smart cities

Review

Thermal Comfort and Energy Efficiency: Challenges, Barriers, and Step towards Sustainability

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Abstract: With the increasing number of people living in cities, the demand for energy in office buildings and homes is constantly increasing; thus, smart buildings were created to provide users with better comfort conditions. However, using artificial systems becomes an unsustainable alternative for these environments. This research conducted a literature review of studies published in Scopus and Web of Science between 1970 and 2022 to identify studies that contained strategies to promote thermal comfort and energy efficiency in buildings, as well as the main challenges and barriers to sustainability. A total of 9195 articles related to the topic were identified, and after applying the defined criteria, 105 were included in this review. Three research questions were investigated, and the main findings of this research are: (i) it is more difficult to assess thermal comfort and thermal sensation than energy efficiency; (ii) to promote a thermally comfortable environment, it is necessary to consider numerous aspects to reduce environmental impacts and energy consumption and to increase sustainability; (iii) actual thermal conditions are influenced by factors such as energy levels, climate, setpoint types, building type, size and orientation, and economic factors, among others; (iv) new technologies found in smart buildings showed distinct performances according to the climates of each region, and their evaluations can cover thermal comfort, energy savings, and payback time.

Keywords: thermal comfort; sustainability; energy efficiency; climate change; adaptive comfort; smart buildings

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1. Introduction

Since the Industrial Revolution in the early 20th century, countless people have left the countryside for cities, contributing to industrialization and economic development. It is estimated that, by 2030, about 60% of the entire population will live in urban centers, making it essential to optimize the spaces in these buildings [1]. According to Fanger [2], people spend most of their day in inside environments; therefore, those environments must be in good condition for these users. In 2019, the building sector accounted for 35% of the world's energy consumption and 39% of gas emissions, the highest ever recorded [3].

This energy is related to thermal comfort and its primary sources of consumption, heating, ventilation, and air conditioning (HVAC) systems [4]. By creating smart buildings, it is possible to promote safety, comfort, and resource savings, and reduce expenses by implementing automated systems, processes, or devices [5].

These systems match the thermal conditions offered by a building design to the needs of the occupants, while also considering sustainability [6]. An energy-efficient environment is vital for human development, especially for carrying out activities [7]. However, comfort is scarce in many cases due to poor insulation, insufficient local thermal control, inadequate temperatures perceived by users, and vertical temperature gradients [8]. Therefore, the energy efficiency assessment of buildings is easier compared to the assessment of thermal comfort. According to Omidvar and Brambilla [9], a significant amount of a building's energy consumption is connected to HVAC systems, making it difficult to find practical solutions to decrease overall consumption without predicting thermal comfort conditions correctly.

Increasing efficiency and saving electricity in buildings have been associated with sustainability in recent decades. Several innovative technologies and materials have been developed to integrate thermal comfort and energy efficiency in pursuit of sustainability [10]. Broday and Gameiro da Silva [11] verified that the Internet of Things (IoT) has been used for understanding the behavior of building occupants; Omrany et al. [12] mention the prioritization of sustainable materials, renewable sources, and energy-efficient equipment; Cirrincione et al. [13] used simplified ARERA (Italian Energy Networks and Environment Regulatory Authority) data sheets to evaluate environmental improvements from energy efficiency interventions in an urban residential building stock; Alvarado et al. [14] proposed effective modifications in the design of homes in Chile, reducing energy and maintaining comfort.

Sachs [15] mentions that, since the Brundtland Report, published in 1987, there has been a growing increase in the number of regions and countries using sustainability as a basis for development, i.e., seeking economic growth that is socially inclusive and environmentally sustainable. It has become relevant today to align thermal comfort with sustainability. Thus, many scientists, environmentalists, and international communities have dedicated their efforts to promoting energy efficiency and sustainability in buildings, raising several strategies and energy technologies.

Consequently, it has become an unsolved research problem in smart and sustainable cities to promote thermal comfort to users while increasing energy efficiency [16]. In this context, through a literature review with articles published from 1970 to June 2022, this research seeks to identify studies that contain strategies for promoting thermal comfort and energy efficiency in buildings: the main barriers to sustainability. To achieve the main objective of this investigation, three research questions (RQs) were proposed in this paper and further explored, and the main characteristics of these studies were ascertained through the Preferred Reporting Items Methodology for Systematic Reviews and Meta-analyses (PRISMA).

2. Methods

For the preparation of this literature review, a methodology consisting of three steps was applied: the presentation of the research questions (RQs) to conduct the literature review, the processes for the execution of the literature search, and use of the software selected for the selection and eligibility of articles and the development of the cloud of words that appeared most in the studies.

2.1. Research Question (RQs)

The main objective of this research was to investigate and synthesize studies that contained strategies associated with sustainability and thermal comfort for reducing energy consumption in buildings. To achieve this objective, three research questions (RQs) were proposed:

(a) The presence of thermal dissatisfaction with environments is very common among users, showing a discrepancy between the energy efficiency and thermal comfort of building interiors [17]. Predicting thermal comfort becomes essential to fill the gap between user comfort and energy efficiency. Using the predicted thermal state of the occupant serves as a method to control heating, ventilation, and air-conditioning systems [18]. Based on this assumption, RQ1 is elaborated:

RQ1: How does the indoor thermal condition influence the energy efficiency of buildings?

(b) The local climate and the types of buildings directly influence the thermal sensation [19]. In addition, the activities performed in buildings reflect the total percentage of energy used due to the great demand for heating, ventilation, and air-conditioning systems to obtain better thermal conditions. However, decreasing energy consumption and preserving environmental comfort conditions is difficult [20]. Moreover, based on this assumption, RQ2 is elaborated:

RQ2: How do different building types, energy levels, and climates influence thermal conditions?

(c) With the advancement of technologies, there has been an increase in pressure to reduce energy consumption, causing consumers to create high expectations concerning the comfort of the indoor climate of environments [21]. Based on this assumption, RQ3 is elaborated:

RQ3: What new technologies and research findings can help improve indoor thermal comfort and reduce energy consumption?

2.2. Procedures for Bibliographic Research

The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) was modified for this study [22]. PRISMA uses combinations of keywords to perform searches in scientific databases and consists of 4 steps that are applied to reduce the number of articles chosen: identification (step 1), selection (step 2), eligibility (step 3), and inclusion (step 4) for analysis. In recent years, several studies have made use of this research method which involve thermal comfort [23], energy efficiency [24], and sustainability [25].

The strategy of search and identification of articles (step 1) was carried out by combinations of keywords and their Boolean operators being inserted into the Scopus and Web of Science databases, as follows: ((“Thermal Comfort” OR “Adaptive Comfort”) AND (“Climate Change” OR “Energy Consumption” OR “Energy Demand” OR “Sustainable Development Goals” OR “Energy Efficiency”)). This search took place on keywords, abstracts, and titles of papers prepared and published between 1971, when the first studies on thermal comfort were started by Fanger [2] and June 2022. This search interval was chosen due to the period when sustainable development goals were being elaborated and for considering more recent studies that could contain more innovations associated with thermal comfort and sustainability.

The final search for articles occurred on 7 June 2022. The Scopus and Web of Science databases were chosen because they are two of the broadest databases in the world and cover most scientific fields [26]. Next, the screening (step 2) process was performed, where criteria for the inclusion and exclusion of articles were determined to present the studies most aligned with the RQs and the suggested objectives. Figure 1 shows all the inclusion and exclusion criteria used.

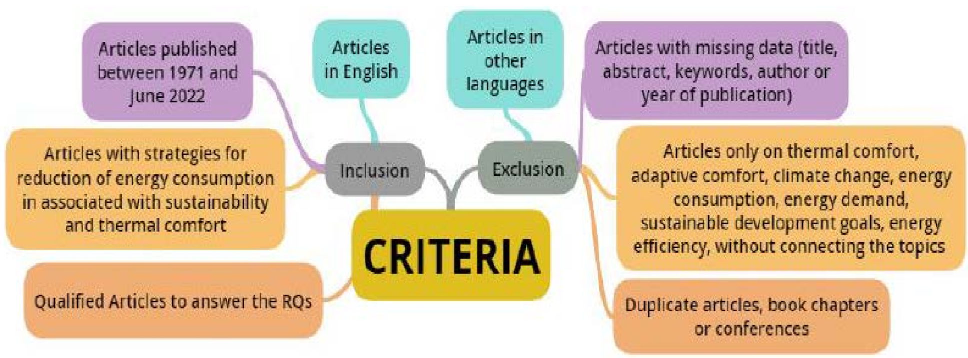

Figure 1. Inclusion and exclusion criteria used in the selection of the articles.

After the screening, the next step comprised a preliminary analysis of the selected articles with the full texts accessible. Eligibility (step 3) consisted of reading the abstracts to examine whether the articles could answer the research questions (RQ1, RQ2, and RQ3), this being a further refinement. Following the refinement, a portfolio of articles was formed to perform the necessary analysis and, thus, insert them into the review (step 4).

2.3. Software Used in the Research

Along with the PRISMA method, the StArt (State of the Art through Systematic Reviews) software was used as a support tool for the development of the Systematic Review for the better visualization of the articles selected and extracted from the databases, helping in the reading of the title, authors, and abstract, and the application of the inclusion and exclusion criteria directly in the system, contributing to the application of the review procedures with superior quality [27].

Another tool used was NVivo software, which organizes and analyses qualitative data [28]. The program contributes to word frequency queries, searching for specific terms in the text, linking materials available in the portfolio, creating graphs and diagrams, and exporting documents [29]. Among the advantages of NVivo is simplicity in managing data and promoting answers to more complex quantitative questions [30]. In this research, the software served as a tool to verify the most frequently-occurring words in the selected articles.

3. Results

3.1. Preliminary Search Results

Through the search strategies and the combination of keywords entered in the Scopus and Web of Science databases, it was possible to obtain the results found in Figure 2:

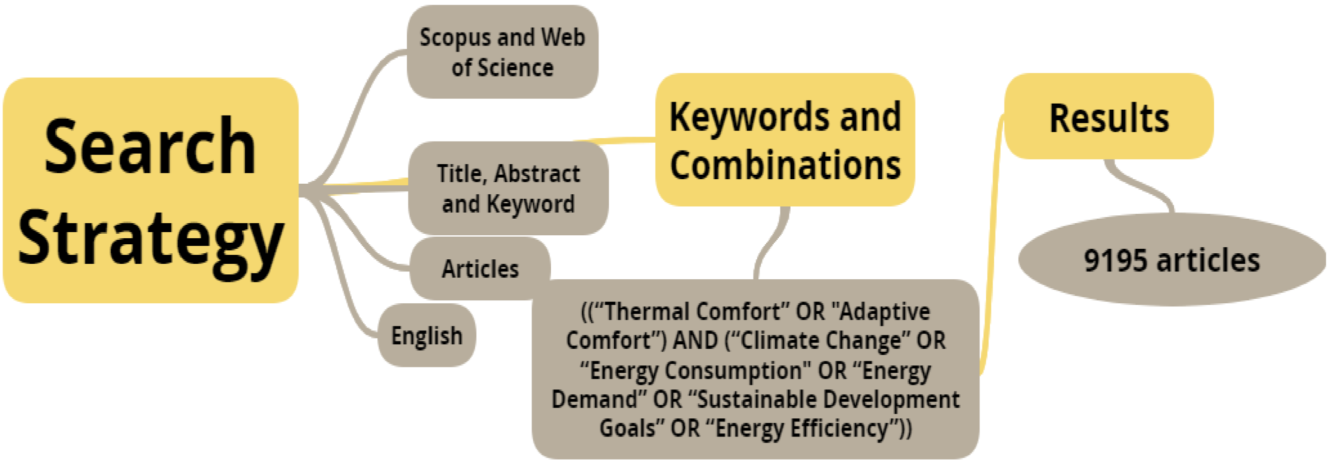

Figure 2. Results obtained through the database search strategy.

By employing the search strategies, 4390 articles were found in the Scopus database and 4805 in the Web of Science database. To perform the selection and confirm the eligibility of papers, the StArt software was used as a reference manager, which simplified this categorization. Then, the PRISMA method was applied, as shown in Figure 3:

Among the 9195 articles found in the databases, the exclusion criteria were used, leaving only 307, which were subjected to reading of the title, abstract, and keywords to ascertain their connection to the theme. Of these 307 articles, 202 were removed for not responding to the RQs. Finally, 105 articles were included in the literature review.

3.2. Bibliometric Results of the Publications

The bibliometric analysis identified the most general characteristics of studies with strategies for reducing energy consumption in buildings which were associated with sustainability and thermal comfort. Figure 4 shows the research published in each journal using vertical bars and the number of publications per year, per the color legend. There was a higher concentration of studies in 2020 with about 10.48%, in 2021 with 29.52%, and in 2022 with 17.14%. For the other years, there was a small expression of developed works; in addition, the journals with the most publications were: Energy and Buildings, Energies, and Building and Environment, with impact factors of 7.201, 3.252, and 7.093, respectively.

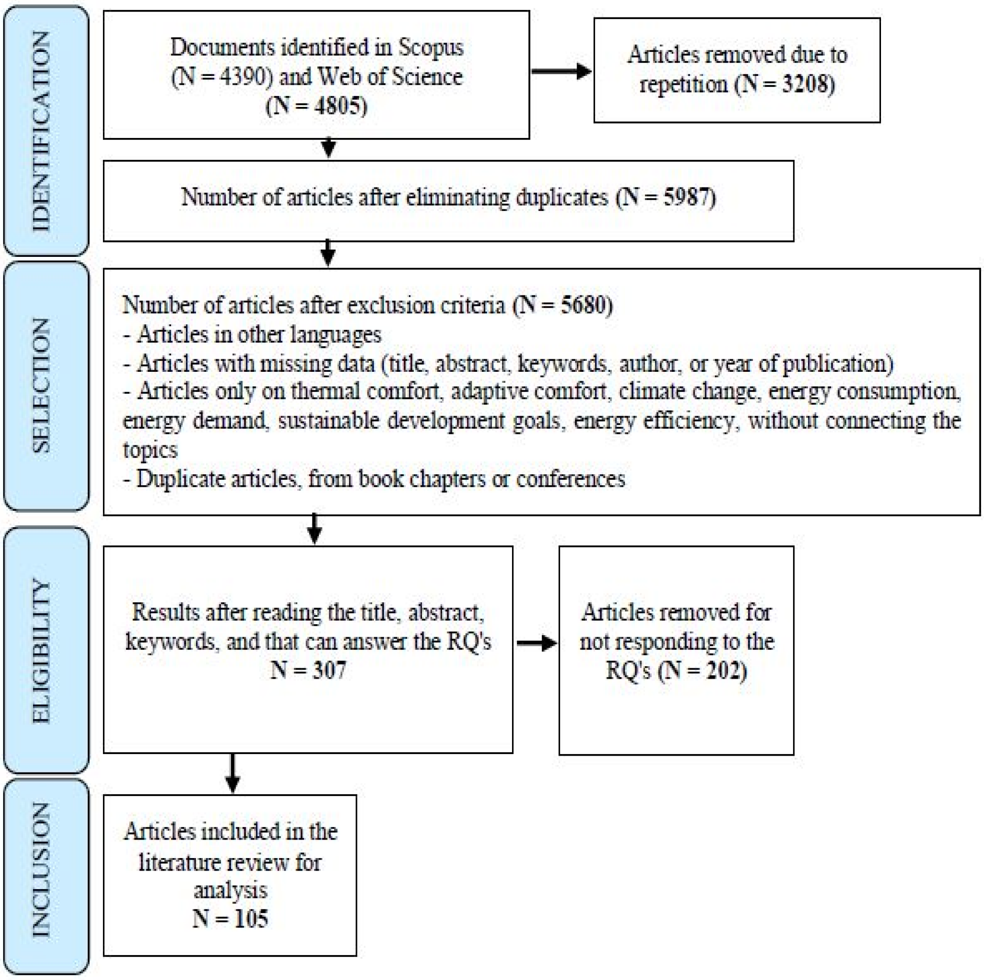

Figure 3. Results after applying PRISMA.

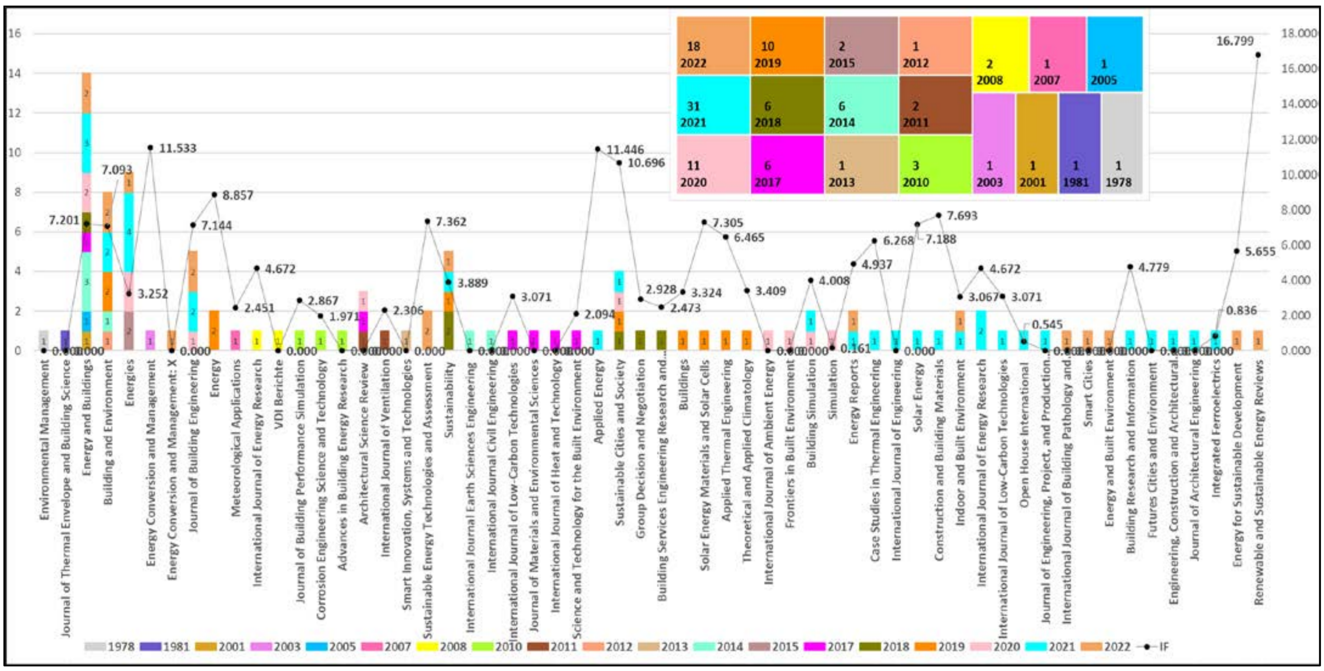

Figure 4. Co-occurrence map.

The NVIVO software tool was applied to discover the words of greatest occurrence in the selected articles. The higher the occurrence of the expression, the higher its representation is. Figure 5 shows the occurrences of the most used words in the studies that were compiled for this review.

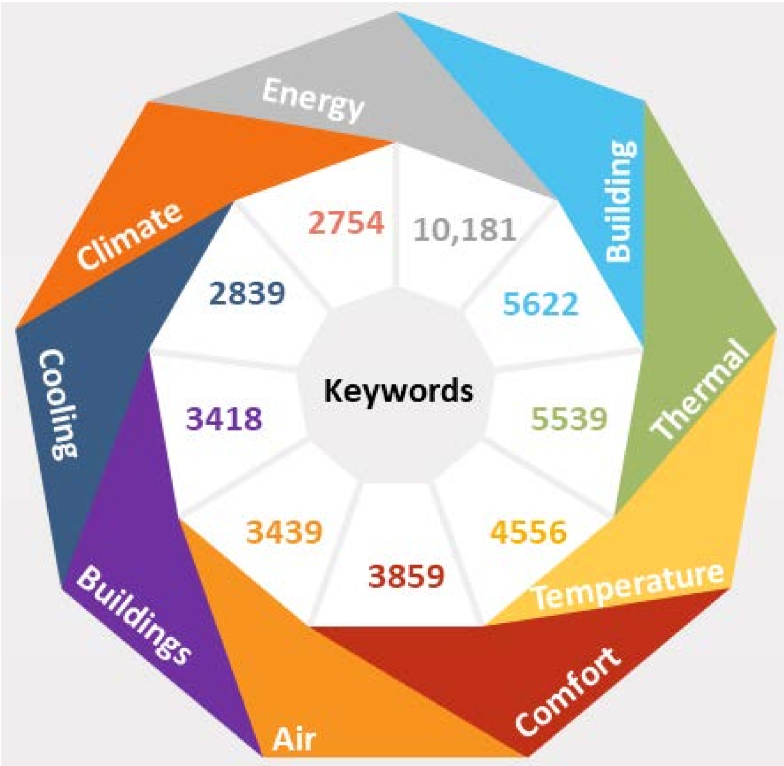

Figure 5. Occurrence of the most-used keywords.

The keyword of greatest evidence in the articles was "energy," with 10,181 opportunities that refer to one of the main topics of this research: energy consumption related to thermal comfort. Also, "building" presented 5622 opportunities to represent the very places where the studies were conducted.

4. Discussion

This section exposes the answers found for the RQs by reading the articles included in the portfolio of this review.

4.1. RQ1: How Does the Indoor Thermal State Influence the Energy Efficiency of Buildings?

In Figure 6, the main aspects of the thermal state found in the studies are presented.

These aspects have a direct influence on energy efficiency. They should be considered in promoting an environment with fewer environmental impacts and greater sustainability, and which meets users' needs. Table 1 presents the effects of these aspects on the energy efficiency of buildings.

In general, building envelopes consist of opaque external walls, vertical fenestration or glazing, and roof systems, and can control the influence of external factors on the internal environment. The main external factors that can generate heat loss or gain are solar radiation, weather conditions, and wind flow, which are characteristic of each region and can be seasonal. By controlling heat loss and gain, indoor temperatures approach comfort temperatures, reducing the need for heating and cooling, and increasing the energy efficiency of buildings.

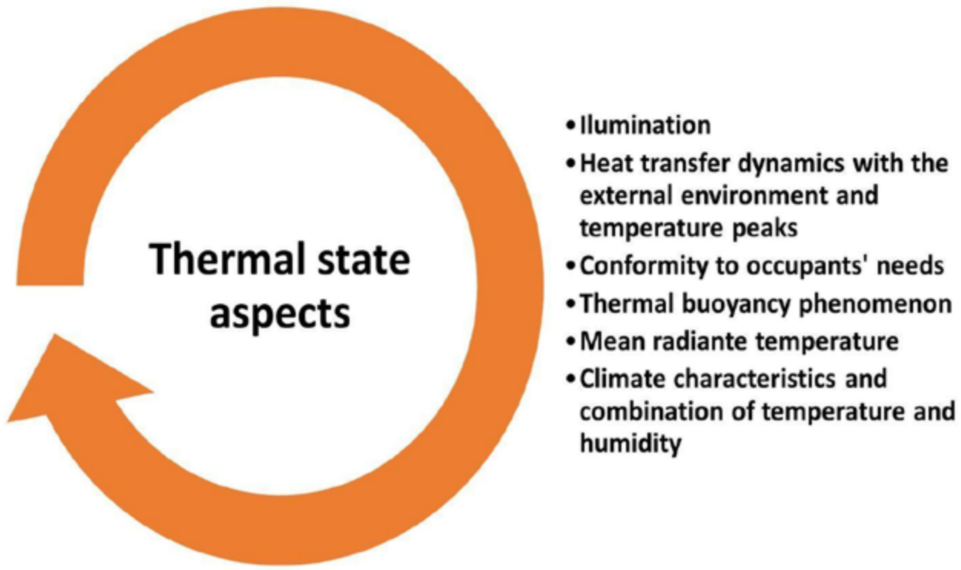

Figure 6. Aspects of the thermal state.

Table 1. Main effects on energy efficiency.

Refs.	Effects on the Building's Energy Efficiency
[31]	To improve the energy efficiency of buildings, the adoption of lighting standards more appropriate to local conditions becomes an alternative
[32]	On days of heating demand, the supply air provided by diffusers on the ceiling of the room did not significantly affect the internal temperature, due to the presence of thermal buoyancy, but, while the supply air presented a temperature between 26 and 36 °C, the room air contained the temperature between 19.8 and 21.8 °C such that this energy for conditioning was wasted
[33–63]	The dynamics of heat transfer between the internal and external environment directly affect the thermal comfort and energy consumption in the building, because it has the potential to be adapted to mitigate temperature peaks and reduce the need for HVAC systems
[41,43,51,64–67]	By determining the real needs of the occupant, HVAC and passive systems can be controlled to act within the correct time and temperature ranges, seeking a reduction in total energy consumption
[68]	The mean radiant temperature influences thermal comfort according to changes in the human body's position in the environment. So, it's possible to predict thermal comfort more accurately and configure the use of the environment in such a way that human activities are performed more thermally comfortable and with less energy consumption
[69]	In tropical climates, the combination of high humidity and high temperatures generates excess energy consumption for conventional air conditioning systems due to the need for dehumidification, which consumes 37% of the systems' energy
[70]	The type of building structure can directly impact on energy consumption and thermal comfort, this is due to the type of material used that can have different performances in relation to the climate and the different seasons

According to Anwar et al. [44], the construction of a building with an adequate envelope or the restoration of an existing one is considered to be a passive measure, being a natural action of the thermal resistance of the envelope to heat exchange by external factors that will help in the interior thermal control. The second-most frequent aspect refers to the conformity of the internal environment to the occupant's needs. From the analysis of the thermal comfort of the occupants, times of occupancy of the environment, and peaks in energy demand, it was possible to identify opportunities for reducing energy consumption. Knowing these details can determine the time and temperature ranges that ensure comfort for users, control HVAC systems to perform at the extremes of the comfort ranges, and define building envelope properties based on these ranges.

4.2. RQ2: How Do Different Building Types, Energy Levels and Climates Influence Thermal Conditions?

Table 2 presents a survey of the factors that can influence thermal conditions.

Table 2. Building types, energy levels, and climate types.

Refs.	Characteristics
[65]	In Qatar, summer temperatures exceed 45 °C, and the average high temperature exceeds 27 °C in the rest of the seasons. Therefore, air conditioning (AC) in Qatar is more of a necessity than a luxury and accounts for about 80% (the highest in the world) of building energy consumption. Air-conditioning systems run uninterrupted all year round to maintain thermal comfort
[66]	The thermal inertia of building structures influences comfort and energy consumption, especially in different climatic types or seasons. This ability to accumulate heat when temperatures change is related to the internal partitions and wall masses that allow passive thermoregulation
[71]	After the 1973 energy crisis, energy-saving concerns negatively impacted Indoor Environmental Quality (IEQ). Designs aimed at energy conservation at the expense of comfort and health resulted in an outbreak of Sick Building Syndrome (SBS)
[72]	In the coming years, global warming is expected to cause a 2 °C rise in temperature, so the use of indoor comfort temperature can provide a heating energy gain. In some Greek areas, such as in the north, air-conditioning systems are no longer needed
[73]	Passive houses have critical ventilation systems, which in some cases can be inefficient, directly impacting the sustainability and energy savings of the environment
[74]	Climatic conditions need to be considered when using cold materials in buildings without insulation, as their use will be advantageous to the extent that the decrease in energy demand for cooling is greater than the increase in energy demand for heating
[75]	In large commercial office buildings with central air conditioning that make use of a variable air volume (VAV) distribution system, the air velocity decreases as the air temperature approaches the setpoint, negatively affecting the thermal comfort of the occupants
[43,76–83]	Climate change can affect people's daily lives in terms of thermal comfort in the workplace and in their personal lives, promoting peak loads, increasing energy consumption per floor area and use of HVAC systems. With the development of adaptive models, it is possible to consider these local characteristics in evaluations
[84]	The Wind-Rain house contains a patio with a glazed roof that facilitates the entry of sunlight into the environment, and this roof can be closed or partially opened to allow ventilation for thermal comfort, in addition to its protection from rain and wind
[85]	World bioclimates have changed over the centuries causing an increase in thermal discomfort both in summer and winter, when comparing the 20th and 21st centuries
[86]	Most Spanish buildings were built before energy standards were mandatory. Although adaptive comfort levels are satisfactory, this will not be the case in the future, given the global warming that provides the discomfort
[87]	Net-zero energy building (NZEB) has become a solution to current energy difficulties caused by climate change that undermines thermal comfort and energy balance
[88]	In a simulated building, by changing the original north orientation to south orientation, the energy demand for cooling decreases by between 0.5% and 1.2%
[89]	For the tropical Aw climate, the adaptive comfort model shows that with air conditioning systems, the comfort temperature is up to 1.0 °C higher than international standards and increasing the setpoint temperature promotes comfort and energy savings
[90]	Residential high-rise buildings take advantage of natural ventilation to improve energy efficiency, but it is only effective if the temperature difference between indoors and outdoors is less than 2 °C. The best configurations are when the building contains an orientation at an oblique angle to the prevailing wind direction, for the upper floors natural ventilation is wind-induced, and for the middle and lower floors there is a need for buoyancy. Energy savings are higher in large apartments by up to 55% compared to only 22% in small apartments, because more occupants result in higher anthropogenic heat generation
[91]	Overheating in apartments was most pronounced on upper floors, especially those with keyboard exposure and westward glazing orientations

Table 2. *Cont.*

Refs.	Characteristics
[92]	By replacing the use of static setpoints of the Spanish Building Technical Code (CTE) standard by using adaptive setpoints of the EN 15,251 standard for category II, there is a reduction in energy demand of 5.91% in zone E1 (CSB climate), 22.86% for zone D3 (BSh climate); and a reduction of 52.78% in zone B4 (Csa)
[93]	A low thermal energy building designed for Germany called PassivHaus (PH) has been successfully implemented in other climates, however, in southern Europe this same building exhibited overheating in the hot season
[94]	City climate, household income and user preferences are responsible for the availability of HVAC systems for use, and habits to change unwanted temperatures that influence adaptive behaviour. Most Brazilians prefer natural ventilation as a means of adaptation
[95]	The window-to-wall ratio (WWR) improves thermal comfort through natural ventilation, visual comfort through access to natural light and views, thus increasing the amount of window area has an influence on total energy demand
[96]	Current (cold climate zone in Beijing; hot summer and cold winter zone in Shanghai) and future (2050) climate scenarios were compared, thus the results indicated that in the future there will be a predicted increase in heating hours of 58–60% and 41–44%, respectively

Some factors can influence thermal conditions, such as energy levels [71], building type and orientation [90], apartment size and orientation [91], setpoint and climate [92], and economic factors [94], among others. This happens due to the specific conditions of each region that directly interfere with the thermal reality experienced by indoor users and in energy consumption, which, in many situations, is related to the use of heating, ventilation, and air conditioning systems as well as the greenhouse effect.

4.3. RQ3: What New Technologies and Research Findings Can Help Improve Indoor Thermal Comfort and Reduce Energy Consumption?

To improve thermal control and reduce energy consumption, numerous technologies and discoveries have been identified and presented in Table 3.

The values presented refer to the results obtained in the studies; however, it is interesting to note that the technologies had different performances because they depended on the climate of the region where they were applied. One example is the study by Valentin, Dabbagh, and Krarti [63], which trialled switchable insulation in walls and windows in several French regions, providing energy savings of up to 81.9% per year in HVAC use in hot climates and 38.1% in cold climates. Another example is the research of William et al. [54], who implemented reflective paint solutions that achieved energy savings of 21% in Aswan, 19% in Cairo, and 17% in Alexandria, all in Egyptian buildings. In Aswan, reflective paints showed superior performance due to high solar radiation, followed by Cairo and Alexandria. These variations represent the subjectivity of the results and show the importance of simulation technologies.

Most studies were concerned with the economic feasibility of the technologies, involving issues beyond thermal comfort and energy savings, such as the return-on-investment time that sometimes ended up being longer than the useful life of the technology, meaning that there were no financial advantages for the technologies' implementation. Of the articles reviewed, at least 26 of them performed modelling and simulations to achieve their results, in addition to measurements in real environments, and the use of meteorological data and projections, as in the research of Akkose, Akgul, and Dino [42], in which simulations were performed to examine the efficiency of retrofit measures under conditions arising from climate change and the aggravation of heat islands.

To complement this analysis, Figure 7 shows the percentages of studies that evaluated thermal comfort using the traditional model, the Predicted Mean Vote (PMV) developed by Fanger in the 1970s; adaptive models; other types of analysis without the use of models, such as the use of new materials and algorithms, among others.

Table 3. New technologies and findings to improve thermal comfort and reduce energy consumption.

Ref.	Technology/Findings	Results
[34]	Recycled paper mill waste (RPMW) bricks and fly ash bricks	The environments became more thermally comfortable and energy efficient, besides being a low-cost material and 72% less thermal conductivity than fly ash brick
[35]	Float-triggered dynamic shading	System has potential cooling energy savings of up to 32.8%
[36]	Cold blinds	25% energy savings over traditional darkroom blinds
[38]	Electrochromic glass	17% reduction in annual energy costs
[39]	Cool roofing and paving stones	The application of cool roofs generated a 17% reduction in the annual cooling demand of the case study building, while the surface temperature of the urban floors was reduced by almost 10 K
[40]	Sodium acetate and urea phase change material	With this material the indoor temperature can be reduced by 7 °C, saving cooling energy by 60% on a summer day
[41]	Schedule for HVAC system set points	The schedule along with shading device achieves 35% reduction in energy consumption and allows 365 thermally comfortable days, without the schedule there would only be 261 days
[43]	Retrofit measures	Retrofit measures were able to reduce the energy load by 39% as well as improve indoor environmental quality (IEQ)
[45]	Passive Dual Heating and Cooling System	The system provides high energy efficiency with a 39% savings rate
[46]	Mortar with internal thermoregulation function	Reduced by 60.94% in thermal conductivity in relation to conventional mortar
[48]	Removable layers on the inner side of the building envelope	PCM layers can achieve up to 50.71% reduction in annual energy consumption
[49]	Window films with low thermal conductivity	6% decrease in heating energy consumption and 3% decrease in percentage of unsatisfactory thermal hours
[51]	Thermal comfort-based control system using PMV	The energy consumption with air conditioning was reduced by approximately 13% in the traditional PMV control compared to the control set at 24 °C
[53]	Cool roofs	Energy savings between 3.5 and 38% for HVAC
[57]	Aerogel for thermal insulation	Reduced energy consumption by 15% for attic and floor slabs
[58]	Windows and exterior walls with switchable insulation systems (SIS)	Results show that the use of SIS results in a 44% reduction in energy use for heating and makes the use of mechanical cooling unnecessary
[59]	Structural wall with biobased earth blocks	This wall improves thermal comfort by regulating humidity and internal temperature and reduces thermal dissatisfaction of users by 24.6%.
[60]	Customized green roofs	Decreased energy consumption, energy cost and environmental impact
[61]	Advanced tombe walls with glazed thermal mass components	Obtained reduced heating period (48.8% on average), improved comfort conditions (23.9%), while increasing cooling periods (22.7%) and overheating (2.2%)
[63]	Exterior walls and windows with dynamic thermal insulation	When SIS is applied to walls and windows, annual HVAC energy savings can reach up to 81.9% in hot climates
[64]	Stochastic model based predictive control (SMBPC)	Reduced the risk of energy unavailability by up to 24%
[65]	Thermal control system	Able to achieve a 21% reduction in energy consumption and improve thermal comfort by 44%

Table 3. *Cont.*

Ref.	Technology/Findings	Results
[66]	Heating controller based on Deep Reinforcement Learning (DRL)	Thermal comfort was improved by 15 to 30% along with 5 to 12% reduction in energy costs related to a traditional thermostat controller
[67]	Energy management in smart home network	In the smart scenario, the energy consumption of the heating system is 15% lower than in the basic scenario and thermal comfort is improved
[68]	System based on Building Information Model (BIM) and Artificial Neural Network (ANN)	Model considers the human position, integrating thermal information to suggest furniture placement in environments reducing energy consumption and maintaining thermal comfort
[69]	Two stage desiccant solar cooling system in recirculation mode	Energy savings between 27.9% to 33.9%
[71]	Integrated design and operation protocol Building Environmental Performance Model (BEPM)	Up to 15% reduction in total energy use
[76]	Adaptive thermal comfort models	Decreased energy use for cooling and heating, and reduced risk of overheating due to climate change
[80]	Green roof with Setcreasea purpurea	The green roof can lower the internal temperature by 1.5 °C and decrease energy use
[83]	Operating Strategy for NZEB	Provides 20% to 40% energy savings, plus 33% to 65% reduction in Photovoltaic Production (PV) area becoming Positive Energy Buildings (PEB)
[88]	Set of improvement strategies	Reduction in energy demand for cooling by 27%, 21%, and 17% for the current climate, 2030, and 2050, respectively, from changes in the thermal insulation of the building envelope, installation of external window shading devices, improved glazed windows, reduced window area, southern orientation of the largest windows
[90]	Natural ventilation facilitated in high-rise residential building	Reduction of energy consumption by up to 25% by replacing the use of mechanical ventilation with natural ventilation and by up to 45% through buoyancy-driven natural ventilation
[92]	Implemented adaptive comfort control model (ACCIM)	The use of adaptive setpoint reduces energy demand by up to 69.91% for the least restrictive category and by 31.34% in the most restrictive category
[95]	Biophilic design principles	Improves daylighting, thermal comfort and reduces energy consumption
[97]	Energy conservation program	By reducing the lighting, changing operating hours, adjusting the thermostat, and eliminating air-conditioning reheating, energy consumption in summer was reduced by up to 54%
[98]	Fuzzy PD control method for air quality, thermal and visual comfort for building occupants	Reduced energy consumption by 25 to 30%
[99]	Cost-effective building operational strategy	Reduced total energy use by up to 15 Able to reduce building maintenance-related costs, improve indoor environmental conditions, and promote an 11% reduction in energy consumption
[100]	Design of experiments methodology	Individuals have more freedom to perform behavioural actions, such as the use of blinds, windows, thermostat, lighting systems, clothing, and fan settings, thus impacting the energy performance of the environment
[101]	Adaptive comfort model	Through the models it is possible to ascertain climate changes and contribute to efficient improvement in the design of thermally comfortable environments

Table 3. *Cont.*

Ref.	Technology/Findings	Results
[102]	Heat-insulating solar glass (HISG)	Reduces solar heat gain by up to 80% compared with ordinary glass and has a 100% UV and 99% IR blocking rate, essential for thermal comfort and human health
[103]	Biomimetic design	The proposed design can reduce the intensity of energy use for room conditioning by up to 66%.
[104]	Integrated control of air conditioning, humidifier, and ventilation system, considering the outside environment	Up to 33% reduction in energy consumption
[105]	Single-glazed radiant solar space and double-glazed radiant solar space in energy-efficient building	Minimization of indoor air temperature fluctuations and reduction of heating energy by approximately 3.3% and 8.7% for the insertion of single-glazed radiant glass and double-glazed radiant glass, respectively
[106]	Adaptive thermal model	Reduced energy consumption, improved thermal comfort of buildings and reduced greenhouse gas emissions, and help designers develop buildings with better thermal efficiency
[107]	Nearly Zero Energy Buildings (NZEB)	The purpose of Nearly Zero Energy Buildings (NZEB) is to promote low energy consumption and high renewable energy production on site, so the building achieved high efficiency with low consumption using only 9.14 kWh/m^3 for cooling and 3.82 kWh/m^3 for heating
[108]	Decision model based on sustainability assessment of insulating materials	The materials selected as most sustainable were glass wool, hemp fibers, Kenaf fibers, polystyrene foam, polyurethane, and rock wool
[109]	Dual-layer PCM system	Increase of thermal comfort from 73% to 93% in dry climate; 63% to 75% in semi-arid climate in winter; reduction of heating energy consumption by 17.5% for hot/dry climate; 10.4% for mild/semiarid climate and reduction in cooling energy by 12.3% for cold climate and 9.8% for mild/humid climate
[110]	Set of passive strategies (Thermal insulation of wall air cavities, changing window frames, optimizing window glazing, establishing regular mechanical ventilation rates for indoor air changes)	Reduction in energy demand by up to 47% and improvement in comfort conditions ranging from 20 to 40% in winter, 35 to 50% in summer
[111]	Advanced thermochromic materials	Energy conservation in the built environment and combating overheating
[112]	Model predictive control for underfloor heating system	Improves thermal comfort and reduces peak period energy consumption and daily electricity costs by 1.82–18.65%
[113]	Trombe wall system of fired brick and reinforced concrete augmented with PCM	Targeted for both cooling and heating purposes through adaptability of the openings
[114]	Internet of Things (IoT)	Development of an individual thermal comfort model with data from wearable devices (smart band) and machine learning
[115]	Adaptive thermal comfort with tracking-based method	Understanding user behavior, ascertaining thermal comfort and identifying how energy consumption is impacted especially in seasonal periods. Through screening it is possible to save up to 34.33% energy
[116]	Shading system with PCM	Cooling energy consumption decreased by 44% and the number of hours of thermal comfort improved by 34%
[117]	Building Automation	Promoted an increase in discussions at the scientific level related to this type of automation and how suitable it should be to promote comfort and allow control by users

Table 3. *Cont.*

Ref.	Technology/Findings	Results
[118]	Cooling tile using PCM	External and internal roof surface temperature reduced by about 8 °C and 12 °C, respectively
[119]	Green roofs (GR)	Considering rising temperatures, for cooling seasons energy consumption is reduced by 20% to 50% for Esch-sur-Alzette and by 3% to 15% for Palermo, improving comfort and reducing roof temperatures by 2 to 5 °C
[120]	Forced ventilation system	Ideal for industries and improves the air speed inside, besides decreasing the percentage of pollution in which the employees are exposed, providing an increase in productivity, improvement in the performance of the machinery and in the workplace.
[121]	Heat pump	Reduction in heat loss
[122]	Residential cluster in orthogonal orientation	Residential clusters provide 46% more hours of thermal comfort and energy savings of between 28% and 32% for rectangular and square row houses
[123]	Interactive waterfall ventilation	The system achieves a 30% higher temperature drop in cooling capacity than in traditional mixed ventilation mode
[124]	Model predictive control (MPC)	The use of Model predictive control (MPC) improves indoor thermal comfort and decreases energy consumption by 22.2% when compared to proportional-integral-derivative control (PID)
[125]	Prefabricated double-skin façade (DSF)	Increased building sustainability through reduced energy consumption and mechanical ventilation in addition to improved thermal comfort, lighting, and natural ventilation
[126]	Sustainability Index in the Energy Life Cycle	The tool was able to evaluate energy efficiency improvement alternatives for a residential building in terms of energy consumption, life cycle CO2 emissions, and final indicators of the degree of cooling discomfort and heating discomfort
[127]	District Cooling System (DCS)	Energy cost and thermal comfort are optimized, saving up to 5% more energy consumption compared to published strategies
[128]	External VO2 thermochromic glazing coating	Reduction of approximately 5 °C in average room temperature
[129]	Compact all-in-one and plug-and-play machine	Recovers heat that is used to preheat fresh air for domestic water heating
[130]	Net-zero energy buildings (NZEB)	Electricity consumption is reduced by at least 60% of the original value
[131]	PCM embedded Radiant Chilled Ceiling (PCM-RCC)	About 70% of the energy consumption was off-peak and in 58% to 70% of the occupancy period the delivered operative temperature was within ISO 7730 Class C
[132]	Natural ventilation in buildings in hot and dry climates in Burkina Faso	Thermal comfort in earth block building and hollow concrete block building reach 26.4% and 25.8% respectively

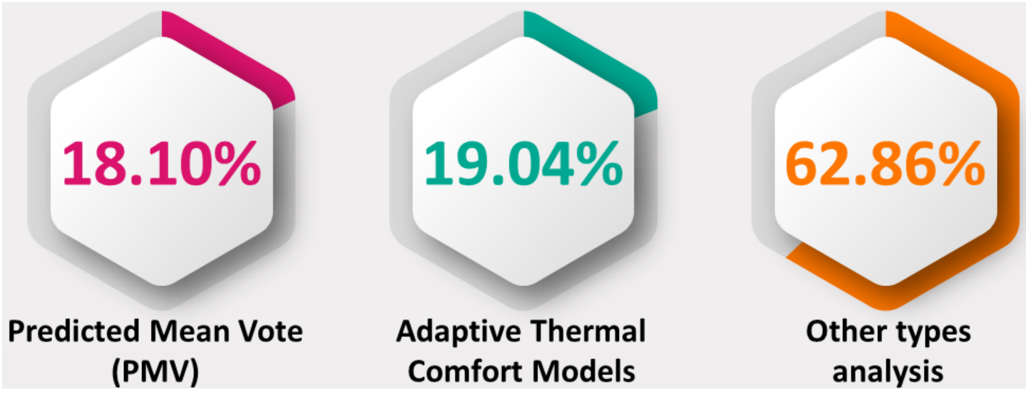

Figure 7. Methods used to evaluate thermal comfort.

Thus, among the analyzed studies, about 19.04% of the authors applied adaptive models [55,71,75,76,79,85,88,91,95,97,100,102,105,109,111,113,114,123,131,133], and 18.10% made use of the traditional PMV model [38,41,45,47,49,51,54,59,65,67,68,82,87,103,108,115, 119,120,134]. It is worth mentioning that the adaptive models usually present a better performance to estimate the thermal reality; however, the PMV continues to be the most-used model to analyze thermal comfort. In this review, the adaptive models had a higher incidence in the publications by about 0.94% compared to the traditional model. Adaptive models can consider different environments and climates, among other factors [135]. Therefore, their application becomes more specific to the analysis site; however, these models can have numerous performances when applied to places with different conditions. The other researchers chose to use other types of analyses focused on energy efficiency; thus, it can be concluded that the evaluation of thermal comfort inside buildings is a little more complex.

4.4. Futures Trends

Smart Cities have a commitment to the development and promotion of the Sustainable Development Goals (SDGs) [136]; therefore, among the future research trends, this association with thermal comfort was found, given the numerous impacts caused by problems related to environmental and social issues [78]. If not considered in new research, then that research will go against nature and the good use of resources. Thus, Figure 8 presents the main topics that relate thermal comfort to the SDGs [137], showing the benefits of this association.

Other relevant trends are the realization of external thermal comfort analysis in urban environments [138]; tree planting in the promotion of comfort through biophilia; making cities increasingly sustainable [139]; performing retrofitting as an alternative aimed at designing and managing more brilliant operation, dispensing the need for the investment of new resources in the implementation or upgrade of equipment [48]; investigating peak energy demand and capacity of electrical networks [140]; integrating comfort, climate change, and environmental sustainability into topics of social, technical, and political debate [141]; using algorithms to evaluate energy consumption and greenhouse gas emissions [142]; improving the thermal conductivity of phase change materials (PCMs) [143]; developing models for estimating building heating and cooling demand in the early design phase [144], and simultaneously addressing Indoor Environmental Quality (IEQ) and energy efficiency [145].

Therefore, by realizing connectivity between environments, humans allow for the expanding of their ability to bring benefits to buildings, such as well-being, satisfaction, and health to users [95]. The construction industry plays a key role due to the high emission rates of gases contributing to the greenhouse effect in all phases of the construction process. Most of the time, construction is not planned correctly, generating energy waste and not providing adequate thermal comfort conditions.

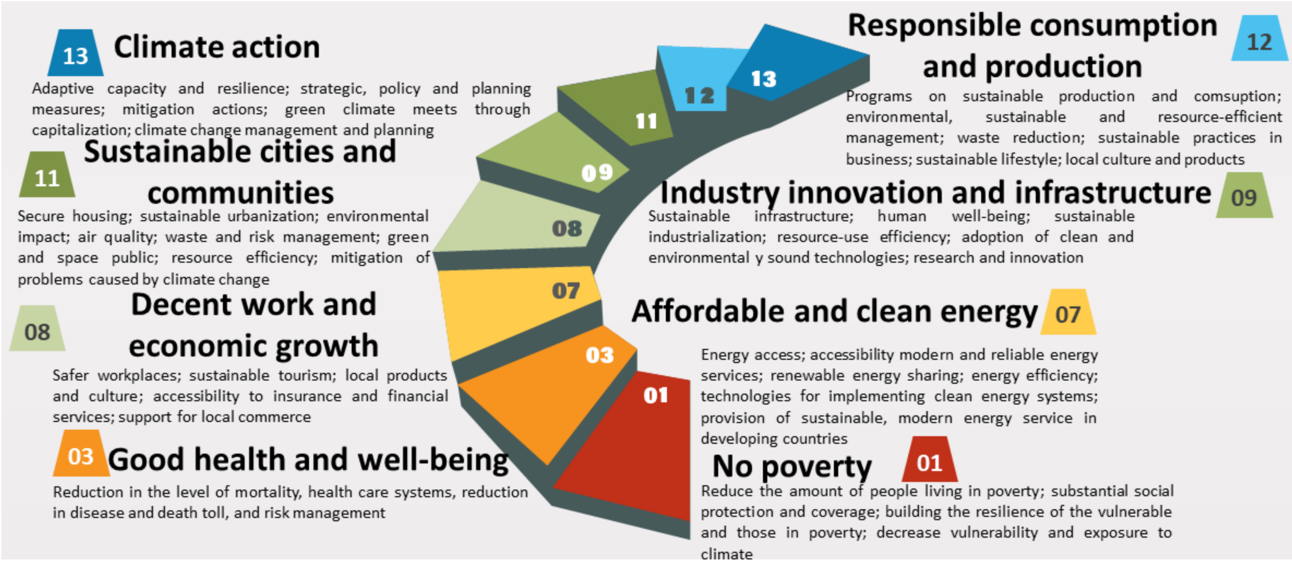

Figure 8. SDGs associated with thermal comfort. Adapted from Yang and Matzarakis [78] and WHO [137].

In this context, the construction sector is one of the largest energy consumers. This has raised a concern that was not important before. However, environmentally friendly production is still in its beginning stages. Assessing the level of thermal comfort that a building is intended to have is important in terms of costs, but also the quality of the work of its employees. It is recommended to increasingly consider sustainability related to thermal standards in building constructions to reduce environmental impact and use current energy efficiency and thermal comfort standards in historic buildings to improve sustainability and energy performance, as well as the maintainability of heritages built from historic structures [146]. Similar environmental goals are also recommended by several governments, that encourage the fulfillment of policies capable of reducing the emission of greenhouse gases and behavioral changes in individuals.

In addition, new research should be focused on investigating the air and thermal quality of indoor environments, the use of alternative heating systems, the effects of climate change, and studies addressing cost optimization to evaluate energy efficiency—the great majority of the analyzed articles were related to the research's aims, especially SDG 11. The construction sector is one of the primary consumers of energy and water, as well as being a primary generator of pollutants, directly influencing the SDGs.

5. Conclusions

The diversity of studies with strategies capable of promoting thermal comfort and energy efficiency in buildings in search of sustainability was verified, in addition to the main challenges and barriers encountered. The main aspects of the thermal state that influence energy efficiency was identified, in addition to the different types of buildings and climates, and new technologies and discoveries, to provide thermally comfortable environments and reduce energy consumption. Even with the limitation of the period of published research from 1970 to June 2022, the year 2021 was the period with the highest concentration of publications, with 31 articles that corresponded to 29.52% of all the studies presented.

This paper proposed three research questions. In answering RQ1, it was noted that, to promote a thermally comfortable environment, it is necessary to consider numerous aspects, from the needs of the occupants, local climatic characteristics, and lighting, among others; thus, it is possible to reduce environmental impacts and energy consumption, and increase sustainability. In consonance with RQ1, RQ2's answer elaborated that numerous buildings are designed so that users can face the actual thermal conditions with greater comfort, besides emphasizing that the climatic conditions of each location directly interfere with the thermal reality experienced by users, who, in many cases, resort to HVAC strategies that are responsible for increasing the levels of energy consumption. Thus, the use of technologies and discoveries arise to mitigate these problems.

In response to RQ3, these new technologies and discoveries have shown to have distinct performances according to the climatic types of each region; in addition, their evaluations can cover thermal comfort, energy savings, reuse of materials, simulations, and the return on investment, which, in some cases, does not present financial advantages given the lifetime of the technology, as in the study of Mahadevan, Francis, and Thomas [144], which had a significant increase in annual energy costs due to the use of 3D-printed concrete structures.

The construction industry is one of the most significant users of energy, water, and pollutant generators, and faces numerous challenges regarding the environment, energy security, and the economy. Undertaking projects and building systems that are adequate to the climate, with natural ventilation and lighting resources, becomes an alternative to avoid energy waste and promote comfort and sustainability indexes as presented in the analyzed studies. Finally, it is worth emphasizing the importance of combining the ODS with thermal comfort to promote increasingly sustainable environments, with better conditions of use and lower emissions of pollutants, in addition to proposing more thermally pleasant environments and with the presence of energy efficiency associated with the help of new technologies on the market.

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