making and predictive analytics. This interconnected web of devices and data paves the way for a more intelligent and responsive built environment

thermal comfort and the effectiveness of different control strategies; which have been published in English with the full text readily accessible. This meticulous approach, encompassing a review of over 80 research articles published between 2010 and the first quarter of 2024, ensured the inclusion of high-quality, pertinent data, ultimately strengthening the reliability and validity of the review's findings.

Underpinning this research is a post-positivist research philosophy, evident in the emphasis on objectivity and systematic analysis. The use of established guidelines lsuch as PRISMA, coupled with the rigorous four-step methodology, reflects a commitment to minimising bias and maximising the replicability of the research process. This approach aligns with the post-positivist aim of uncovering objective knowledge by rigorously examining existing research and synthesising findings in a structured, transparent manner.

Three primary techniques are employed to estimate energy and thermal performance: mathematical modelling, experimental

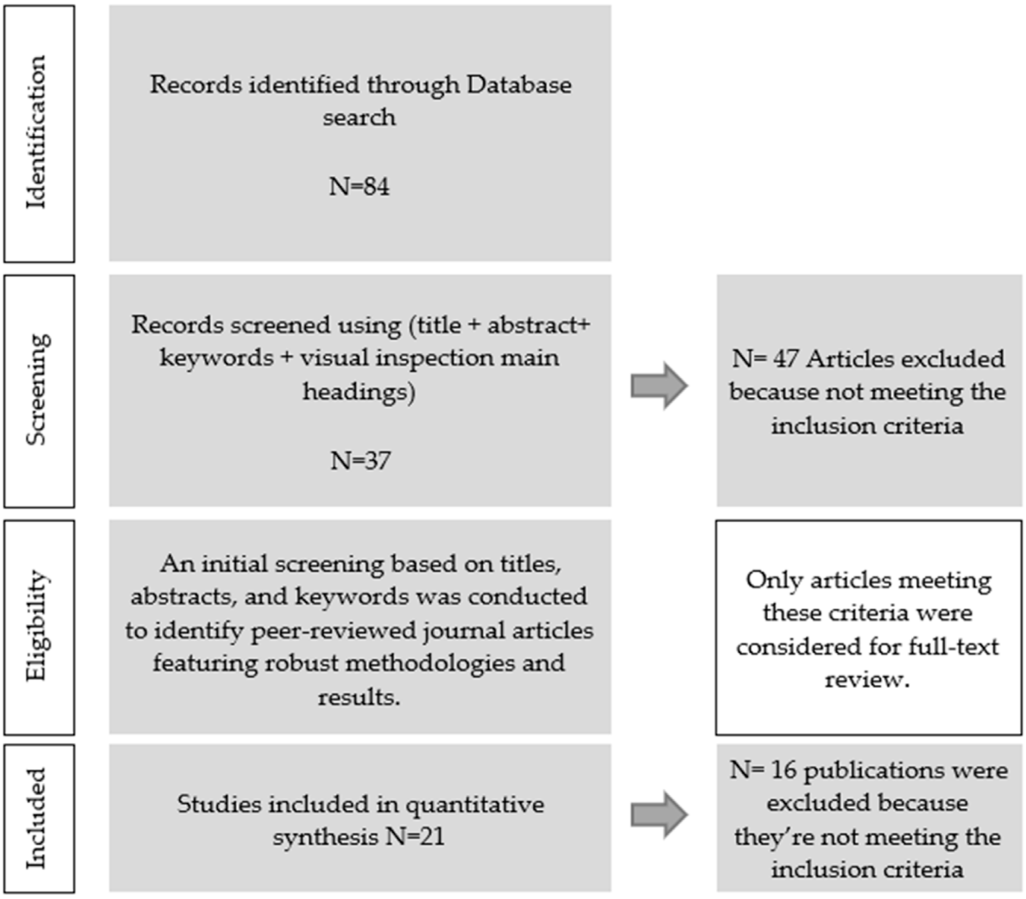

FIGURE 1
F flowchart depicting the literature selection process.

analysis, and computer simulation (Zhai, 2003; García-Fuente et al., 2022). While mathematical modelling can be complex and highly sensitive to minor variations, experimental approaches have been proven to be impractical for evaluating multiple design scenarios due to their time-consuming and costly nature. Computer simulation, however, mitigates these limitations (Bano and Sehgal, 2018), offering greater feasibility, accuracy, and informativeness (Zhai, 2003). Recognising the advancements in computer simulation methodologies after 2010 (Elnabawi and Raveendran, 2024), this review focuses on studies published from 2010 onwards. To ensure a comprehensive and unbiased literature review, a rigorous and multi-step screening process, illustrated in Figure 1, was implemented to ensure the selection of high-quality, relevant studies for this literature review. Initially, 84 articles were identified through a comprehensive search of five prominent academic databases using a defined set of keywords and search parameters, as detailed in Table 2. This initial pool of articles underwent a preliminary screening based on titles and abstracts to identify studies potentially meeting the inclusion criteria (Umar, 2021). Following this initial screening, the full texts of the remaining articles were retrieved and assessed against the full set of inclusion criteria. Only peer-reviewed journal articles published in English that met all inclusion criteria–focusing on the performance of hybrid ventilation systems in buildings within hot climates, utilizing empirical measurements or validated simulations–were included in the final analysis. This rigorous process resulted in the selection of 21 articles deemed relevant and suitable for inclusion.

3 Early insights from the literature

This section analyses trends in research on mixed-mode building performance in hot climates, similar to the Middle East from 2010 to the first quarter of 2024. It summarises key aspects of these studies, including publication year, building typology, comfort standards employed, and assessment methods.

3.1 Hybrid ventilation research: a growing trend

Figure 2 provides data on publications concerning hybrid system controls for mixed-mode buildings in hot climates from 2010 to the first quarter of 2024, with only one study included from 2008. The study employs a rigorous, systematic approach using

TABLE 2 Literature review search strategy: Hybrid ventilation in hot climates.

Identification	Screening and eligibility		
	Inclusion criteria 1	Inclusion criteria 2	Inclusion criteria 3
Databases: ScienceDirect, IEEE Xplore, Web of Science, Scopus	Studies investigating the performance of hybrid ventilation systems in buildings	Studies explicitly focusing on hot arid, hot humid, Middle Eastern, or Mediterranean climates	Studies employing empirical measurements in real-world buildings or utilizing validated computer simulations
Time Frame: 2010 – first quarter of 2024. To capture recent advancements in the field	Exclusion Criteria		
Keywords and logic: ('hybrid ventilation' OR 'mixed-mode ventilation' OR 'mixed mode ventilation') AND ('hot arid climate' OR 'hot humid climate' OR 'Middle East' OR 'Mediterranean climate') AND ('energy consumption' OR 'thermal comfort' OR 'indoor air quality' OR 'IAQ' OR 'life cycle assessment' OR 'LCA')	1. Studies solely focused on naturally ventilated or mechanically ventilated buildings (excluding hybrid systems) 2. Studies published in languages other than English 3. Conference papers, dissertations, and reports without peer review		

EnergyPlus simulations to evaluate various mixed-mode cooling strategies across different arid climate scenarios. This allows for a comprehensive understanding of the effectiveness of each strategy. The bar chart analysis reveals a clear trend of increasing research interest in recent years, particularly after 2020. While the field experienced limited activity between 2008 and 2019, with only sporadic publications, there has been a noticeable surge in research output since 2020. The period from 2008 to 2019 was marked by sporadic research activity, with a total of only eight publications over 12 years. This trend aligns with the findings of other worldwide reviews, such as those by Peng et al. (2018) and Ledo Gomis et al. (2021). This suggests a relatively niche area of study during this period. However, the field witnessed a significant shift in 2021, with the number of publications increasing to four. This upward trend persisted, with three publications in 2023 and two in 2024. This recent surge in research output indicates a growing recognition of the importance of hybrid system controls for mixed-mode buildings in hot climates. This could be attributed to several factors, including increasing global temperatures, a greater emphasis on sustainable building practices, and technological advancements in building systems. The data suggests that this is a dynamic and evolving field of study, with increasing research interest and potential for future innovation.

3.2 Research trends in hybrid ventilation: Simulations dominate

The provided data, presented as a pie chart in Figure 3, reveals a strong preference for simulation-based research in the field of hybrid ventilation, with 17 studies utilising this approach. This popularity likely stems from the ability of simulations to model complex systems and test a wide range of parameters with relative ease and cost-effectiveness. However, the research landscape also includes a smaller but significant number of experimental (4 studies) and case studies (3 studies). These methodologies provide real-world validation and context-specific insights that complement the theoretical explorations of simulations. The presence of all three approaches–simulation, experimental, and case study–indicates a multifaceted effort to understand and optimise hybrid ventilation systems. This balanced approach is crucial for translating research findings into practical applications and driving wider adoption of this energy-saving technology.

3.3 Building types in hybrid ventilation research: commercial sector leads

The bar chart, in Figure 4, illustrates the distribution of hybrid ventilation research across different building types. Commercial buildings represent the most popular research focus, with 10 studies dedicated to this building type. This emphasis probably stems from the significant energy consumption of commercial buildings (Deng et al., 2018; Zheng et al., 2023) and the potential for substantial energy savings through hybrid ventilation. Residential buildings follow as the second most studied building type with six studies, highlighting the growing interest in applying hybrid ventilation to improve energy efficiency and comfort in homes. Interestingly, a smaller number of studies focus on “Several types,” indicating a trend towards comparative research that explores the performance of hybrid ventilation across different building typologies. Educational buildings, with only one study, represent the least explored category. his distribution aligns with the findings of Peng et al. (2018) and Ledo Gomis et al. (2021), who reported similar trends in their reviews. This gap suggests a potential area for future research, given the unique occupancy patterns and ventilation needs of educational spaces.

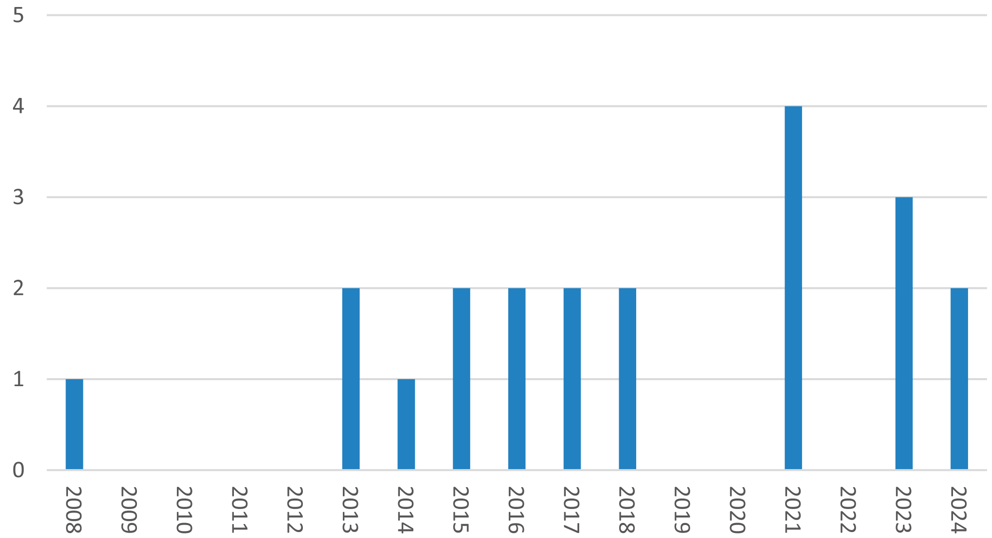

FIGURE 2
Annual trend of relevant publications.

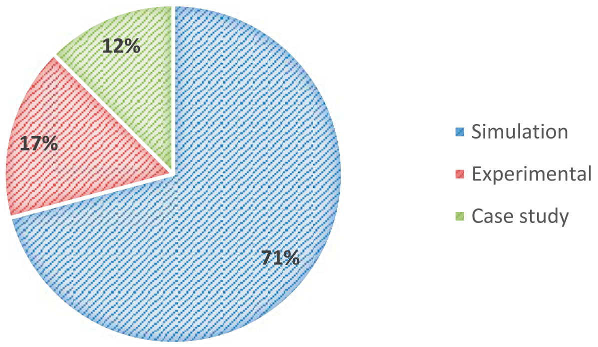

FIGURE 3
Fraction of Simulation, Experimental, and Case studies.

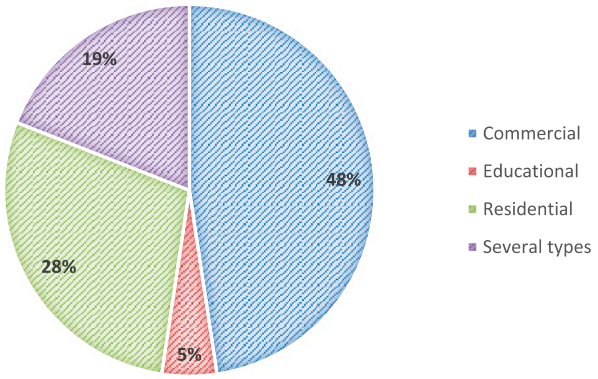

FIGURE 4
Typologies of buildings studied.

4 Hybrid ventilation in hot climates: performance variations and optimisation strategies

Despite the prevalence of hot-dry climates in regions like the Middle East, research on hybrid ventilation systems for reducing cooling energy consumption remains limited. Most existing studies focus on climates in North America and Europe, leaving a significant research gap in addressing the specific needs of hot climates. Table 3 summarizes various studies investigating the potential of hybrid ventilation systems to enhance cooling energy efficiency in buildings located in hot regions. These studies explored diverse operational strategies for hybrid ventilation, reflecting a range of approaches to system optimization.

Some studies, such as those by Ezzeldin and Rees (2013), Rizk et al. (2015), and Rashad et al. (2024), focused on switching to natural ventilation when outdoor conditions were favorable. Others, like Brittle et al. (2016) and Daaboul et al. (2018), adopted fixed schedules aligned with typical office hours, emphasizing operational simplicity. Taleb (2015), meanwhile, explored various HVAC operation scenarios during the winter months. Additionally, researchers examined different hybrid ventilation modes. While Ezzeldin and Rees (2013) and Brittle et al. (2016) concentrated on the Change-Over mode, Abou Hweij et al. (2017) investigated the Concurrent mode. Other studies, including those by Chenari et al. (2016), Ledo Gomis et al. (2021), and Muhy Al-Din et al. (2023), explored multiple operational modes. However, a comprehensive analysis comparing the performance of these modes under various hot-dry climate conditions is still absent, highlighting a critical gap in the literature.

Although frameworks like Leadership in Energy and Environmental Design Accredited Professional (LEED AP) provide valuable guidelines for hybrid ventilation in hot and humid climates (Merabet et al., 2021), they often lack detailed performance metrics and empirical data tailored to the unique

TABLE 3 Major research developments (2008–2024) that describe the implementation and effectiveness of HV systems.

References	Building type	Operation schedules	Mode used	Simulation, exp., case study	Comfort standard used	Experimental study tool used	Min. And max. cooling reduction	Heating and cooling set-points
Ezzeldin et al. (2008)	Commercial	Switching to NV when outdoor conditions are favourable	Discusses several operation modes	Simulation	ASHRAE Standard 55	Monitoring	59%–83.4%	24°C
Ezzeldin and Rees (2013)	Commercial	Use of NV when outdoor conditions are favourable	The study integrates these modes dynamically, depending on real-time data and seasonal variations	Simulation	ASHRAE Standard 55	Monitoring	Approx. half of the plant energy consumption	21°C–24°C
Ezzeldin and Rees (2013)	Commercial	Typical office hours	Change-Over Mode	Simulation	ASHRAE Standard 55	Monitoring	10%–40%	26°C
Honnekeri et al. (2014)	Several types	Summer (April-August)	Zoned	Experimental	ASHRAE Standard 55	Monitoring and surveying	Not mentioned	23°C–29°C
Rizk et al. (2015)	Residential	Switching to NV when outdoor conditions are favourable	Change-Over Mode	Simulation	ASHRAE Standard 55	Monitoring	Up to 40%	Not mentioned
Taleb H (2015)	Residential	Summer (April 1st – October 31st): HVAC system operates continuously. Winter (November 1st – March 31st): Various scenarios were tested	Change-Over Mode	Simulation	ASHRAE Standard 55	Monitoring	Up to 30%	23°C
Chenari et al. (2016)	Several types	Switching to NV when outdoor conditions are favourable	Discusses several operation modes	Simulation studies, experimental validations, and case studies to evaluate	ASHRAE Standard 55, EN 15251, and ISO 7730	Monitoring	Up to 50%	Not mentioned
Brittle et al. (2016)	Commercial	Typical office hours	Change-Over Mode	Simulation	ASHRAE Standard 55	Monitoring	21.31%–39.77%	24°C–28°C
Cui et al. (2017)	Commercial	Typical office hours	Change over	Case study	Not mentioned	Monitoring	Not mentioned	25°C
Abou Hweij et al. (2017)	Commercial	14:00 and 17:00	Concurrent	Simulations and experiments	ASHRAE Standard 55	Monitoring	Up to 10%	Not mentioned
Daaboul et al. (2018)	Commercial	Typical office hours	Change-Over	Simulation	ASHRAE Standard 55	Monitoring	10%–75%	24.5°C

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TABLE 3 (*Continued*) Major research developments (2008–2024) that describe the implementation and effectiveness of HV systems.

References	Building type	Operation schedules	Mode used	Simulation, exp., case study	Comfort standard used	Experimental study tool used	Min. And max. cooling reduction	Heating and cooling set-points
Barbadilla-Martín et al. (2018)	Commercial	Monday to Friday 09:00 to 21:00	Change-over	Experimental	ASHRAE Standard 55	Monitoring and surveying	Up to 27.5%	22.3°C–24°C
Ledo Gomis et al. (2021)	Several types	Switching to NV when outdoor conditions are favourable	Discusses several operation modes	Simulations	ASHRAE Standard 55	Monitoring and survey	Up to 55%	21°C–26°C
Elnabawi and Saber (2021)	Educational	8:00 to 17:00	Change-Over Mode	Simulation	BS EN 15251	Monitoring	17.1%–33.5%	25°C
Ibrahim et al. (2021)	Residential	Typical daily occupancy patterns	Change-over	Simulation	ASHRAE Standard 55	Monitoring and surveying	Up to 27%	21°C–23°C
Elshafei et al. (2021)	Residential	Typical daily occupancy patterns	Change-over	Simulation	ASHRAE Standard 55	Monitoring	Not mentioned	Not mentioned
Muhy Al-Din et al. (2023)	Residential	Typical daily occupancy patterns	Several operation modes	Simulations and case studies	ASHRAE Standard 55	Monitoring and Surveying	Not mentioned	20°C–26°C
Bosu et al. (2023)	Several types	Daytime: HV Nighttime: NV	Several operation modes	Simulation	ASHRAE Standard 55	Monitoring and Surveying	16%–30.6%	Not mentioned
Abdollahzadeh et al. (2023)	Residential	10:00 to 18:00	Change-over	Experimental	ASHRAE Standard 55	Monitoring and surveying	Not mentioned	Not mentioned
Rashad et al. (2024)	Commercial	Switching to NV when outdoor conditions are favourable	Change-over and concurrent	Simulation	ASHRAE Standard 55	Monitoring	Up to 50%	24°C–28°C
Al and Ahmed (2024)	Commercial	Typical office hours	Change-over	Simulation	Givoni	Monitoring	13%–29%	24°C

challenges of hot-dry environments. This underscores the urgent need for more targeted research to develop comprehensive, context-specific design guidance, enabling the optimization of hybrid ventilation systems for energy efficiency and occupant comfort in these climates.

4.1 Operational schedules and mode analysis

The analysis of operational schedules in reviewed hybrid ventilation studies reveals a predominant trend of utilizing natural ventilation (NV) opportunistically, guided by favorable outdoor conditions. Notably, 43% of the studies (9 out of 21) explicitly mention switching to NV under suitable conditions, reflecting a data-driven, responsive approach to system operation. This strategy aligns with the core principle of hybrid ventilation: maximizing natural ventilation while relying on mechanical systems only when necessary. Studies such as those by Ezzeldin and Rees (2013), Brittle et al. (2016), Cui et al. (2017), Daaboul et al. (2018), and Al and Ahmed (2024), presented in Table 3, highlight the integration of real-time monitoring and control to optimize the use of NV.

In contrast, a smaller subset of studies adopted fixed schedules, often aligned with conventional office hours, prioritizing user familiarity and ease of implementation. While these fixed schedules simplify operation, they may miss opportunities to capitalize on varying outdoor conditions. The findings underscore the importance of flexible and context-aware control strategies. Opportunistic NV utilization offers significant potential for energy efficiency but requires robust monitoring and control systems. Future research should prioritize the development of intelligent algorithms and predictive models capable of anticipating favorable outdoor conditions and dynamically adjusting ventilation modes to enhance both energy performance and occupant comfort. Moreover, exploring the trade-offs between fixed schedules and more adaptive, responsive approaches is essential to identify optimal strategies tailored to diverse building types, climates, and occupant needs.

Regarding operational modes in hybrid ventilation, the reviewed studies highlight a clear preference for the Change-Over mode, with 71% of the studies (15 out of 21) employing it as a dominant control strategy. This mode involves a distinct switch between natural and mechanical ventilation based on predefined conditions or schedules (Brager et al., 2007), offering simplicity in implementation and control. Studies such as those by Ezzeldin and Rees (2013), Rizk et al. (2015), Taleb (2015), and Brittle et al. (2016) underscore the widespread adoption of this approach, reflecting its practicality in minimizing system complexity and control challenges.

However, a smaller group of studies, including those by Ezzeldin et al. (2008), Ezzeldin and Rees (2013), Chenari et al. (2016), Ledo Gomis et al. (2021), and Muhy Al-Din et al. (2023), explore multiple operational modes, indicating a growing interest in more dynamic and responsive strategies. These studies advocate for adapting ventilation modes to real-time conditions and occupant needs, offering the potential for enhanced energy efficiency and indoor environmental quality.

The findings suggest that while the Change-Over mode remains popular for its simplicity, more sophisticated control modes, such as concurrent or dynamic transitions between NV and mechanical ventilation, could unlock greater energy savings and comfort optimization. Future research should focus on advancing and validating control algorithms that effectively manage these complexities. By addressing the trade-offs between simplicity and performance, intelligent and adaptive hybrid ventilation systems could be developed to meet the evolving demands of sustainable building design.

4.2 Heating and cooling setpoints

The analysis of heating and cooling setpoints in hybrid ventilation studies highlights a significant focus on cooling, reflecting the priority of addressing heat stress in buildings using these strategies. Among the reviewed studies, 14 out of 21 (67%) specified cooling setpoints, while only 10 (48%) detailed heating setpoints. This imbalance underscores the widespread adoption of hybrid ventilation in warmer climates, where cooling demands often dominate.

Cooling setpoints varied considerably across the studies, reflecting diverse approaches to thermal comfort. For example, Ezzeldin et al. (2008) used a cooling setpoint of 24°C, while Ezzeldin and Rees (2013) adopted a higher setpoint of 26°C. Similarly, Honnekeri et al. (2014) and Rashad et al. (2024) reported broader ranges, with cooling setpoints spanning 23°C–29°C and 24°C–28°C, respectively. This variability highlights the challenge of establishing universal thermal comfort standards, as preferences are likely shaped by factors such as local climate, building design, and occupant demographics.

These findings underscore the importance of a context-specific approach to determining setpoints in hybrid ventilated buildings. Designers and operators must move beyond generic standards to account for local climate conditions, building characteristics, and occupant needs and preferences. The emphasis on cooling setpoints further suggests the potential benefits of integrating adaptive comfort principles and control strategies. By enabling occupants to exercise some control over their thermal environment—such as through operable windows or personal cooling devices—it may be possible to widen the acceptable temperature range, improve occupant satisfaction, and reduce dependence on energy-intensive mechanical cooling systems.

4.3 Thermal comfort standards in hybrid ventilation research

Evaluating thermal comfort in hybrid-mode buildings presents significant challenges, particularly in differentiating comfort standards between mechanically and naturally ventilated environments. Among the reviewed studies, 85% (18 out of 21) relied on ASHRAE Standard 55 to assess thermal comfort (American Society of Heating, 2017), while only a few referenced ISO 7730, BS EN 15251, or the Givoni adaptive approach (Givoni, 1992), each cited in just one study (5%). This reliance on ASHRAE Standard 55 underscores its widespread acceptance in hybrid ventilation research. However, the limited use of alternative standards raises concerns about the comprehensiveness of relying solely on this standard, especially when addressing diverse climates and populations. Expanding the range of standards used in research could offer a more nuanced perspective on thermal comfort.

Brager and de Dear (2000) observed that occupants in naturally ventilated buildings tend to tolerate a broader range of temperatures, though this tolerance varies significantly with location (Humphreys et al., 2015). Similarly, studies conducted in various climate zones, such as those by Elnabawi and Hamza (2020), support the notion that local conditions influence thermal adaptability. These findings question the universal applicability of methods used for international comfort standards, particularly in hybrid ventilation scenarios. For instance, Carrilho da Graça and Linden (2016) argue that reliance on natural cooling and ventilation can enhance occupants' thermal tolerance. Adaptive comfort models, such as those outlined in ASHRAE Standard 55 and CIBSE TM52 (CIBSE, 2013), are often more suitable for naturally ventilated structures compared to Predicted Mean Vote (PMV)-based models.

Interestingly, some studies suggest that hybrid-mode buildings can improve comfort levels by leveraging precise indoor environmental controls and well-designed systems (Saber et al., 2021). This highlights an important avenue for future research: investigating adaptive comfort specifically in hot, arid climates. Understanding how occupants adapt to such conditions is crucial for accurately evaluating the advantages of natural ventilation over active cooling. Natural ventilation, by providing direct exposure to outdoor air, offers a contextually appropriate thermal balance, potentially leading to improved occupant comfort. This emphasizes the need to explore adaptive strategies tailored to specific climatic and cultural contexts, fostering a more effective integration of hybrid ventilation systems.

4.4 Minimum and maximum cooling reduction

Figure 5 summarizes the minimum and maximum cooling reduction percentages reported in various simulation studies of hybrid ventilation systems in hot climates. These studies typically present a range of potential cooling reductions for analyzed case study buildings, reflecting the influence of diverse weather conditions and building contexts. The data illustrates the significant cooling potential of hybrid ventilation while also exposing inconsistencies in its application and effectiveness. Maximum cooling reductions reach up to 65%, demonstrating the technology's capability to mitigate cooling loads in hot climates. Several studies, such as those by Ezzeldin et al. (2008), Ezzeldin and Rees (2013), and Ledo Gomis et al. (2021), report reductions exceeding 30%, reinforcing this potential. However, many studies, including those by Taleb (2015), Rizk et al. (2015), and Rashad et al. (2024), report a minimum cooling reduction of 0%. This indicates that hybrid ventilation's effectiveness is highly dependent on specific design and operational factors, including climate variations, building typology, occupancy patterns, and control strategies. On average, the studies report cooling reductions of approximately 8.6% (minimum) and 30.5% (maximum), suggesting that while the average building might achieve significant reductions, poorly implemented systems often yield negligible benefits.

Several factors contribute to the variability in the cooling reductions observed. First, hybrid ventilation's effectiveness is closely tied to outdoor climate conditions. Studies that fail to specify climate data or analyze diverse climatic zones naturally exhibit inconsistent results. Second, the design and control strategies of the hybrid system play a crucial role in maximizing its potential. Research by Peng et al. (2022), Flourentzou et al. (2017), and Cho et al. (2021) underscores the importance of selecting appropriate system designs, ensuring integration with building architecture, and employing advanced control algorithms. Third, building characteristics, such as typology (Ledo Gomis et al., 2021), orientation (Fernandes et al., 2020), window-to-wall ratios (Liu et al., 2022), and thermal mass (Wang and Chen, 2013; Neves et al., 2019), significantly influence the effectiveness of natural ventilation, a key component of hybrid systems. Finally, occupant behavior also plays a critical role. The extent to which occupants interact with operable windows and their thermal comfort preferences can significantly impact system performance, as noted by Peng et al. (2018) and Day et al. (2020).

To enhance the effectiveness of hybrid ventilation in hot climates and address inconsistencies in performance, several actions are recommended. Climate-specific design guidelines should be developed, taking into account local weather patterns and building characteristics to optimize hybrid ventilation strategies. Advanced control algorithms that adapt to real-time occupancy, indoor and outdoor conditions, and building thermal dynamics are essential for maximizing energy efficiency. Additionally, further studies should examine the impact of occupant behavior and develop educational strategies to encourage users to maximize the benefits of hybrid ventilation. Addressing these aspects will enable the technology to deliver more consistent and significant cooling benefits, unlocking its full potential for sustainable cooling in hot climates.

5 Discussion

This section highlights key trends observed in hybrid ventilation research, including the challenges and opportunities by drawing upon data from the reviewed studies.

- The recent surge in research on hybrid system controls for mixed-mode buildings in hot climates reflects a growing recognition of their importance in a world facing increasing global temperatures and a greater emphasis on sustainable building practices. This upward trend in publications highlights the dynamism of this evolving field, driven by technological advancements in building systems and the potential for future innovation. The increasing interest in research further underscores the perception of hybrid ventilation as an effective measure for reducing energy consumption in buildings.
- The survey revealed a significant reliance on simulation studies within hybrid ventilation research for hot climates. This trend likely stems from the challenges of conducting experimental studies, where replicating identical conditions in real-world buildings is nearly impossible. While simulations offer a valuable tool for navigating this complexity and exploring the potential of hybrid ventilation, the wide variability in assumptions made across studies hinders direct comparison and real-world validation. Therefore, a balanced research approach that incorporates experimental and case studies

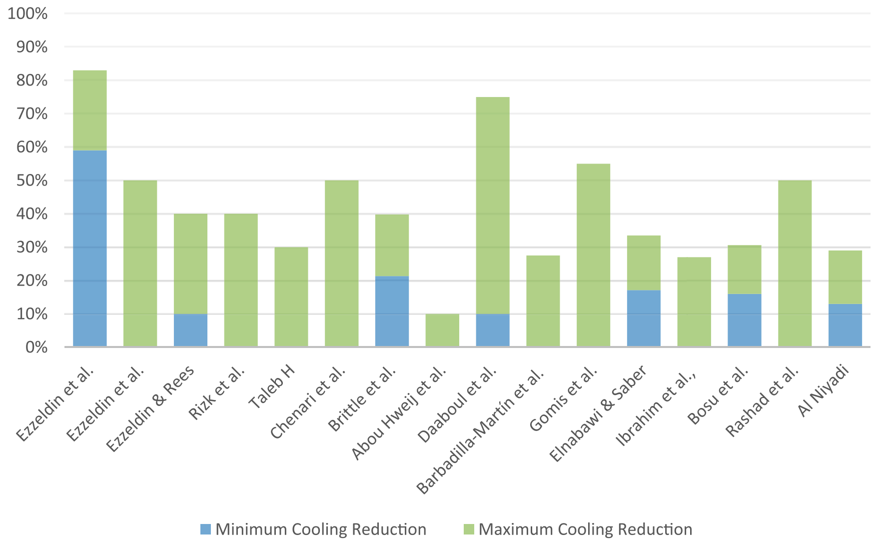


FIGURE 5
Reported minimum and maximum cooling reductions in the studies.

alongside simulations is crucial to bridge the gap between theoretical projections and practical application in these demanding climatic conditions.

- The focus on current research into hybrid ventilation within commercial buildings, likely due to their high energy consumption and potential for significant savings. While residential buildings also garner attention, a notable gap exists in research exploring hybrid ventilation within educational settings, presenting a valuable avenue for future investigation.
- The review highlights a clear preference for an opportunistic operation of hybrid ventilation systems, leveraging natural ventilation when outdoor conditions are favourable. This data-driven approach, often reliant on real-time monitoring and control, aligns with maximising energy efficiency. However, a smaller subset of studies employed fixed schedules, potentially prioritising user familiarity and ease of implementation. This suggests a need for further research into flexible, context-aware control strategies that balance energy optimisation with occupant needs and system complexity.
- Furthermore, the dominant use of the Change-Over mode for managing transitions between natural and mechanical ventilation underscores a focus on practicality and control simplicity. Nevertheless, the emergence of studies exploring multiple operational modes suggests growing interest in more dynamic and responsive strategies that could further enhance energy efficiency and indoor environmental quality.
- The analysis of heating and cooling setpoints in hybrid ventilation studies reveals a clear emphasis on cooling, reflecting the dominant application of these systems in warmer climates. However, the considerable variation in reported cooling setpoints highlights the challenge of establishing universal comfort standards. This emphasises the need to move beyond generic standards by prioritising a context-specific design approach. Factors such as local climate, building characteristics, and occupant preferences should be carefully considered when determining appropriate setpoints. Furthermore, integrating adaptive comfort principles and control strategies, which empower occupants to adjust their thermal environment, presents a promising avenue for enhancing comfort and reducing reliance on mechanical cooling.
- Our review highlights a significant reliance on ASHRAE Standard 55 for assessing thermal comfort in hybrid ventilation studies. Notably, the majority of experimental studies utilised monitoring surveys to evaluate thermal comfort. While this underscores the standard's widespread acceptance, the limited use of alternative standards, particularly those considering adaptive comfort, raises concerns about the comprehensiveness of current evaluation methods. This over-reliance on a single standard may overlook the nuanced comfort perceptions across diverse populations and climates, especially the potential for greater thermal tolerance in naturally ventilated buildings. Future research should explore a wider range of comfort standards, particularly adaptive models, to gain a more nuanced understanding of occupant comfort in hybrid buildings, especially in hot, arid climates where adaptation plays a crucial role.
- The review reveals a significant, albeit inconsistent, potential for cooling reduction through hybrid ventilation in hot climates. While some studies report remarkable reductions of up to 65%, the frequent occurrence of negligible or even nonexistent cooling benefits in others highlights a critical point: design, operation, and building context significantly influence real-world effectiveness. Therefore, a key takeaway from this review is the need to move beyond simply acknowledging the potential of hybrid ventilation and further investigate into the understanding of the factors driving both successful and inadequate performance. This deeper understanding is crucial for developing robust and reliable hybrid ventilation systems capable of consistently, delivering on their energy-saving promise in hot climates.

This analysis of hybrid ventilation design reveals a crucial need to move beyond standardised approaches and embrace context-specific solutions. Over-reliance on a single comfort standard, coupled with the wide variation in cooling setpoints, highlights the importance of considering local climates, building characteristics, and occupant preferences. Furthermore, our review has identified a significant gap in current research: most reviewed articles lacked a climate-specific focus, with a majority of studies originating from North America and temperate climates. This geographic bias limits the applicability of findings to diverse climate regions, particularly hot, arid climates where adaptive comfort considerations are paramount. Addressing these nuanced factors and achieving truly adaptive, occupant-centric hybrid ventilation systems necessitates a paradigm shift in design and operation. The integration of Industry 4.0 technologies offers a promising pathway to address these challenges and unlock the full potential of hybrid ventilation for a more sustainable, comfortable built environment.

6 AI-powered hybrid ventilation: unlocking energy efficiency in buildings

This comprehensive review of recent research on hybrid ventilation systems for cooling energy reduction reveals several key trends as well as highlights critical areas for advancement. And while hybrid ventilation shows promise for energy-efficient buildings, realizing its full potential necessitates leveraging AI and Industry 4.0 technologies to address key research gaps (Alavi et al., 2021). This transition from traditional ventilation methods to AI-powered systems can be facilitated through the application of dynamic programming. This approach allows for subtle, yet impactful, changes in the system's performance. By leveraging dynamic programming, the ventilation system can continuously adapt and optimize its operation based on real-time data, weather forecasts, and occupant preferences. This dynamic adaptation enables the system to respond to changing conditions, leading to enhanced energy efficiency and improved occupant comfort. The integration of dynamic programming with AI-driven control algorithms can create a more responsive and intelligent ventilation system, capable of anticipating future ventilation needs and proactively adjusting the system's operation. This subtle, yet significant, shift towards a more dynamic and adaptive approach can pave the way for a more sustainable and comfortable built environment. This approach is exemplified in Figure 6, which proposes a framework based on the seamless integration of four application levels: hybrid system controls, heating and cooling setpoints, thermal comfort standards, and minimum and maximum cooling reduction. By identifying the shortcomings of conventional methods at each level and proposing Industry 4.0-based solutions, the framework not only transcends the limitations of existing research but also offers practical guidelines. Additionally, it suggests specific tools and instruments for each phase of implementation.

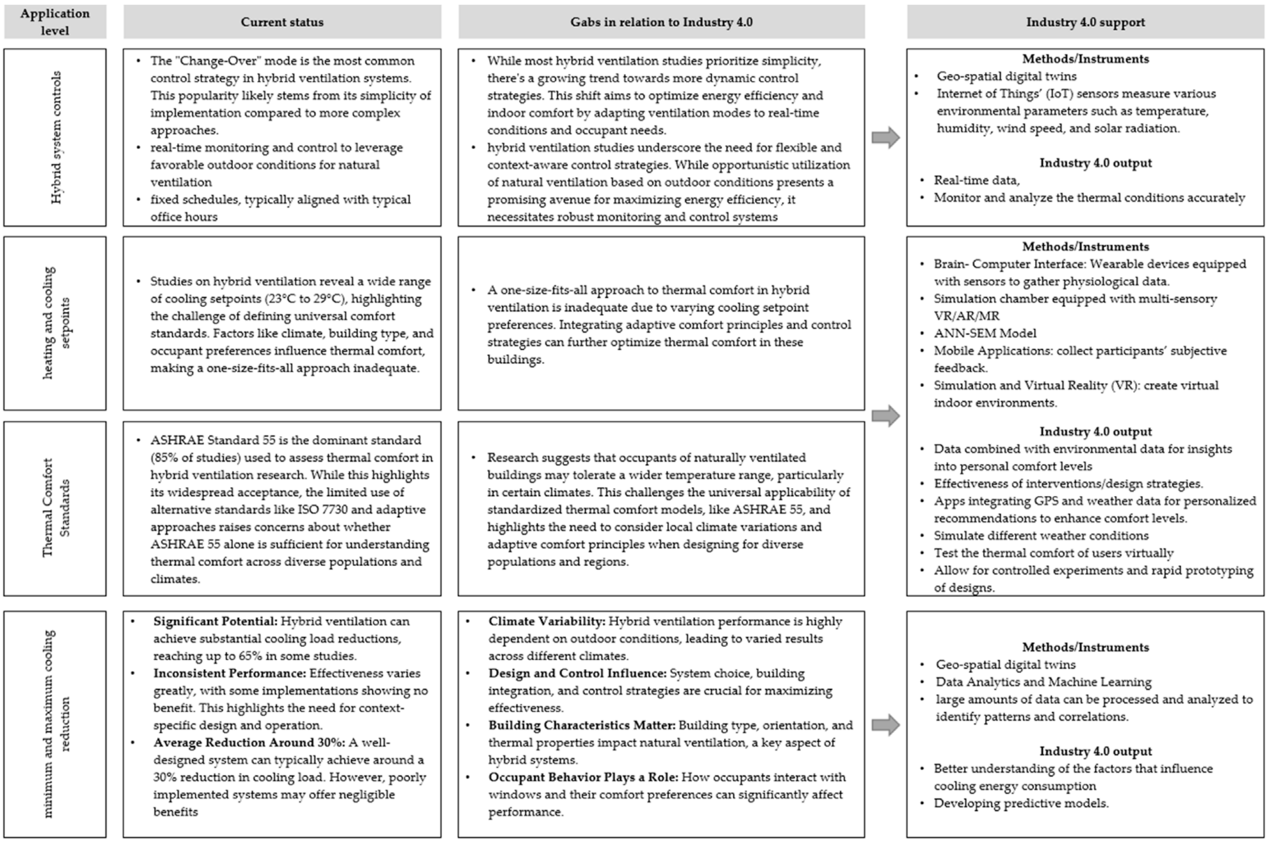
For instance, Traditional approaches to hybrid ventilation system controls often rely on simpler methods like the "Change-Over" mode, where the system switches between natural and mechanical ventilation based on predefined conditions or schedules. This approach is favoured for its ease of implementation. While these systems may incorporate real-time monitoring to leverage favourable outdoor conditions for natural ventilation, they often operate on fixed schedules, typically aligned with standard office hours. However, these traditional approaches have limitations. They lack the dynamism to adapt to rapidly changing conditions or individual occupant preferences, limiting their ability to optimise energy efficiency and indoor comfort. Furthermore, the opportunistic use of natural ventilation, while promising, necessitates robust and reliable monitoring and control systems.

This is where Industry 4.0 technologies offer significant advantages. By integrating geo-spatial digital twins and the Internet of Things, there is the potential to create smarter hybrid ventilation systems. IoT sensors distributed throughout the building can measure various environmental parameters, including temperature, humidity, wind speed, and solar radiation. This real-time data, collected and analysed through the IoT network, allows for a more accurate and dynamic understanding of the thermal conditions pertaining to the buildings.

Furthermore, while hybrid ventilation systems show great potential for energy efficiency, the traditional methods for defining and achieving thermal comfort within these systems have significant limitations. Studies reveal a wide range of cooling setpoints (23°C–29°C) used in hybrid ventilation, highlighting the inadequacy of a generic approach. Thermal comfort is not solely determined by temperature but is influenced by a complex interplay of factors, including climate, building type, and individual preferences. Over-reliance on standardised thermal comfort models like ASHRAE Standard 55, while prevalent in research, further underscores this limitation. Research suggests that occupants of naturally ventilated buildings, particularly in certain climates, may tolerate a wider temperature range than these standards typically account for. This is where Industry 4.0 technologies offer a path towards more nuanced and personalised comfort solutions. By integrating wearable sensors, mobile applications, and advanced simulation environments, we can gather both physiological data and subjective feedback from occupants. This data, combined with real-time environmental information, can be used to develop personalised comfort models and adaptive control strategies. Imagine a system that understands your individual preferences and dynamically adjusts the indoor environment to ensure your comfort, regardless of external conditions. Furthermore, simulation and virtual reality technologies allow us to test and optimise different design strategies for thermal comfort before physical implementation, accelerating the development of more effective and responsive hybrid ventilation systems.

The true power of Industry 4.0 lies in its ability to process this data and translate it into actionable insights. Intelligent algorithms and predictive models can be developed to anticipate favourable outdoor conditions and preemptively adjust ventilation modes. This proactive approach ensures optimal energy performance without compromising occupant comfort. In essence, Industry 4.0 paves the way for hybrid ventilation systems that are not only more efficient but also more responsive to the dynamic needs of both the building and its occupants.

While Industry 4.0 technologies hold immense potential for creating more comfortable and personalised hybrid ventilation systems, their effectiveness hinges on a robust foundation of research and data. This is where AI can play a crucial role, by addressing a key challenge: the lack of standardised research and reporting in the field.



Application level	Current status	Gabs in relation to Industry 4.0	Industry 4.0 support
Hybrid system controls	• The "Change-Over" mode is the most common control strategy in hybrid ventilation systems. This popularity likely stems from its simplicity of implementation compared to more complex approaches. • real-time monitoring and control to leverage favorable outdoor conditions for natural ventilation • fixed schedules, typically aligned with typical office hours	• While most hybrid ventilation studies prioritize simplicity, there's a growing trend towards more dynamic control strategies. This shift aims to optimize energy efficiency and indoor comfort by adapting ventilation modes to real-time conditions and occupant needs. • hybrid ventilation studies underscore the need for flexible and context-aware control strategies. While opportunistic utilization of natural ventilation based on outdoor conditions presents a promising avenue for maximizing energy efficiency, it necessitates robust monitoring and control systems	**Methods/Instruments** • Geo-spatial digital twins • Internet of Things' (IoT) sensors measure various environmental parameters such as temperature, humidity, wind speed, and solar radiation. **Industry 4.0 output** • Real-time data, • Monitor and analyze the thermal conditions accurately
heating and cooling setpoints	• Studies on hybrid ventilation reveal a wide range of cooling setpoints (23°C to 29°C), highlighting the challenge of defining universal comfort standards. Factors like climate, building type, and occupant preferences influence thermal comfort, making a one-size-fits-all approach inadequate.	• A one-size-fits-all approach to thermal comfort in hybrid ventilation is inadequate due to varying cooling setpoint preferences. Integrating adaptive comfort principles and control strategies can further optimize thermal comfort in these buildings.	**Methods/Instruments** • Brain- Computer Interface: Wearable devices equipped with sensors to gather physiological data. • Simulation chamber equipped with multi-sensory VR/AR/MR • ANN-SEM Model • Mobile Applications: collect participants' subjective feedback. • Simulation and Virtual Reality (VR): create virtual indoor environments. **Industry 4.0 output** • Data combined with environmental data for insights into personal comfort levels • Effectiveness of interventions/design strategies. • Apps integrating GPS and weather data for personalized recommendations to enhance comfort levels. • Simulate different weather conditions • Test the thermal comfort of users virtually • Allow for controlled experiments and rapid prototyping of designs.
Thermal Comfort Standards	• ASHRAE Standard 55 is the dominant standard (85% of studies) used to assess thermal comfort in hybrid ventilation research. While this highlights its widespread acceptance, the limited use of alternative standards like ISO 7730 and adaptive approaches raises concerns about whether ASHRAE 55 alone is sufficient for understanding thermal comfort across diverse populations and climates.	• Research suggests that occupants of naturally ventilated buildings may tolerate a wider temperature range, particularly in certain climates. This challenges the universal applicability of standardized thermal comfort models, like ASHRAE 55, and highlights the need to consider local climate variations and adaptive comfort principles when designing for diverse populations and regions.	
minimum and maximum cooling reduction	• **Significant Potential:** Hybrid ventilation can achieve substantial cooling load reductions, reaching up to 65% in some studies. • **Inconsistent Performance:** Effectiveness varies greatly, with some implementations showing no benefit. This highlights the need for context-specific design and operation. • **Average Reduction Around 30%:** A well-designed system can typically achieve around a 30% reduction in cooling load. However, poorly implemented systems may offer negligible benefits	• **Climate Variability:** Hybrid ventilation performance is highly dependent on outdoor conditions, leading to varied results across different climates. • **Design and Control Influence:** System choice, building integration, and control strategies are crucial for maximizing effectiveness. • **Building Characteristics Matter:** Building type, orientation, and thermal properties impact natural ventilation, a key aspect of hybrid systems. • **Occupant Behavior Plays a Role:** How occupants interact with windows and their comfort preferences can significantly affect performance.	**Methods/Instruments** • Geo-spatial digital twins • Data Analytics and Machine Learning • large amounts of data can be processed and analyzed to identify patterns and correlations. **Industry 4.0 output** • Better understanding of the factors that influence cooling energy consumption • Developing predictive models.

FIGURE 6
Industry 4.0 integration for next-generation hybrid ventilation systems in hot climates.

Currently, the ability to compare findings across different studies and draw meaningful conclusions is hampered by inconsistencies in data collection, analysis, and reporting. AI-powered platforms offer a solution by enabling the analysis of vast datasets from diverse sources, including building management systems, weather stations, and even research papers (Luo et al., 2020; Pang et al., 2021). This data-driven approach can facilitate the development of standardised performance metrics and benchmarks, enabling more accurate comparisons across studies and facilitating meta-analyses (Gao and Malkawi, 2014; Zhang et al., 2018). Imagine a future where researchers can easily access and analyse a global repository of hybrid ventilation data, all standardise and readily comparable. This would significantly accelerate the pace of innovation and knowledge sharing in the field.

Furthermore, AI algorithms offer a powerful tool for advancing hybrid ventilation research by automating the tedious process of extracting relevant information from research papers and technical reports, as highlighted by Chong et al. (2017). This streamlined knowledge synthesis and dissemination allows researchers to focus on higher-level analysis and interpretation, ultimately leading to a more comprehensive understanding of hybrid ventilation systems and their potential. Additionally, existing building performance models can provide invaluable data for optimizing the design and retrofitting of hybrid ventilation systems, particularly in challenging hot climates. These models can simulate the complex thermal and moisture dynamics within a building, accounting for factors like occupancy patterns, environmental conditions, and energy consumption. By leveraging this data, designers can gain a clearer understanding of how different hybrid ventilation strategies will perform under various scenarios. This allows for the optimization of system design and controls to enhance energy efficiency, indoor air quality, and occupant comfort. Moreover, insights from these model-based analyses can inform the integration of predictive control algorithms, enabling hybrid ventilation systems to adapt to real-time changes in occupancy and environmental conditions, further improving their effectiveness. By incorporating data from existing building performance models, researchers and practitioners can develop more robust and versatile hybrid ventilation solutions that address the unique challenges of hot climates, paving the way for more sustainable and user-centric building environments.

This standardised, data-rich environment fostered by AI not only benefits researchers, but also paves the way for addressing another crucial aspect of hybrid ventilation: occupant behaviour and engagement. After all, even the most sophisticated system will fall short if it doesn't align with the needs and preferences of its users.

Here again, AI offers powerful tools: Machine learning algorithms can analyse occupant preferences, patterns, and interactions with hybrid ventilation systems, enabling the development of personalised control strategies that cater to individual needs. Imagine a system that learns your preferred temperature range, anticipates your schedule, and adjusts the ventilation accordingly, ensuring your comfort throughout the day.

Natural language processing and chatbots can also facilitate more intuitive user interfaces, empowering occupants to understand and interact with the system effectively. This increased transparency and control can lead to higher user satisfaction and greater acceptance of hybrid ventilation systems.

Beyond improving existing systems, AI is also crucial for expanding the applicability of hybrid ventilation to understudied building types and emerging technologies. By analysing large datasets, AI can identify trends and patterns, guiding research efforts towards areas with the highest potential impact (Goyal et al., 2018; Dong et al., 2019). For instance, machine learning algorithms can analyse energy consumption data from educational buildings to identify opportunities for optimising hybrid ventilation strategies during different school schedules and occupancy patterns (Gunay et al., 2016). Additionally, AI can accelerate the development and integration of emerging technologies, such as predictive control algorithms that anticipate future ventilation needs based on weather forecasts and occupancy patterns, further enhancing energy efficiency and occupant comfort (Zhan et al., 2021; Vadamalraj et al., 2020).

7 Conclusion

Hybrid/mixed ventilation research reveals a significant gap, despite the field's potential for reducing cooling energy consumption, particularly in hot, arid climates. This gap stems from the complex, context-dependent nature of hybrid ventilation, leading to inconsistencies in reported performance and limitations in current approaches. The following conclusions can be inferred:

- Inconsistent Performance: While some studies show significant cooling load reductions (up to 65%) in hot climates, others report minimal or no energy savings. This inconsistency highlights the influence of various factors such as climate, building design, control strategies, and occupant behaviour, which are often overlooked in generalized approaches.
- Limitations of Standardised Approaches: The heavy reliance on ASHRAE Standard 55, a standard primarily developed for temperate climates and a specific demographic, fails to capture the nuances of adaptive thermal comfort prevalent in naturally ventilated buildings, especially in diverse climates and cultures
- Context-Specific Design Gap: Research suggests a greater tolerance for temperature variations in naturally ventilated structures, emphasising the need to move beyond generic standards and prioritise context-specific design approaches. This is particularly crucial in understudied regions such as the Middle East, where the hot climate necessitates tailored solutions for effective energy reduction.

Addressing these challenges requires a shift towards:

- Integrating AI and Industry 4.0 Technologies: AI-powered platforms can analyse vast datasets to develop standardised performance metrics, enabling more accurate comparisons across studies and facilitating the development of context-specific design strategies. This data-driven approach can also optimise hybrid ventilation systems dynamically, ensuring optimal energy savings and thermal comfort for occupants.
- Embracing Personalised Control Strategies: AI can facilitate occupant engagement through personalised control strategies based on individual preferences and real-time environmental data. This shift towards a human-centric approach can enhance comfort and encourage the adoption of hybrid ventilation systems.
- Focusing Research on Underrepresented Climate Zones: More research is needed in regions as in the case of the Middle East to develop region-specific solutions and thermal comfort standards that account for adaptive comfort and cultural preferences.
- By embracing these transformative technologies and approaches, the transition towards wider and more effective implementation of hybrid ventilation systems can be significantly accelerated. This will lead to a more energy-efficient, comfortable, and sustainable built environment, contributing to a greener, eco-friendlier infrastructure for our cities and communities.

To fully realize the potential of hybrid ventilation systems, future research should prioritize several key areas. First, developing standardized performance metrics and benchmarks is crucial to enable accurate comparisons across studies and facilitate informed decision-making. This standardization will be aided by integrating AI-powered platforms that can analyze building data, optimize system performance dynamically, and enable intelligent control strategies. Equally important is addressing the challenge of occupant engagement by developing personalized ventilation strategies that cater to individual preferences and behaviors. This requires further interdisciplinary research to understand the complex interplay between hybrid ventilation systems and varying occupant behaviors across different cultural and operational contexts. Finally, exploring the potential synergies between hybrid ventilation and other emerging technologies, such as predictive control algorithms and adaptive building envelopes, can unlock further efficiency and comfort gains. By addressing these research gaps and leveraging the power of AI and Industry 4.0 technologies, we can accelerate the transition towards wider and more effective implementation of hybrid ventilation systems, creating a more sustainable and comfortable built environment.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SA: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Writing–original draft. ME: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

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