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Review

Enhancing Thermal Comfort Through Leading-Edge Design, Monitoring, and Optimization Technologies: A Review

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Abstract: The study reviewed thermal comfort enhancing strategies in built environments through the utilization of advanced design, monitoring, and optimization technologies. This research is driven by increasing challenges arising from climate change and the need for sustainable, energy-efficient building solutions. These passive design strategies work best with optimum building orientation, natural shading, and a means of enabling natural ventilation to reduce the dependency on energy-intensive Heating, Ventilation, and Air Conditioning (HVAC) systems. Technologies that help realize real-time monitoring, powered by sensors, data analytics, and Building Information Modeling, will provide a precise understanding of indoor environmental conditions. This allows adaptation to dynamic conditions and improves occupant comfort. It also elaborates on the contribution of wearable devices and related occupant feedback systems for capturing subjective thermal experiences, thereby enhancing fine-grained analysis. Lastly, it explains optimization technologies, mainly the application of machine learning and artificial intelligence to predict thermal comfort and optimize the operation of the HVAC to reduce energy use, increasing building sustainability. It shows the potential of these technologies to yield more resilient built environments and to focus on energy efficiency and well-being principles toward human-centered approaches.

***Keywords*:** thermal comfort, energy utilization, energy efficiency, air conditioning, ventilation, cooling

1. Introduction

In the quest for sustainable and human-centered built environments, achieving optimal thermal comfort emerges as a pivotal objective [1-4]. In the face of challenges posed by climate change, urbanization, and a burgeoning global population, the imperative to craft spaces fostering occupant well-being becomes increasingly urgent [5-10]. This paper undertakes a comprehensive examination of advancements in elevating thermal comfort through the integration of cutting-edge design, monitoring, and optimization technologies. Thermal comfort, a nuanced concept shaped by environmental, physiological, and psychological factors, holds the key to unlocking productivity, health, and overall satisfaction within indoor spaces. Traditional approaches have predominantly fixated on simplistic temperature control, often neglecting the intricate interplay between indoor environmental parameters and occupant perception [11-14]. Acknowledging this limitation, contemporary research explores innovative strategies transcending conventional norms, embracing a holistic perspective that includes avant-garde design principles, state-of-the-art monitoring technologies, and advanced optimization techniques [15-17].

The architectural and engineering communities increasingly endorse sustainable design, emphasizing a symbiotic

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relationship between the built environment and its occupants [18-22]. With this paradigm shift, the integration of passive design strategies gains prominence, leveraging the inherent qualities of materials and architectural elements to regulate temperature and enhance thermal comfort [23-26]. Examples include natural ventilation, daylight harvesting, and strategically placed shading devices, showcasing how design ingenuity can mitigate the impact of external climatic conditions, fostering a harmonious indoor environment. Simultaneously, smart technologies usher in a new era of building management and occupant-centric control. Sensing and monitoring technologies, ranging from advanced sensors to Internet of Things (IoT) devices, empower building operators and occupants with real-time data on indoor environmental conditions [27-29]. This information not only enables proactive responses to changing thermal conditions but also facilitates the development of personalized comfort solutions tailored to individual preferences and needs [30-32].

However, optimizing thermal comfort extends beyond initial design and real-time monitoring; it necessitates a dynamic and adaptive approach. This paper explores the evolving landscape of optimization technologies that leverage machine learning, artificial intelligence, and data analytics to continuously refine and customize thermal comfort solutions. By learning from historical data, predicting occupant behaviours, and adapting to changing environmental conditions, these technologies offer a promising avenue for achieving unprecedented levels of energy efficiency and occupant satisfaction. The scope of this review encompasses a diverse range of studies, experiments, and projects contributing to the collective knowledge in enhancing thermal comfort. From groundbreaking architectural designs blurring the boundaries between indoor and outdoor spaces to sophisticated sensor networks creating a feedback loop for building systems, each facet plays a vital role in the overarching goal of fostering environments prioritizing the well-being of occupants [33-36]. By critically examining successes and challenges encountered in the pursuit of enhanced thermal comfort, this review aims to inform and inspire researchers, practitioners, and policymakers to embrace a holistic and forward-thinking approach in creating indoor environments prioritizing the well-being of occupants [37-40]. Figure 1 shows the co-occurrence analysis of the keywords in literature.

2. Literature review

The search for improved thermal comfort of the built environment has accelerated to a forefront position in architectural and engineering research in view of mounting challenges of climate change, urbanization, and global demand for sustainable living [1, 4, 8-10]. At first, the built environment takes a substantial share of global energy through HVAC systems; therefore, innovative strategies need to be developed in optimizing thermal comfort with minimal energy use. The traditional comfort models, Fanger's predicted mean vote(PMV) and Predicted Percentage Dissatisfied (PPD), have been the mainstay to assess an indoor thermal environment. These have been empirical, using averaged values for many factors such as temperature, humidity, air velocity, and clothing insulation. These models, however, have many criticisms, especially throwing major assumptions toward people's comfort preferences [5-7]. As research in this area continued, adaptive thermal comfort models were developed that recognized people could adapt to a wide variety of environmental conditions. The Adaptive Comfort Model, as is now incorporated into American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55, recognizes the linkage between outdoor climate and indoor comfort. This permits a much more flexible approach to design and operation of HVAC. These improvements reflect the progress away from static and prescriptive models and toward more dynamic, probabilistic methods that consider individual variations in human thermal perception.

The integration of smart technologies in building systems has opened new avenues for the improvement of thermal comfort [1, 4, 8-9]. This has become possible mainly due to the IoT, which has enabled the use of a network of sensors continuously monitoring the indoor environment [3, 24-28]. IoT-enabled sensors track real-time information in terms of temperature, humidity, occupancy, and air quality, from which derivations for dynamic adjustments in HVAC systems can be called forth. BIM enhances this capability by providing an overall framework for the integration of these data streams into the management system [3, 8-12]. BIM software could be used not only for the effective designed building layouts to maximize the thermal performances but also for continuous monitoring and maintaining activities with the help of 3D digital representation.

Further, the use of machine learning in these systems enables modeling rather than operating in an intelligent way so that the building management systems are provided with the change in thermal conditions and constantly setting the new parameters awaiting them [2, 7-10]. These technologies learn from historical data together with weather forecasts and the patterns of occupancy, allowing optimum operation of HVAC for energy efficiency together with maintained comfort levels of the occupants. It has been demonstrated through studies that with AI-enhanced climate control systems, energy consumption can be reduced drastically while actually maintaining or even improving the overall levels of thermal comfort.

A significant step forward in the domain of thermal comfort is the development of individual comfort models [7-9, 15-17]. This infers that conventional model sometimes lacked consideration of individual differences in thermal sensation; thus, most of the time, the occupants did not seem satisfied. To address this gap, the researchers developed various personal comfort models by integrating physiological data of the individual, such as skin temperature, metabolic rate, and personal preferences with wearable technologies, which monitor the real-time physiological responses to the environmental conditions. These devices collect data to shape comfort profiles for use in building management systems, adjusting the indoor conditions automatically according to individual preferences [12-15, 16-18]. This would not only serve the purpose of increasing comfort but also would likely improve productivity and well-being in workplaces.

Another important facet where thermal comfort is assured is through building envelope design [14-18, 20-22]. Advanced insulation materials, like aerogels, phase changing materials, and VIPs, have been developed for increasing the thermal performance of buildings. These materials offer increased resistance to heat transfer, which reduces the dependence on other systems, like HVAC, to maintain indoor temperatures at a desirable level [2, 4, 14-18]. For example, the PCMs are able to take up and release heat during phase change and therefore maintain indoor temperatures over the daily peaks and troughs. Moreover, adaptive facade technologies provide control of heat and light transfer between indoor and outdoor environments in a dynamic manner. These technologies adjust themselves according to the external conditions so that the potential of natural light and ventilation can be maximized while reducing heat gain or loss.

Although so much has been revolutionized due to this, some of the constraints still remain for these thermal comfort technologies [2-4, 17-19]. A very big challenge is in integrating numerous such systems and technologies, especially on domestic applications [2, 24-28]. These result in interoperability problems between devices and systems from different manufacturers if standardized protocols are not taken into account. Besides, this is, at first, a scheme of technology that happens to be expensive in application toward thermal comfort policies, which is a barrier, especially when dealing with old buildings. While it may be easy to appreciate long-term benefits like energy savings and improvements in comfort, the upfront investment might deter some of the stakeholders. User acceptance and behavior remain critical enablers for proper functioning among these technologies [3-7, 29-33]. Occupants must be ready and enabled to interact with any new systems that impose a requirement on their changed behavior or toward greater automation reliance on their part.

3. Methodology

This research paper is centered on improving thermal comfort through cutting-edge design, monitoring, and optimization technologies. The methodology employed for this study revolves around an exhaustive literature review and a bibliometric analysis to amalgamate existing knowledge and pinpoint trends in the field. A methodical exploration of academic databases, including but not confined to PubMed, IEEE Xplore, ScienceDirect, and Google Scholar, was executed. Keywords such as "thermal comfort," "building design," "monitoring technologies," and "optimization strategies" were utilized to unearth pertinent articles. Inclusion criteria comprised the selection of peer-reviewed articles, conference papers, and pertinent books published within a specified timeframe. Exclusion criteria involved disregarding non-English publications, irrelevant topics, and studies lacking empirical evidence. Studies were identified and classified based on their focus areas, such as building design, sensor technologies, and optimization strategies. Network analysis techniques were applied to visualize co-authorship networks, keyword co-occurrence, and citation networks. Relationships between different research entities were scrutinized to identify influential authors, seminal works, and emerging trends. Bibliometric findings were presented through network diagrams, enhancing the clarity and accessibility of the information.

4. Results and discussion

4.1 *Co-occurrence and cluster analysis*

Figure 1 shows the co-occurrence and cluster analysis. This is quite evident from the complex network of interrelated concepts that emanates from the analysis of keywords, thus indicating that there is a multifaceted nature of the research on thermal comfort. This visualization shows the clusters of keywords representative of other scientific studies, all of which are distributed around this central theme of thermal comfort. The largest and most important cluster of green coloration relates back to the keyword “thermal comfort.” The context of these keywords with regard to physiological and environmental factors that mean thermal comfort includes “temperature,” “humidity,” “ventilation,” “thermal sensations,” and “perception.” These terms describe the interdisciplinarity of thermal comfort: human physiology, environmental conditions, and subjective experiences. The presence in the cluster of terms such as relative humidity, atmospheric temperature, and thermal stress would indicate a lot of work put into understanding how different factors affect human comfort. It is especially the condition in the changing climatic scenario. The keyword “urban heat islands” gives reflections on growing interest in how urbanization shapes thermal comfort, which especially affects the densely populated areas, where heat retention remains high and hence more discomfort is found.

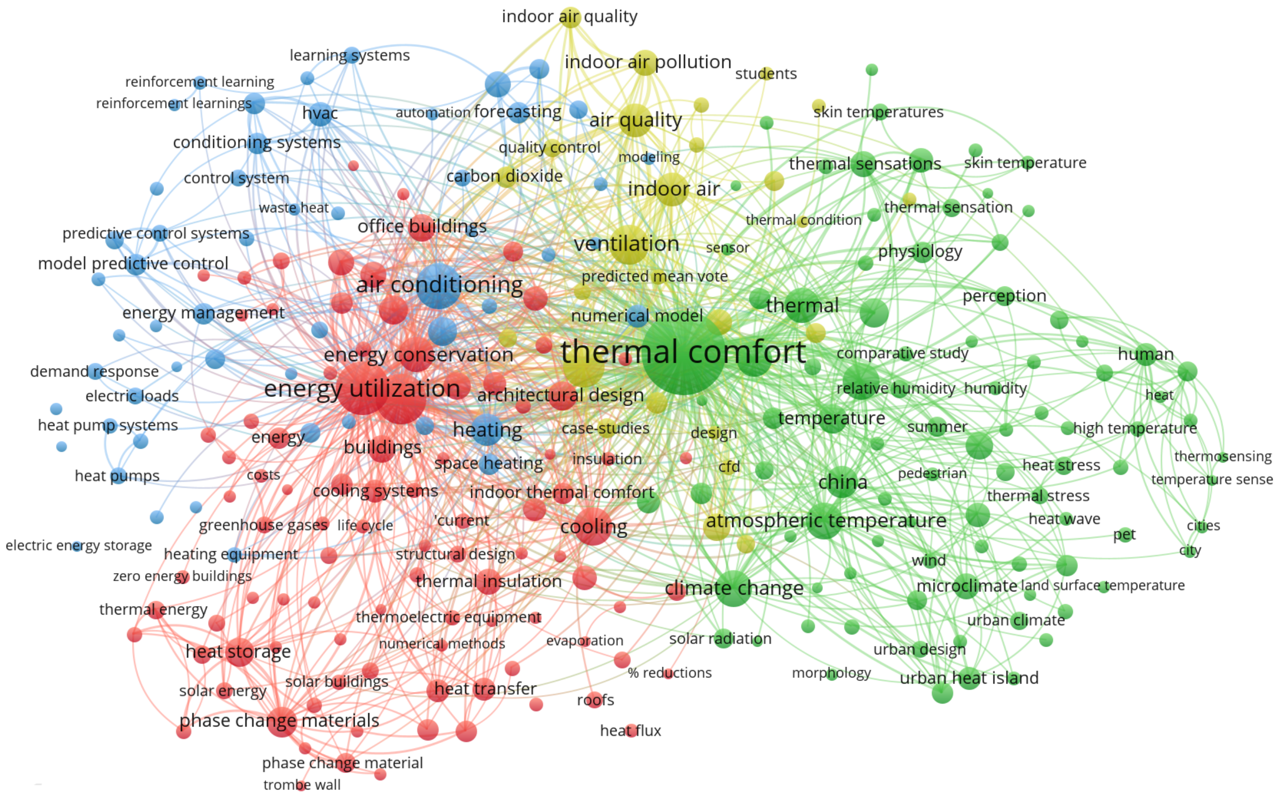

Figure 1. Co-occurrence analysis of the keywords in literature

Next to the central green cluster is the red grouping, which orbits around “energy utilization” and “energy conservation.” Research into this area includes the terms “heating,” “cooling,” “phase change materials,” “solar energy,” and “heat storage,” indicative of technological and material developments to optimize energy use in buildings for thermal comfort. The fact that “buildings,” “architectural design,” and “thermal insulation” are co-occurring predicates within this topic indicates that much of the research in this cluster pertains to the design and development of buildings that are as much energy-efficient as is compatible and, at the same time, comfortable enough for living without waste of energy resources. The strong relationship between “energy utilization” and “thermal comfort” reflects the challenge to ensure comfort in indoor environments while seeking to minimize the use of energy in buildings-a key one in sustainable building design.

This is the technology/system-oriented cluster, which includes “air conditioning,” “HVAC,” “energy management,” and “model predictive control” for enhanced thermal comfort. In so doing, this cluster draws a technological perspective that underlines an approach through the use of such advanced or changing control systems such as heating, ventilation, and air conditioning to provide indoor environments with optimal thermal conditions. Keywords such as “predictive control systems” and “reinforcement learning” were used to show that the research area is currently evolving with many inclusions of artificial intelligence and machine learning techniques focused on the optimization of such systems toward more adaptiveness and efficiency. This cluster has also shown the role of monitoring and forecasting for maintaining thermal comfort for words like “automation forecasting” and “control system.”

Furthermore, the yellow cluster watches “air quality,” “indoor air pollution,” and related terms, for example “carbon dioxide,” “quality control,” and “ventilation.” This basically relates to the knowledge that thermal comfort is not only a function of temperature and humidity but also of indoor air quality. Poor air quality is almost certain to greatly reduce comfort, so it is one of the prime considerations in the design and operation of buildings. The proximity of that cluster to the green cluster of “thermal comfort” itself shows the interlinkage between air quality and thermal conditions in order to achieve overall indoor comfort. Ultimately, keywords such as “climate change,” “urban climate,” and “microclimate” pervade the clusters and quite resonate with an overriding concern: what constitutes the impact of broader environmental changes with regard to thermal comfort? This is where climate-related terms intersect with building design and energy use for a holistic way to tackle the challenges related to climate change in urban setups, prominently noticed with global warming and urbanization.

4.2 *Leading-edge technologies for thermal comfort*

Ensuring thermal comfort is a fundamental aspect of designing buildings and promoting the well-being of occupants [8-9]. The attainment of ideal thermal comfort encompasses the maintenance of appropriate indoor temperatures, humidity levels, and air quality. Recent advancements in technology have been instrumental in significantly enhancing thermal comfort across diverse environments [19, 23]. Table 1 shows the leading-edge design, monitoring, and optimization technologies for Enhancing thermal comfort. Figure 2 shows the flowchart of enhancing thermal comfort through leading-edge design, monitoring, and system optimization technologies.

4.2.1 *Smart HVAC systems*

The regulation of indoor temperatures is pivotal, and Heating, Ventilation, and Air Conditioning (HVAC) systems play a central role in achieving this [41-43]. Smart HVAC systems utilize sophisticated sensors, automation, and connectivity to optimize both energy efficiency and occupant comfort [44-47]. These systems dynamically adapt to changing conditions by leveraging real-time data, ensuring a consistently comfortable indoor environment.

a. IoT-enabled Sensors: Internet of Things (IoT) sensors are crucial for collecting data on temperature, humidity, occupancy, and air quality [28, 32]. Smart HVAC systems leverage this data to make instantaneous adjustments. For example, sensors can detect the number of occupants in a room, prompting the HVAC system to optimize settings and prevent unnecessary energy consumption in unoccupied areas.

b. Machine Learning Algorithms: Incorporating machine learning algorithms into smart HVAC systems enables the analysis of historical data to predict future thermal needs [48-52]. This predictive capability empowers the system to proactively adjust settings based on anticipated changes in occupancy or weather conditions [49, 53-57]. Additionally, machine learning algorithms learn from occupant preferences, customizing thermal comfort settings over time.

c. Zoning Systems: Unlike traditional HVAC systems that treat entire buildings as a single zone, zoning systems divide spaces into smaller, more manageable zones. This allows for precise control over individual areas, enabling occupants to set different temperatures for various zones and thus optimizing both comfort and energy efficiency.

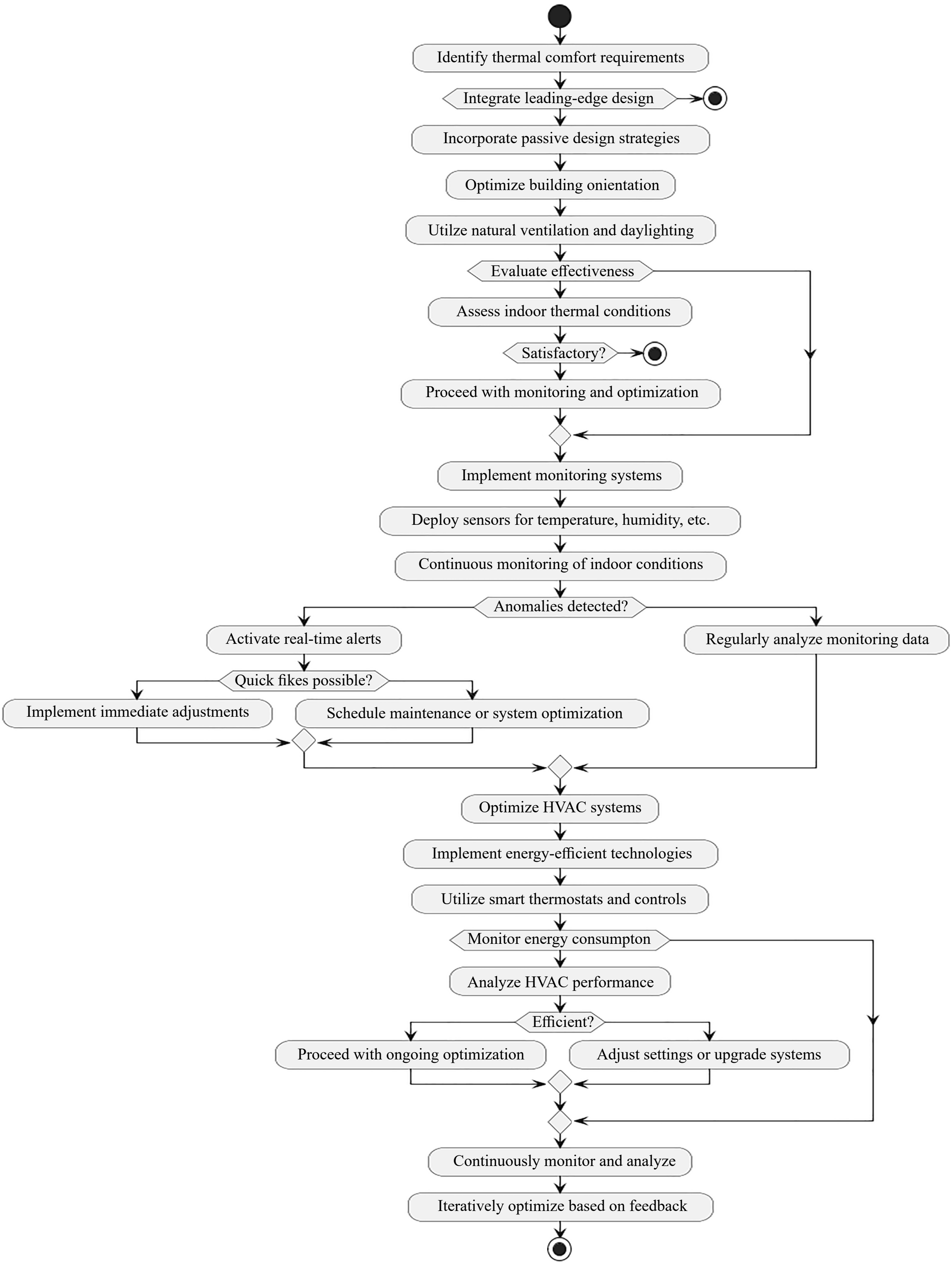

Figure 2. Enhancing thermal comfort through leading-edge design, monitoring, and system optimization technologies

4.2.2 *Advanced insulation materials*

Innovative insulation materials play a vital role in maintaining stable indoor temperatures and reducing dependence on HVAC systems [58-62]. These materials provide enhanced thermal resistance and can be applied in various architectural elements to improve a building's overall thermal performance [63-66].

a. Aerogels: Aerogels, being lightweight and highly porous, possess exceptional thermal insulating properties. Comprising a gel with a gas replacing the liquid component, aerogels effectively prevent heat transfer, contributing to stable indoor temperatures.

b. Phase Change Materials (PCMs): PCMs can absorb and release substantial amounts of heat during phase transitions. Incorporating PCMs into building materials helps regulate indoor temperatures by storing and releasing thermal energy. For instance, PCMs integrated into walls or ceilings can absorb excess heat during the day and release it at night, ensuring more consistent thermal comfort.

c. Vacuum Insulation Panels (VIPs): VIPs, with a core material enclosed in a vacuum, minimize heat transfer through conduction and convection. These thin panels, suitable for space-constrained applications, effectively reduce heat loss, improving thermal comfort in buildings.

4.2.3 *Adaptive facade technologies*

Building facades play a crucial role in controlling heat and light transfer between the interior and exterior environments [67-70]. Adaptive facade technologies utilize responsive materials and intelligent systems to optimize natural light, ventilation, and thermal insulation [71-74].

a. Electrochromic Windows: Electrochromic windows can dynamically adjust their tint based on external conditions, regulating sunlight entering a building. This technology reduces the need for artificial lighting and minimizes heat gain, contributing to energy efficiency and improved thermal comfort.

b. Smart Shading Systems: Automated shading systems respond to changing sunlight and weather conditions to optimize natural light levels and mitigate heat gain. These systems, either programmed or linked to sensors, adjust the position of blinds or shades for optimal thermal conditions and reduced glare.

c. Dynamic Insulation: Some innovative facade systems incorporate materials with adjustable insulating properties based on environmental factors [68, 70]. For example, materials with variable thermal conductivity can adapt to temperature changes, providing better insulation during colder periods and allowing more heat transfer during warmer times [71, 74, 75-80].

4.2.4 *Human-centric environmental controls*

Empowering occupants with control over their immediate environment enhances overall satisfaction and comfort [10-14]. Human-centric environmental controls leverage technology to offer personalized settings, creating a more adaptable and responsive indoor environment [24-28].

a. Smartphone Apps: Mobile applications enable occupants to control various environmental aspects directly from their smartphones, integrating seamlessly with building management systems for effective communication.

b. Personalized Thermal Comfort Systems: Emerging technologies aim to provide individualized thermal comfort experiences. Wearable devices equipped with sensors monitor an individual's body temperature, activity levels, and preferences, adjusting the local environment to create a personalized comfort zone.

c. Voice-Activated Controls: Voice-activated systems, powered by artificial intelligence (AI) and natural language processing, allow occupants to interact with their environment using voice commands. This hands-free approach enhances accessibility and convenience, enabling users to adjust settings without physical interfaces.

4.2.5 *Data-driven building management*

Data collection and analysis are pivotal in optimizing thermal comfort within buildings [12-16]. Data-driven approaches leverage advanced analytics and AI to make informed decisions about HVAC operations, occupancy patterns, and environmental conditions [24-28].

a. Predictive Maintenance: Data analytics predict equipment failures and maintenance needs in HVAC systems.

Monitoring component performance and analyzing historical data enables proactive maintenance scheduling, minimizing downtime and ensuring peak system efficiency.

b. Occupancy Analytics: Understanding space utilization and occupancy patterns is crucial for optimizing HVAC settings. Occupancy analytics, often powered by sensors and machine learning algorithms, provide insights for fine-tuning temperature and ventilation in specific zones, optimizing energy use and comfort.

c. Continuous Monitoring: Real-time monitoring of indoor environmental parameters allows immediate responses to changes in conditions [28, 30, 16-20]. Sensors throughout a building detect fluctuations in temperature, humidity, and air quality, triggering automatic adjustments to HVAC settings to maintain optimal thermal comfort.

Figure 2 provides the flowchart of an integrated approach to enhancing the thermal comfort of buildings with advanced technologies in design, monitoring, and system optimization. This process becomes very relevant in the present context when climate change and energy efficiency requirements have put a premium on the delivery of comfort conditions indoors without depending on traditional HVAC systems. Important steps include:

1) Initial design and planning: The first step should be to employ Building Information Modeling and effective building layouts with respect to the thermal considerations. BIM binds the several aspects of design into a single 3D model, which makes provisions for factors like insulation, shading, and natural ventilation from the initial design stage itself. Here, perhaps one of the most widely used indices to assess thermal comfort is one that would afford the possibility of predicting the degree of overall comfort in relation to variables such as temperature, humidity, and air velocity, known as Predicted Mean Vote model.

2) Passive design strategies to be embedded: From there, it goes on to passive design strategies: orientation, shading devices, materials selection-all strategies aimed at further reducing the energy needs of buildings by allowing maximum natural lighting and ventilation. Thermal comfort is most often tackled at this stage through the Adaptive Comfort Model from ASHRAE Standard 55, which provides that the thermal environment shall be adjusted based on adaptive behaviors of occupants and seasonal changes, so that occupants can feel comfortable without excessive energy use.

3) Monitoring technologies: During the monitoring phase, IoT-enabled advanced sensors will be fitted all over the building, receiving real-time data related to temperature, humidity, occupancy, and air quality. This information shall be provided to Building Management Systems that keep continuously monitoring the environmental parameters and make adjustments accordingly. The Predicted Percentage Dissatisfied (PPD) model would help to estimate at any moment in time the percentage of occupants who may feel uncomfortable, so adjustment is done prior to ensuring comfort is maintained.

4) System optimization: Monitoring technologies gather data that is then processed by Machine Learning Algorithms and AI to predict future thermal conditions against historical data, occupancy patterns, and external weather conditions. This predictive modeling shall optimize HVAC operations to ensure thermal comfort while minimizing energy consumption. At this stage, personal comfort models are integrated, attaining all of the above-mentioned individual physiological data and preferences to personalize comfort settings for different occupants.

5) Adaptive feedback loop: Finally, an adaptive feedback loop-constantly gathering data to be analyzed for refinement of the system’s predictions and settings-is how this flowchart completes. AI, via its Reinforcement Learning techniques, will guarantee that the system learns from each such adjustment toward further comfort and efficiency. The Satisfaction Index is one such advanced metric, comprising subjective occupant feedback and objective environmental data, which are to be used to assess the general success of the whole system in attaining thermal comfort.

4.3 *Utilizing cutting-edge artificial intelligence for improving thermal comfort*

In the pursuit of crafting more intelligent and sustainable surroundings, the integration of cutting-edge artificial intelligence (AI) technologies has emerged as a transformative influence [14-18]. An integral facet of this technological evolution is the refinement of thermal comfort across diverse environments, spanning residences, workplaces, and public structures [2-4, 25-27]. Thermal comfort, a pivotal element of overall well-being, is influenced by variables such as temperature, humidity, air quality, and individual preferences.

4.3.1 *AI-Enhanced climate control systems*

Cutting-edge AI technologies are transforming climate control systems by introducing adaptability and intelligence [14-17, 55-57]. Machine learning algorithms, a subset of AI, scrutinize historical and real-time data to anticipate patterns and optimize heating, cooling, and ventilation systems accordingly. Such systems assimilate insights from user behaviours, external weather conditions, and occupancy patterns to make real-time adjustments, ensuring a harmonious balance between energy efficiency and thermal comfort [14-17, 65-68].

4.3.2 *Sensors and IoT integration*

The Internet of Things (IoT) plays a pivotal role in the AI-driven enhancement of thermal comfort. Smart sensors embedded in structures gather data on temperature, humidity, occupancy, and individual preferences [28, 31]. These sensors establish an interconnected network of devices that communicate, facilitating a comprehensive understanding of the thermal environment. AI algorithms process this data to make informed decisions about adjusting HVAC parameters, resulting in a responsive and personalized thermal experience.

4.3.3 *Predictive analytics for energy efficiency*

The predictive analytics capabilities of AI significantly contribute to energy efficiency in climate control systems. By scrutinizing historical data and considering external factors, AI algorithms forecast peak usage times and adjust heating or cooling systems in advance. This proactive approach not only minimizes energy consumption but also ensures the maintenance of thermal comfort, even during periods of high demand.

4.3.4 *Personalized thermal comfort*

A remarkable advancement facilitated by AI is the ability to personalize thermal comfort settings for individuals [20-25]. AI algorithms analyze data related to user preferences, historical comfort levels, and behavioral patterns to craft personalized thermal profiles [23-24, 37-40]. These profiles seamlessly integrate into smart climate control systems, enabling the environment to adapt to the specific preferences of each occupant [42-45, 50, 55]. This level of personalization not only enhances comfort but also contributes to energy savings by avoiding unnecessary adjustments.

4.3.5 *Adaptive learning and feedback loops*

AI-driven systems excel in adaptive learning, continually refining their models based on feedback loops. Occupant feedback, collected through sensors or direct input, enables AI algorithms to adapt and enhance their predictions and recommendations over time. This iterative learning process ensures that the system becomes more attuned to the unique thermal comfort needs of a particular space and its occupants, fostering a dynamic and responsive environment [68, 70-75].

4.3.6 *Integration with building management systems*

Cutting-edge AI technologies seamlessly integrate with building management systems (BMS), creating a holistic approach to thermal comfort. BMS serves as the central hub for monitoring and controlling various building functions, including HVAC, lighting, and security. AI enhances BMS by providing intelligent insights, optimizing energy consumption, and ensuring that thermal comfort remains a top priority within the broader context of building operations.

Following equations represent fundamental concepts and algorithms frequently used in artificial intelligence [3-5, 11-14, 18, 24-28];

1) Logistic Regression Equation:

$$P(Y=1)=\frac{1}{1+e^{-(mx+b)}} \tag{1}$$

Where,
$P(Y = 1)$ Probability of the dependent variable being 1
e Euler's number (base of the natural logarithm)
m and b Parameters to be learned from the training data.
2) Linear Regression Equation:

$$y = m\,x + b \tag{2}$$

Where,
y Dependent variable
x Independent variable
m Slope of the regression line
b Y-intercept of the regression line.
3) Support vector machine (SVM) decision function:

$$f(x) = \text{sign}(w \cdot x + b) \tag{3}$$

Where,
$f(x)$ Decision function output
w Weight vector
x Input vector
b Bias term
4) Neural network activation function (e.g., Sigmoid):

$$\sigma(z) = \frac{1}{1 + e^{-z}} \tag{4}$$

Where,
$\sigma(z)$ Sigmoid function output
z Weighted sum of inputs
5) Backpropagation update rule for weights (gradient descent):

$$W_{ij} = W_{ij} - \alpha \frac{\partial E}{\partial W_{ij}} \tag{5}$$

Where,
W_{ij} Weight between neuron i and neuron j
α Learning rate
$\alpha \frac{\partial E}{\partial W_{ij}}$ Partial derivative of the error with respect to the weight.
6) Reinforcement Learning - Q-Learning Update Rule:

$$Q(s, a) = (1 - \alpha) Q(s, a) + \alpha (R + \gamma \max_{a'} Q(s', a')) \tag{6}$$

Where,
$Q(s, \alpha)$Value of state-action pair (s, α)
α Learning rate
R Immediate reward

γ Discount factor

$\max_{a'} Q(s', a'))$ Maximum value of the next state-action pair

7) Softmax Function (Multiclass Classification):

$$\operatorname{softmax}(z)_i = \frac{e^{z_i}}{\sum_{j=1}^{K} e^{z_j}} \tag{7}$$

Where,

softmax $(z)_i$ Probability of class i in a multiclass classification

e_z Exponential of the input for class i

$\sum_{j=1}^{K} e^{z_j}$ Sum of exponentials over all classes

8) Bayes' Theorem:

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \tag{8}$$

Where,

$P(A|B)$ Probability of event A given event B

$P(B|A)$ Probability of event B given event A

$P(A)$ and $P(B)$ Marginal probabilities of events A and B

9) K-Means Clustering Objective Function:

$$J = \sum_{i=1}^{k} \sum_{j=1}^{n} || x_j - \mu_i ||^2 \tag{9}$$

Where,

J Objective function (sum of squared distances)

k Number of clusters

μ_i Centroid of cluster i

x_j Data point

10) Gaussian Distribution Probability Density Function:

$$f\left(x|\mu, \sigma^2\right) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \tag{10}$$

Where,

$f(x|\mu, \sigma_2)$ Probability density function of the Gaussian distribution

μ Mean of the distribution

σ_2 Variance of the distribution.

11) ReLU (Rectified Linear Unit) Activation Function:

$$f(x) = \max(0, x) \tag{11}$$

Where,

$f(x)$ Output of the ReLU activation function

x Input to the activation function

12) PCA (Principal Component Analysis) Objective Function:

$$J = \frac{1}{m} \sum_{i=1}^{m} || x^{(i)} - \overline{x}^{(i)} ||^2 \tag{12}$$

Where,
J Objective function (mean squared reconstruction error)
m Number of data points
$x^{(i)}$ Original data point
$\overline{x}^{(i)}$ Reconstructed data point.

4.4 *Modeling approaches for thermal comfort*

Thermal comfort holds paramount importance within indoor environmental quality, exerting profound effects on the well-being, productivity, and overall satisfaction of occupants. Achieving an optimum thermal environment necessitates a profound comprehension of intricate interactions between diverse environmental elements and human physiology.

4.4.1 *Traditional thermal comfort models*

In the past, thermal comfort models relied heavily on empirical relationships derived from field studies [14-17, 24, 57]. Examples such as the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) models, although widely employed for decades, had limitations due to their reliance on averaged data and assumptions of homogeneous comfort preferences within populations.

Recent advancements in modeling approaches have overcome these limitations, ushering in more accurate and personalized predictions of thermal comfort.

4.4.2 *Occupant-centric models*

A notable evolution in thermal comfort modeling is the shift towards occupant-centric approaches. Traditional models treated occupants as passive entities with uniform preferences, while newer models acknowledge the diverse nature of human thermal perception. Occupant-centric models incorporate individual differences in factors like metabolic rate, clothing insulation, and physiological responses, allowing for more personalized and accurate predictions of thermal comfort. One important step toward greater personalization in thermal comfort, human-centric environmental controls directly engage the occupant in the process of control. Modern technologies exploit all possibilities for making the indoor environment more responsive and adaptive to human individual preferences.

4.4.3 *Smartphone apps*

Smartphone applications can be viewed as the most accessible and most frequently used aid for indoor climate management. These are apps that allow one to control the environment about them in terms of temperature, lighting, and humidity from their device. For example, there is an app by Nest that integrates with smart thermostats, enabling users to change temperature settings from virtually anywhere. The Ecobee app for this purpose enables one to control different zones within their home so that each room could be set to a preferred temperature. These often include other features, such as energy usage reports and on/off scheduling, which enhance convenience and efficiency.

4.4.4 *Personalized thermal comfort systems*

The personalized thermal comfort systems go a step further to include real-time data from wearable devices or sensors embedded into them. These track the individual physiological reactions of users to the environment, like their skin temperature, heart rate, or even the amount of sweat they are producing, and adjust the environment accordingly. For example, firms like Dyson have developed personal climate control systems that utilize data from wearable sensors in order to adjust the air flow and temperature on fans or heaters. What this does is guarantee each occupant’s thermal comfort, reducing the chances of discomfort and thus improving general well-being.

4.4.5 *Voice-activated controls*

Artificial intelligence-powered and voice-activated controls, combined with natural language processing technologies, provide a hands-free way for managing environmental conditions. They can be integrated with Amazon Alexa, Google Assistant, or Apple's Siri so that settings can be changed just by issuing relevant voice commands. For instance, one will say, "Alexa, set the thermostat to 72 degrees;" that is what the system will do. This technology will provide more access, especially for the physically challenged and with a few added conveniences that will be more user-friendly for those who don't want to bother with physically changing settings.

Table 1 identifies some of the technologies used in enhancing thermal comfort: Building Information Modeling, state-of-the-art design strategies, monitoring technologies, and optimization methods of systems. The explanation leads to the table, explaining what every one of these technologies does to achieve the optimal thermal comfort through the integration of design and technological innovations. This is summarized in the table, focusing on these core technologies and their applications, which will clearly support indoor environmental quality and energy efficiency.

Table 1. Leading-edge design, monitoring, and optimization technologies for Enhancing thermal comfort

Sr. No.	Technology	Description	Application for Thermal Comfort
1	Building Information Modeling (BIM)	Utilizes 3D models for efficient building design, incorporating thermal considerations.	Optimizes building layouts to enhance insulation and passive heating/cooling.
2	Smart Facade Systems	Dynamic building envelopes adjusting transparency, reflectivity, and insulation based on external conditions.	Maintains indoor comfort by adapting to external weather conditions.
3	Phase Change Materials (PCMs)	Materials absorbing and releasing heat to regulate indoor temperatures.	Integrated into building structures to store and release thermal energy, stabilizing indoor climate.
4	Internet of Things (IoT) Sensors	Wireless sensors monitoring temperature, humidity, and occupancy in real-time.	Enables continuous monitoring and data collection for precise thermal comfort analysis.
5	Thermal Imaging Cameras	Captures infrared radiation to visualize temperature variations.	Identifies thermal discomfort zones, facilitating targeted adjustments to HVAC systems.
6	Wearable Thermal Comfort Sensors	Personal devices measuring individual thermal preferences.	Provides personalized thermal comfort by adjusting local environmental conditions.
7	Building Energy Management Systems (BEMS)	Centralized control systems for HVAC, lighting, and other building systems.	Optimizes energy usage and indoor conditions for enhanced thermal comfort.
8	Machine Learning Algorithms	Analyzes historical data to predict thermal comfort patterns and adjusts HVAC settings.	Adapts HVAC parameters in real-time for optimal thermal conditions.
9	Occupancy-based HVAC Controls	Adjusts heating and cooling based on real-time occupancy data.	Reduces energy waste by focusing on occupied areas, improving overall thermal comfort.
10	Solar Thermal Systems	Collects solar energy for space heating or cooling.	Utilizes renewable energy to maintain comfortable indoor temperatures.
11	Geothermal Heating and Cooling	Utilizes the earth's stable temperature to assist HVAC systems.	Enhances energy efficiency and reduces environmental impact.

a. Adaptive Thermal Comfort Models: Adaptive thermal comfort models recognize occupants' ability to adapt to their environment over time. Considering dynamic factors such as seasonal variations, acclimatization, and individual preferences, models like the Adaptive Comfort Model (ASHRAE Standard 55) and the Adaptive Predicted Mean Vote (aPMV) incorporate the concept of adaptation.

b. Personal Comfort Models: Personal comfort models take customization to the next level by considering individual physiological data, behavioral patterns, and preferences. Leveraging real-time data from wearable technology sensors, these models continuously adjust thermal conditions based on occupants' comfort requirements, with machine learning algorithms enhancing prediction accuracy over time.

4.4.6 *Computational fluid dynamics (CFD)*

Computational Fluid Dynamics has emerged as a potent tool for simulating complex interactions between airflow, temperature distribution, and occupant comfort [14-17, 54-56]. CFD modeling facilitates a detailed analysis of indoor environments, accounting for factors such as air velocity, turbulence, and thermal stratification. Integration with thermal comfort models enables designers to optimize HVAC system performance and indoor air quality. These variables therefore become very important in the description of Adaptive Thermal Comfort Models and Personal Comfort Models since they give detail on thermal comfort beyond what is observable merely through temperature and humidity. These models consider individual physiological responses, behavioral adaptations, and environmental conditions-very important considerations in the optimization of the indoor environment. The variables for the Adaptive Thermal Comfort Model include the outdoor temperature, indoor temperature, clothing insulation, and metabolic rate. These variables are dynamic and therefore seasonal in nature, dependent on the activity levels of the occupants. The adaptive model provides that thermal comfort can be achieved with more flexibility. This model shows that an occupant's ability to adapt to differences in the environment is very important in reducing energy consumption while maintaining comfort. Things underlined in the Personal Comfort Models are personal preferences, historical data of comfort, and real-time physiological feedback, including skin temperature and heart rate. These variables can enable the system to create for each occupant a personalized comfort profile so that it will secure an indoor climate that answers human individuality. These variables can now be continuously monitored with integration of wearable devices and advanced sensors, hence ascertaining more accurate and responsive adjustments in the indoor environment. In expounding on the results from a Computational Fluid Dynamics calculation, it would be appreciable to note that normally, CFD simulations visualize the temperature distribution, airflow patterns, and humidity levels in a space. These simulations help in locating thermal discomfort areas and give a lead time for changes in the HVAC systems or building design. The key variable here is the predicted thermal comfort level, which shall be the enhancing thermal comfort indicator, derived from combined analyses of airflow and temperature distribution. The latter will be directly influenced by both adaptive and personal comfort models to make sure that the CFD results achieve the general goal of minimizing occupants' discomfort.

a. Coupled CFD-Thermal Comfort Models: These models combine CFD simulations with thermal comfort indices, providing a holistic understanding of indoor conditions. By analyzing airflows and temperature gradients alongside thermal comfort parameters, designers can pinpoint potential discomfort areas and implement targeted interventions.

4.4.7 *Machine learning and artificial intelligence*

The integration of machine learning (ML) and artificial intelligence (AI) has revolutionized thermal comfort modeling by leveraging large datasets to identify patterns, correlations, and nonlinear relationships challenging for traditional models to capture.

a. Predictive Modeling: ML algorithms trained on historical data predict thermal comfort outcomes based on various input parameters, enabling real-time adjustments to HVAC settings considering factors like weather conditions, occupancy patterns, and individual preferences.

b. Reinforcement Learning: Reinforcement learning algorithms optimize HVAC system control strategies by learning from feedback loops, ensuring dynamic and responsive thermal environments that adapt to changing environmental conditions and occupant behavior.

4.4.8 *Digital twin technology*

Digital twin technology involves creating virtual replicas of physical environments for real-time monitoring and simulation. In the context of thermal comfort, digital twins replicate building systems and occupants' interactions, providing a platform for predictive analysis and performance optimization.

a. Dynamic Simulation Models: Digital twins allow dynamic simulation of thermal conditions in response to changing variables, accurately predicting and optimizing thermal comfort in real-time by integrating data from sensors, weather forecasts, and occupancy patterns.

b. Sensitivity Analysis: Digital twin technology enables sensitivity analysis to identify influential factors affecting thermal comfort. Designers can use this information to prioritize interventions and investments that have the greatest impact on occupants' well-being.

4.5 *Factor affecting thermal comfort*

The concept of thermal comfort expresses satisfaction with the state of the environment pertaining to temperature [33-34, 47-51]. It is dependent on a complex interrelation of a few environmental or sometimes personal parameters [2, 8-12]. These could be grouped into six main groups: air temperature, radiant temperature, air velocity, humidity, metabolic rate, and clothing insulation. Very important is the knowledge of these factors during the design of spaces: comfort and productivity, especially of work environments, dwelling houses, and public spaces.

4.5.1 *Air temperature*

Air temperature is probably the most recognized factor having something to do with thermal comfort. This is the temperature of the air that the human skin encounters in its surroundings and is measurable by the regular thermometer. The feeling of warmth or cold is a direct consequence of the air temperature. If the air temperature is too high, it might be led to an effect of discomfort, which means sweating and subsequent high body temperature. On the other hand, if the air temperature is too low, chills can occur along with depressed core body temperature. However, preference for air temperature does not equate to achieving thermal comfort. People's perception of temperature can be a result of other factors such as humidity, air velocity, and their individual metabolism. For example, a room with a cooled air temperature of around 22 °C may be quite comfortable for some' but for other occupants, it may be too hot or too cold, relative to those other determining factors.

4.5.2 *Radiant temperature*

Radiant temperature is the temperature developed through the emission of heat from objects and surfaces. It theoretically differs from air temperature due to the fact that it takes place in the absence of the transfer of heat by air molecules, as is the case with air temperature. The radiant temperature implies the infrared radiation from the surfaces, primarily represented by walls, ceilings, and windows. Temperature of these surfaces remains a great factor in causing the sensation of warmth or coolness. For example, even if the air temperature in a room may be acceptable, a cold check is received from the low radiant temperature in the atmosphere-on the contrary: standing next to a warm surface like a heated floor or sunlit wall makes one feel warmer. The human body also radiates heat, and the balance between the heat given off by the body and the heat it absorbs from the environment can influence thermal comfort. Radiant temperature is especially influential in environments with a great deal of glass in walls or close proximity of occupants to bare outer walls, which are generally perceptibly cooler. Air velocity, or the velocity of air over an individual, greatly affects human thermal comfort. Comfort can increase dramatically with very modest air movement, especially in warm conditions. The reason for this is that the movement of air increases the rate of heat loss through convection and evaporation of sweat. At hot conditions, higher air velocities can make people feel the air is cooler than it really is, which is why ceiling fans and ventilation systems work well in improvement of comfort in warm climates. However, in cool environments, high-velocity air can also be distressful because of the cooling effect on human skin, also sometimes referred to as a "wind chill." For that reason, sometimes air drafts from a window or door may have a room temperature feel cooler than the genuine measured air temperature. Towards a person's body would, rather than across it, be of more concern with direction in the blowing air. Air velocity should be properly managed in heating and cooling strategies to ensure human comfort.

4.5.3 *Humidity*

Humidity is the amount of water vapor present within the air, and is a factor in human comfort. Excessive humidity reduces the body's ability to dissipate heat through the process of evaporation resulting in the perception that it is hotter than it really is under high temperatures. This is the reason why miserable, muggy climates feel worse in the summer, when the temperature is the same as a dry climate. A low relative humidity, on the other hand, could make the air feel colder than the actual temperature. It may also cause bodily irritation by drying the skin, eyes, and respiratory tract, providing the feeling of itchiness and irritation. The most comfortable relative humidity usually is from 30% to 60%. Within this range, the air is neither too dry nor too moist, and the body has no problems regulating temperature. Temperature and ambient humidity interact to such a large extent that indices exist for calculating the effective temperature, like, for example, the Heat Index or Humidex. The thermal comfort level in these applications is determined quite appropriately by such indices than by the action of temperature alone, just through the interaction of the humidity levels.

4.5.4 *Metabolic rate*

The metabolic rate is the amount of heat that the body produces from its metabolic processes. It varies according to the person's level of physical activity, body size, and other individual parameters. Accordingly, persons with high metabolic rates would, in the same environment, naturally feel warmer than those with low metabolic rates. Physical activity raises the metabolic rate substantially and, therefore, the internal temperature of the body. At rest, a quiet individual may be comfortable in an ambient temperature of 22 °C, while the same individual exercising to exhaustion may be uncomfortable in the same temperature. This is the basic reason that thermal comfort standards most often take into consideration the activity continuum when setting standards for a comfortable thermal environment. Age, gender, and health are also important, by affecting a body's metabolic rate. For example, a young person has classically a higher average metabolic rate compared to an older person and males usually have a higher topic rate compared to females, leading to variance in comfort preferences. Thereby, knowledge of these variances may explain an approach to design spaces to serve a varied population, so that everyone is able to claim thermal comfort.

4.5.5 *Clothing insulation*

Insulation in clothing and other insulation systems has a basic function in thermal comfort; it creates a barrier to body heat loss or gain to the environment. This influences how the body loses or gains heat. In colder climates, many layers of clothing hold the heat close to the body, helping to maintain a comfortable temperature in the vicinity of the body. In warmer climates, lighter clothing allows heat to escape from the body more easily, keeping the body cool. Thermal resistance of clothing is given in units of "clo," with one clo equal to the insulation needed to maintain a subject at rest at thermal comfort in a room with an air temperature of 21 °C and average airspeed of under 40 mm/sec. The insulation value varies greatly according to the material used and how the clothes are designed. For example, wool and down are highly insulating and optimally used for relatively cold situations, whereas cotton and linen are more breathable and optimally used for warm conditions. Cultural norms and personal preferences also determine what the dress code should be, leading to different perceptions of thermal comfort. For instance, some cultures may experience discomfort in the sense that there is a need to put on official attire-even in conditions of high heat. In contrast, the casual or traditional garments of other civilizations will tend more toward the natural ambient temperature. Clothing insulation should then be factored in when designing the thermal comfort guidelines, particularly in an environment where the dress code is quite strict, or similarly, when one would want to design clothing similar to that for diverse populations with different cultural practices.

4.6 *Challenges associated with implementing new technologies, methods, and models for thermal comfort*

Implementing novel technologies, methodologies, and models to enhance thermal comfort poses a myriad of challenges spanning technical, social, economic, and environmental dimensions [14-17, 24-26].

4.6.1 *Technical complexity*

The primary hurdle in incorporating new technologies for thermal comfort lies in their inherent complexity. Sophisticated heating, ventilation, and air conditioning (HVAC) systems, intelligent sensors, and adaptive control mechanisms demand specialized knowledge for installation, operation, and maintenance. Integrating these technologies into existing infrastructures can be a intricate process, often requiring the reconfiguration of building systems and components. The potential for technical glitches, system failures, and the need for continuous updates further compounds the complexity.

4.6.2 *Cost implications*

Despite the long-term benefits promised by advancements in thermal comfort technologies, the initial implementation costs can be substantial. Upgrading or replacing existing HVAC systems, installing intelligent sensors, and incorporating energy-efficient building materials all entail significant expenses. For many stakeholders, especially in the case of existing buildings, the economic burden of retrofitting may discourage the adoption of innovative solutions. Striking a balance between upfront costs and long-term energy savings is crucial for widespread adoption.

4.6.3 *Interoperability and integration*

The compatibility and interoperability of different technologies and systems present a significant challenge. Many thermal comfort solutions involve a mix of hardware and software components from various manufacturers. Ensuring seamless integration and communication between these components is essential for optimal performance. The lack of standardized protocols and interfaces can lead to interoperability issues, making it difficult for stakeholders to mix and match technologies from different vendors.

4.6.4 *User acceptance and behaviour*

The success of thermal comfort technologies also hinges on user acceptance and behavior. The human factor is critical in achieving energy savings and maintaining occupant satisfaction. Resistance to change, lack of awareness, and insufficient training on how to use new systems can impede successful implementation. Additionally, occupant behavior plays a crucial role in the effectiveness of certain technologies, such as adaptive control systems that rely on user feedback. Overcoming these social and behavioral barriers is essential for realizing the full potential of innovative thermal comfort solutions.

4.6.5 *Data privacy and security concerns*

With the increasing reliance on smart technologies, the collection and utilization of vast amounts of data become inevitable. However, this raises concerns about privacy and security. Smart sensors and HVAC systems often gather sensitive information about occupants' behaviors and preferences. Protecting this data from unauthorized access and ensuring compliance with privacy regulations are paramount. Stakeholders must implement robust cybersecurity measures to safeguard against potential threats and breaches.

4.6.6 *Regulatory compliance*

Building codes and regulations play a crucial role in shaping the adoption of new thermal comfort technologies. However, these regulations can vary significantly across regions and may not always keep pace with technological advancements. Navigating the regulatory landscape and ensuring compliance with standards can be challenging for both technology developers and building owners. The absence of clear guidelines may create uncertainty and hinder the widespread adoption of innovative solutions.

4.6.7 *Environmental impact*

While the goal of implementing new technologies is often to improve energy efficiency and reduce environmental impact, there can be unintended consequences. The production, installation, and disposal of certain technologies may have environmental implications. Assessing the life cycle of these technologies and ensuring that the overall environmental footprint is minimized is a challenge that requires a holistic approach.

4.6.8 *Lifecycle considerations*

Considering the entire lifecycle of thermal comfort technologies is essential. This involves not only the manufacturing and installation phases but also maintenance, upgrades, and eventual disposal. Planning for the long-term sustainability of these technologies and accounting for their entire lifecycle helps minimize environmental impact and ensures that the benefits are realized over an extended period.

4.7 *Summary and suggestions*

Leading-edge design technologies, particularly those involving monitoring and system optimization, have significantly advanced the way thermal comfort is managed in modern buildings. These technologies not only enhance energy efficiency but also improve occupant comfort through more precise control of environmental factors. However, there is always room for improvement to ensure these systems are as effective and efficient as possible.

4.7.1 *Monitoring technologies*

Monitoring technologies involve the use of IoT-enabled sensors that collect real-time data on various indoor environmental parameters such as temperature, humidity, air quality, and occupancy. These sensors provide the data needed for systems to adjust conditions dynamically, ensuring consistent thermal comfort. Advanced monitoring systems can now integrate with Building Management Systems (BMS) to provide a comprehensive view of the building's environmental conditions, allowing for precise adjustments.

4.7.2 *System optimization technologies*

System optimization technologies utilize data gathered by monitoring systems to make informed decisions about how to adjust HVAC operations and other environmental controls. Machine learning algorithms and artificial intelligence (AI) are increasingly used to predict future thermal conditions based on historical data, external weather patterns, and current occupancy levels. These systems can optimize energy usage while maintaining or even enhancing thermal comfort, thus achieving a balance between comfort and efficiency.

4.7.3 *Suggestions for improvement*

4.7.3.1 *Enhanced data integration*

While current systems effectively use data from sensors, there is potential for improvement by integrating a wider array of data sources. For instance, incorporating data from external sources like weather forecasts, energy grid demands, and even social factors (e.g., events that could affect building occupancy) could enhance the system's predictive capabilities. This broader data integration would allow systems to preemptively adjust settings for optimal comfort and energy use, even before environmental changes occur.

4.7.3.2 *Improved user feedback mechanisms*

The effectiveness of thermal comfort systems can be significantly improved by enhancing user feedback mechanisms. Currently, some systems rely on manual inputs from users to adjust settings, which may not always reflect the actual comfort levels accurately. Incorporating more sophisticated feedback tools, such as wearable devices that track physiological responses (e.g., skin temperature, heart rate), can provide real-time, objective data on occupant comfort. This would enable the system to make more accurate adjustments tailored to individual needs.

4.7.3.3 *Adaptive learning algorithms*

Although machine learning is already a part of many optimization systems, the development of more advanced adaptive learning algorithms could further enhance performance. These algorithms should be capable of continuous learning, adjusting not just based on historical data but also on real-time feedback and changing conditions. For example, an algorithm could learn the specific comfort preferences of different users and adapt the environment accordingly, even predicting preferences based on subtle changes in behavior or context.

4.7.3.4 *Integration with renewable energy sources*

As sustainability becomes an increasingly critical concern, integrating thermal comfort systems with renewable energy sources could be a key area of improvement. For example, systems could be designed to optimize thermal comfort based on the availability of solar or wind energy, storing excess energy during peak production times and using it to maintain comfort during periods of low energy availability. This would not only reduce reliance on non-renewable energy but also ensure that thermal comfort is maintained even during energy fluctuations.

4.7.3.5 *Scalability and interoperability*

Another area for improvement is the scalability and interoperability of these technologies. As building sizes and complexities vary greatly, ensuring that these systems can scale effectively while maintaining performance is essential. Additionally, developing standardized protocols that allow different systems and devices to work together seamlessly will be crucial as more buildings adopt these technologies. This will reduce installation and maintenance costs and improve the overall reliability of the systems.

5. Conclusions

In the pursuit of crafting sustainable and comfortable built environments, the incorporation of cutting-edge design, monitoring, and optimization technologies emerges as a promising avenue to enhance thermal comfort. This thorough review has explored various aspects of these technologies, shedding light on their potential impact on indoor thermal environments and the overall well-being of occupants. The cornerstone of any effective thermal comfort strategy lies in considerate and adaptive design. Our analysis underscores the significance of architectural elements such as building orientation, shading devices, and insulation in shaping the indoor thermal environment. By harnessing state-of-the-art design principles, architects and engineers can devise spaces that not only reduce reliance on mechanical heating and cooling systems but also promote natural ventilation and daylighting. These considerations not only enhance energy efficiency but also play a pivotal role in mitigating the urban heat island effect, fostering sustainable urban development. Advancements in monitoring technologies have transformed our ability to comprehend, measure, and optimize thermal comfort conditions. The integration of sensors, smart meters, and data analytics platforms allows for real-time assessment of indoor environmental parameters. This not only empowers building occupants with personalized comfort control but also aids facility managers in making data-driven decisions to improve overall building performance. Through continuous monitoring, it becomes possible to identify patterns, anomalies, and potential areas for improvement, fostering a proactive approach to thermal comfort management.

Furthermore, the advent of the Internet of Things (IoT) has opened up new possibilities in building automation, enabling the seamless integration of various systems to create intelligent, responsive environments. From smart thermostats that learn occupant preferences to dynamic lighting systems that adjust based on daylight availability, the synergy of these technologies enhances occupant satisfaction and reduces energy consumption. Optimization technologies, powered by machine learning algorithms and artificial intelligence, play a pivotal role in ensuring continuous improvement in thermal comfort conditions. These technologies can analyse vast datasets generated by monitoring systems, identify trends, and predict future thermal comfort scenarios. By dynamically adjusting HVAC systems, lighting, and other environmental parameters in response to occupant behaviour and external conditions, optimization technologies offer a proactive and adaptive approach to maintaining thermal comfort. This not only enhances energy efficiency but also ensures that the built environment evolves in harmony with the changing needs and expectations of its occupants. The journey towards enhanced thermal comfort is dynamic, and the integration of these technologies marks a significant stride towards a future where our built environments are not just structures but nurturing and responsive habitats for human flourishing.

Monitoring technologies highlighted the role of advanced sensors, IoT devices, and Building Information Modeling (BIM) in providing real-time data for the continuous assessment and adjustment of indoor environmental parameters.

Optimization technologies highlighted the integration of machine learning algorithms and artificial intelligence for predictive modeling of thermal comfort, optimizing HVAC operations, and minimizing energy consumption.

Sustainable building design showcased how passive design strategies and smart technologies contribute to more sustainable and resilient built environments, particularly in the face of climate change.

Occupant-centric solutions addressed the significance of wearable devices and personalized feedback systems in capturing subjective thermal perceptions, enabling more tailored comfort solutions.

Challenges recognized the barriers to implementing new technologies, including technical complexity, cost, interoperability issues, and user acceptance.

Future outlook suggested the ongoing evolution of these technologies will continue to enhance energy efficiency, occupant well-being, and sustainability in building design.

Conflict of interest

The authors declare there is no conflict of interest at any point with reference to research findings.

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