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Factors Influencing Outdoor Thermal Comfort: A Review

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Abstract

Outdoor thermal comfort holds a pivotal role in the functionality of urban open spaces with these areas contributing significantly to thermal comfort and thereby elevating the overall quality of city life. The influence of thermal comforts on the built environment impacts outdoor activities and may contribute to the decline of environmental quality, posing a complex challenge. Consequently, there is a growing emphasis on outdoor thermal comfort studies, recognizing it as a multifaceted issue shaped by various factors. These factors encompass both direct and indirect influences, such as physical, physiological, and psychological factors, behavioural, personal, social, and cultural factors, as well as thermal history, site characteristics, and expectations. The assessment of outdoor thermal comfort is determined not only by the "physical state" but also by the "state of mind". It involves a static and objective evaluation, considering physical and physiological characteristics that should be measured. This review aims to identify effective parameters and approaches for assessing outdoor thermal comfort studies in urban open spaces. It serves as a valuable reference for researchers, architects, and planners, enhancing their understanding of outdoor thermal comfort and aiding in the creation of thermally comfortable urban open spaces.

Keywords: Outdoor Thermal Comfort, Physiological Factors, Psychological Factors, Urban Built Environment.

Introduction

The increasing urbanization and the impacts of climate change have intensified the necessity to understand outdoor thermal comfort, especially in densely populated areas. Outdoor thermal comfort refers to the subjective satisfaction individuals derive from their thermal environment, which is significantly shaped by various factors, including climatic, geographical, and cultural influences. As urban areas expand, the interaction among these factors becomes more complex, necessitating a comprehensive approach to study and assess thermal comfort in outdoor spaces. Initially, outdoor thermal comfort has been primarily defined through the lens of physiological responses to environmental conditions. Early research focused on identifying key climatic parameters such as air temperature, humidity, wind speed, and solar radiation that affect human thermal comfort. For instance, studies have demonstrated a strong correlation between air temperature and thermal sensation, if temperature increases, thermal sensation increases (1). This relationship underscores the importance of understanding microclimatic conditions, which can vary significantly within urban built environments due to factors like building density and vegetation etc. (2). The integration of objective measurements with subjective assessments has proven effective in capturing the multifaceted nature of thermal experiences (3). This combined approach allows researchers to derive more nuanced insights into individual perceptions and preferences, facilitating a deeper understanding of how different environments impact comfort levels (4). Moreover, the influence of urban design on outdoor thermal comfort has gained considerable attention. Various design strategies have been proposed to enhance thermal comfort in urban spaces. For example, some studies indicated that type of urban morphology, building height, spacing between buildings, and materials can significantly affect microclimatic and, in turn, thermal comfort (5–8). Compact urban forms often provide increased shading and reduce solar exposure, while the selection of materials influences heat absorption and retention (9). The integration of green spaces is also vital, as vegetation can

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alleviate the urban heat island effect, fostering cooler microclimates and improving overall comfort (10). UHI have been carried out for metropolitan (Tier-I) cities in India like Delhi and Mumbai, not much has been analyzed for emerging (Tier-II) cities Lucknow (11). In UHI was identified in different zones of the Ahmedabad city using the satellite and field data. It was indicated that LST was higher near industrial areas and densely built residential and commercial areas of the city (12). Another study in India assessed the LST across various land cover types at macroscale, generating the spatial distribution of UHI in Bhopal (11). Physical parameters that are part of urban canyon geometry profoundly impact UHI (13). However, the effectiveness of these design strategies can vary across different climate regions. For this reason, a current evaluation of the literature on thermal comfort in urban outdoor areas is required in order to comprehend the present status of the research and to identify current issues as well as future research directions. In addition to environmental and physiological considerations, psychological aspects significantly influence outdoor thermal comfort. Social and Cultural background, personal experiences, and individual expectations can greatly shape how different populations perceive thermal conditions (14)**.** Understanding these dimensions is essential for designing urban spaces that meet diverse people needs and preferences. Studying outdoor thermal comfort utilizes a combined approach; objective measurements with subjective questionnaire responses across diverse climatic regions globally. This review paper encompasses published studies that focus on the concept of thermal comfort as it relates to the urban built environment. Key factors such as urban morphology, surface materials, vegetation, and other landscape parameters collectively influence microclimatic conditions, which in turn affect human sensation and perception. Additionally, the interaction of environmental, physiological, and psychological factors plays a crucial role in shaping perceptions of thermal comfort. The subsequent sections provide a thorough overview of the key concepts associated with thermal comfort, including relevant assessment parameters and various approaches.

Relevant Approaches for Outdoor Thermal Comfort

Thermal comfort is defined as "the condition of mind that expresses satisfaction with the thermal environment" (15). Assessing thermal comfort in urban outdoor environments is essential for understanding individuals' thermal experiences and enhancing the overall quality of urban spaces. Many studies highlighted that outdoor thermal comfort is influenced by a variety of direct and indirect factors, including environmental, psychological, and physiological factors (Figure 1). To effectively assess thermal comfort, studies adopt a combined approach that integrates objective measurements with subjective responses collected through questionnaires. This method allows researchers to gather insights into individuals' subjective feelings and satisfaction regarding outdoor conditions. Questionnaires or field interviews can be employed to derive thermal indices such as the outdoor thermal comfort range or neutral temperature, acceptable range through statistical analysis. The primary advantage of utilizing subjective questionnaires is their ability to directly reflect individual sensations. However, this method also faces challenges, as individual differences, psychological influences, and the design of the questionnaire can create variability, complicating the establishment of a standardized measure. Conversely, environmental parameters are typically obtained through meteorological measurement. The weather monitoring system can be used to capture microclimatic parameters such as air temperature, humidity, wind direction and wind movement. By combining both subjective and objective approaches, a more comprehensive assessment of outdoor thermal comfort can be achieved, enhancing the understanding of how various factors interact to affect human thermal comfort in varying outdoor environments.

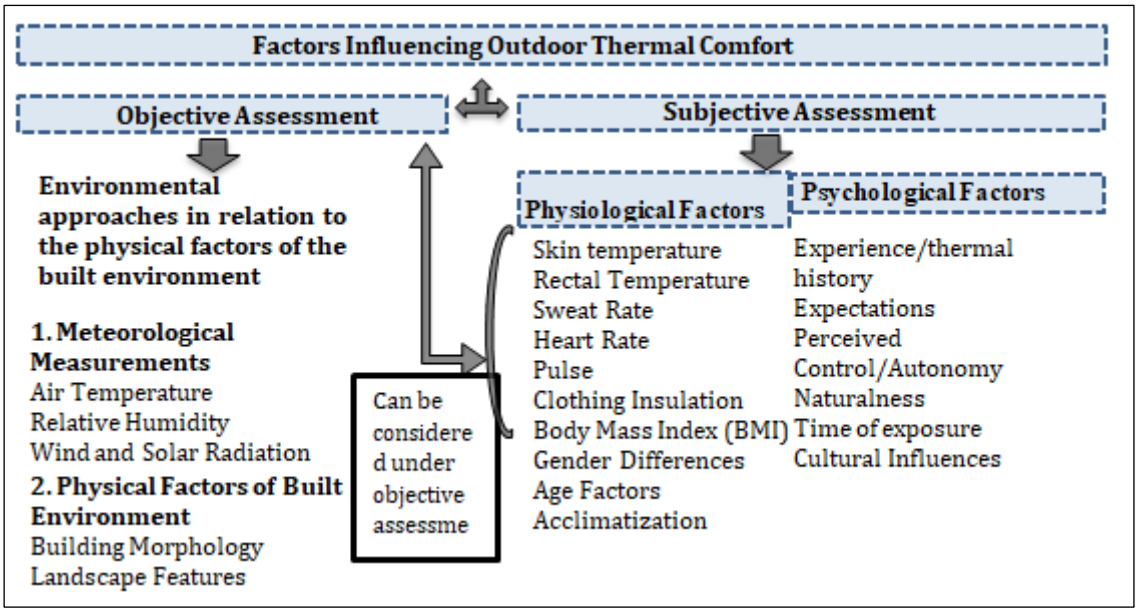

Figure 1: Environmental Approaches in Relation to the Physical Factors of the Built Environment

Analysing outdoor thermal comfort through micro-meteorological measurements and the physical characteristics of the urban built environments is a widely adopted method in urban planning studies. This method focuses on elements of the built environment, including urban morphology and landscape design, while also measuring meteorological variables. Numerous studies highlighted that key climatic factors, such as air temperature, humidity, wind speed, and solar radiation, are essential in characterizing urban microclimates and are crucial to outdoor thermal comfort. Therefore, microclimate of any outdoor spaces is significantly influenced by the physical attributes of the built environment, which in turn directly impacts outdoor thermal comfort.

Environmental Factors/Meteorological Measurements

Air temperature is a crucial environmental factor influencing outdoor thermal comfort. Studies indicates that elevated air temperatures, particularly in urban settings, can result in thermal discomfort and increased heat stress (16). The effect of air temperature on thermal comfort is further moderated by various other environmental elements, including humidity and wind speed. Numerous studies have established that air temperature exhibits the strongest correlation with human thermal sensation, making it the most significant microclimate parameter in this context (13, 17–19). Air temperature has a good correlation with the vegetation cover and H/W ratio (20). Solar radiation is often regarded as the most critical environmental factor that influences outdoor thermal comfort, primarily affecting the body's radiant heat transfer. Direct radiation having the most significant impact on people than scattered and reflected radiation. In outdoor environments, solar radiation is typically represented by the mean radiant temperature (Tmrt), which integrates both long-wave and short-wave radiation. Tmrt is closely linked to the surface temperatures, highlighting the importance of various surface materials like building facades and pavements in shaping thermal comfort. Humidity, particularly the amount of water vapour present in the air, can influence outdoor thermal comfort by hindering the body's cooling mechanisms through evaporation. In regions where high temperatures coincide with high humidity, the body's sweating and heat dissipation mechanisms can be impaired, resulting in discomfort, especially in warm and humid environments (21, 22). However, some studies indicates that the impact of humidity on outdoor thermal comfort may be minimal, suggesting it is one of the less significant factors affecting outdoor thermal comfort (16, 17, 23). Wind speed is another essential environmental element that affects outdoor thermal comfort. It can provide a cooling effect by increasing the body's convective heat loss, contributing to psychological comfort. The influence of wind speed on thermal comfort is shaped by various factors, including air

temperature, variations in wind speed, and the insulation provided by clothing. Numerous studies highlighted that wind is often perceived as more intense in low-temperature climates, likely due to the increased convective heat loss at lower temperatures (24–26).

Physical Factors

The built environment of any outdoor space significantly influences outdoor thermal comfort through various physical factors, including urban morphology, building height, density, and material selection. Numerous studies have explored how these morphological and physical factors affect microclimates and, consequently, outdoor thermal comfort. Specifically, the geometrical and morphological attributes of urban settings have been examined across different scales, including streets, urban open spaces, neighbourhoods, districts, and entire cities. Compact urban forms generally enhance shading and reduce direct solar exposure, while taller buildings may create wind tunnels that improve air circulation but may also obstruct sunlight, leading to varied thermal comfort levels depending on the climate. A research in Maling Village, Henan, China, indicated that denser configurations resulted in higher thermal discomfort due to reduced airflow and increased heat retention (27). In contrast, a study of urban squares in Mediterranean cities found that areas with lower building heights experienced improved thermal comfort due to better airflow and diminished solar exposure (28). Moreover, the choice of materials significantly impacts thermal dynamics; high albedo materials reflect more solar radiation and keep surrounding areas cooler, whereas dark materials absorb heat, leading to higher surface temperatures. A case study in Barcelona, Spain, demonstrated that streets with reflective pavements and lighter building facades resulted in lower ambient temperatures compared to those with darker materials Additionally, integrating vegetation into urban designs - such as green roofs and shaded areas – serves as an effective strategy for enhancing outdoor thermal comfort and mitigating the urban heat island effect (29, 30). Therefore, these findings underscore the intricate relationship between physical factors of any built environment and outdoor thermal comfort, emphasizing the need for thoughtful urban planning that considers these elements to create more comfortable and sustainable environments.

Physiological Factors

Physiological factors play a critical role in determining outdoor thermal comfort, referring to the biological and physical processes occurring within the human body that influence how individual perceives and responds to environmental thermal conditions. These factors operate through mechanisms of heat exchange between the human body and its surroundings, which is essential for regulating body temperature that can significantly affect comfort levels in outdoor settings. The body's thermoregulatory is key to maintaining a stable internal temperature around 37°C. It adjusts blood flow to the skin and triggers sweating or shivering in response to external temperatures. Any deviation from this range can lead to discomfort or heat-related issues. Furthermore, individual differences such as metabolic rate, body composition, and acclimatization to climatic conditions can significantly affect thermal comfort levels. For example, individuals with higher metabolic rates may generate more body heat, making them more sensitive to hot environments, while those who have acclimatized to warmer conditions may tolerate heat better than those who have not. Recent studies have increasingly focused on elucidating the relationship between physiological factors and thermal comfort. Notably, skin temperature serves as a key indicator of thermal comfort, reflecting the body’s efficiency in dissipating heat. Higher skin temperatures can lead to discomfort, particularly in hot and humid conditions, where evaporating cooling becomes challenging (31).

In summary, physiological factors are directly related to the body's responses to thermal stimuli. Therefore, recognizing these physiological factors is crucial for the design of urban spaces that promote comfort and well-being, as they help predict how different populations will respond to thermal stressors in various settings. Skin temperature, defined as the temperature of the body’s outer layer, varies with environmental conditions and serves as a critical indicator of thermal comfort. Changes in skin temperature reflect the effectiveness of heat exchange between the body and its surroundings; higher skin temperatures often signal discomfort in hot

conditions, while lower temperatures may indicate discomfort in cold environments. There are studies highlighting the correlation between variations in skin temperature and perceived thermal comfort in outdoor settings, demonstrating that elevated skin temperatures are associated with increased discomfort. Overall, studies underscore that fluctuations in skin temperature significantly affect individuals' perceptions of thermal comfort, emphasizing its importance in understanding outdoor thermal experiences (32–37). Rectal temperature is widely regarded as a reliable indicator of core body temperature, reflecting the body's internal thermal state and being less influenced by external conditions compared to skin temperature. Significant deviations from normal rectal temperature can indicate thermal stress or discomfort, underscoring its importance in assessing outdoor thermal comfort. For instance, one of the study investigated the relationship between rectal temperature and thermal comfort levels under various outdoor conditions, revealing that physiological parameters beyond skin temperature are often overlooked in outdoor thermal comfort studies (38). Although few studies have confirmed that rectal temperature serves as a dependable measure of core body temperature, the existing research suggests that substantial changes in rectal temperature can lead to thermal stress and discomfort, further emphasizing its relevance in understanding thermal comfort dynamics (39). Sweat rate measures the amount of sweat produced by the body, which is a crucial mechanism for thermoregulation, indicating the body's attempt to cool itself in response to heat stress. A higher sweat rate typically suggests the body is experiencing heat stress, while insufficient or ineffective sweating, particularly in high humidity, can lead to discomfort. For example, some studies examined how sweat rates vary under different thermal conditions and their correlation with perceived comfort levels (40, 41). Their findings highlight that sweat rate is a vital physiological response to heat exposure, closely linked to perceived thermal comfort, especially in humid environments where evaporation is less effective. This underscores the importance of monitoring sweat rate as a key factor in understanding thermal comfort dynamics. Heart rate measures the number of heart beats per minute and serves as an indicator of the body's metabolic response to thermal stress, with elevated rates often signifying increased physiological strain due to exposure to extreme temperatures. Monitoring heart rate can provide valuable insights into overall thermal comfort and stress levels. A study investigated how heart rate fluctuates in response to different outdoor thermal environments, establishing a link between heart rate changes and comfort perception, highlighting the importance of heart rate monitoring as a means to assess individual comfort levels in varying thermal conditions (42). Similar to heart rate, pulse rate reflects the number of heart beats per minute and can indicate the body's response to thermal conditions. A rapid pulse may suggest discomfort or stress due to high temperatures. A rare study has included pulse rate measurements to assess the physiological responses associated with outdoor thermal comfort (40).

Gender Differences: Physiological and hormonal differences between men and women can lead to variations in thermal comfort thresholds. Women generally report feeling colder than men in similar conditions due to differences in body composition and metabolic rates (43, 44).

Age is an important factor that affects how comfortable people feel in different temperatures. As individuals age, their bodies undergo various physiological changes that can affect thermoregulation. Older adults may experience reduced sweat gland activity and diminished cardiovascular responses, making them more susceptible to heat stress and discomfort when it's hot outside. Additionally, older adults may have altered sensitivity to temperature changes, which can further influence their perception of comfort (45, 46).

Clothing Insulation: The type and amount of clothing worn can significantly impact thermal comfort. Different fabrics and insulation levels affect heat retention and evaporation. There are numerous studies focused on clothing insulation for thermal comfort studies (47, 48).

Body Mass Index: Influences thermal comfort, with higher BMI usually have more body fat, which acts like insulation, keeping heat in, potentially leading to discomfort in hot weather (49–52).

Acclimatization: It refers to physiological adaptations to specific thermal environments. Individuals acclimatized to heat may sweat more

efficiently, enhancing comfort in extreme temperatures. Indian studies highlighted the importance of acclimatisation (53). Other studies around the world shown the importance of acclimatization (54–57).

Psychological Factors

Outdoor thermal comfort is significantly influenced not only by physiological and environmental factors but also by psychological aspects, which encompass the mental, emotional, and cognitive aspects that affect an individual's perception of thermal comfort. These factors are subjective and influenced by personal experiences, expectations, cultural background, and social interactions etc. Personal and past experiences or thermal history significantly influence how individuals perceive thermal comfort. Past interactions with different thermal environments can establish an individual's comfort thresholds. This concept has been supported by various studies. For example, someone who frequently participates in outdoor activities during hot weather may develop a higher tolerance for heat compared to someone who is less accustomed to such conditions. Few research reveals that there is a strong correlation between the physiological equivalent temperature PET and ambient air temperature in different climatic setting (51, 52). The neutral PET range can vary in different season (3). This suggests that individuals' perceptions of a season are influenced by their experiences from the preceding season, such as how summer affects perceptions of autumn and winter shapes views of spring. Expectations regarding thermal conditions can also significantly impact perceived comfort. Individuals often form expectations based on prior experiences, cultural norms, and social influences. For instance, if a person expects a particular outdoor setting to be comfortable based on its design or previous visits, they may feel discomfort if actual conditions do not align with those expectations. Studies have shown that discrepancies between expected and actual thermal conditions can lead to feelings of discomfort and dissatisfaction (58, 59). Furthermore, the anticipation of thermal comfort can influence behaviour, as individuals may choose to avoid certain outdoor spaces if they expect them to be uncomfortable. Perceived control, often synonymous with autonomy, is a significant psychological factor influencing outdoor thermal comfort, as it refers to individuals' belief in their ability to influence their environment and make choices that affect their well-being. This sense of autonomy is crucial for psychological health, fostering resilience and effective coping strategies, with studies showing that higher perception of control tend to experience better psychological health, along with reduced levels of anxiety and depression (60). In outdoor settings, individuals who feel they can control their thermal environment such as by seeking shade, adjusting clothing or choosing when to engage in activities - tend to report higher comfort levels. Studies indicate that this sense of control can mitigate the negative effects of extreme temperatures, enhancing satisfaction and reducing stress associated with uncomfortable conditions (61). Furthermore, understanding the role of perceived control has important implications for urban design and public policy, as creating environments that empower individuals through shaded areas, water features, and flexible social spaces can significantly improve thermal comfort and overall well-being (62). Future research should continue exploring the dynamics of perceived control in various contexts to develop effective strategies for enhancing outdoor experiences. Naturalness is a significant psychological factor that influences how individuals perceive and interact with their environments. Some studies define that naturalness as an environment free from artificiality, suggesting that people exhibit a greater tolerance for substantial changes in their physical surroundings when these changes occur naturally (63, 64). This concept is particularly relevant in the context of outdoor spaces, where the natural environment plays a crucial role in shaping human experiences and perceptions. Time of exposure significantly affects how individuals perceive thermal comfort in outdoor settings. For example, the transition from a warm vehicle to a cool building in winter is often accepted without substantial dissatisfaction. This tolerance is particularly important in recreational outdoor areas, where individuals can modify the time they spend based on their comfort levels and personal preferences. The amount of time people choose to stay in different environments can vary widely, but their thermal perception is a key determinant of this choice. Factors such as the individual's current thermal experience and prior exposure to similar

conditions play crucial roles (65). To effectively evaluate and predict outdoor thermal comfort levels among individuals in various regions, it is essential to consider social and cultural factors. Cultural background significantly influences how individuals respond to thermal environments. Various cultures have distinct norms and practices related to comfort, impacting how temperature changes are perceived and reacted to. For instance, in some cultures, higher temperatures may be associated with relaxation and leisure, while in others, they may be linked to discomfort and stress. Studies have demonstrated that these cultural differences can lead to considerable variations in thermal comfort preferences. Individuals who identify as outdoor enthusiasts may adapt better to extreme thermal conditions and tend to spend more time outdoors. The social context in which individuals experience outdoor thermal conditions also affects their comfort levels. Social interactions and company of others can alter individuals' temperature perceptions. For instance, individuals often feel more at ease in warmer conditions when they are in social settings rather than alone (63). The social dynamics present in outdoor areas can foster a sense of belonging and shared experience, helping to alleviate discomfort associated with thermal extremes. Moreover, designing outdoor spaces that encourages social interaction and adopting culturally sensitive approaches can significantly enhance thermal comfort in urban environments.

Discussion

This paper has provided a comprehensive examination of the relevant approaches, and influencing factors that shape outdoor thermal comfort, particularly in urban environments. The integration of objective measurements with subjective questionnaire responses has emerged as a critical strategy for assessing thermal comfort across diverse climatic regions. By focusing on the interplay between urban morphology, surface materials, vegetation, and other landscape parameters, the review highlights how these factors collectively influence microclimate conditions and affect human sensation and perception.

The findings underscore the multifaceted nature of outdoor thermal comfort, which is influenced by a variety of environmental, physiological, and psychological factors. Key environmental elements such as air temperature, solar radiation, humidity, and wind speed were identified as significant determinants of thermal comfort. Furthermore, Physiological factors, including skin temperature, rectal temperature, sweat rate, and heart rate, further elucidate the body's response to thermal stimuli. These indicators are essential for understanding individual comfort levels and highlight the variability in responses based on factors such as age, gender, body composition, and acclimatization. Recognizing these physiological differences is vital for designing urban spaces that promote well-being and comfort. Psychological factors, including personal experiences, expectations, perceived control, and cultural influences, also significantly impact how individuals perceive thermal comfort. The subjective nature of thermal comfort means that psychological aspects can lead to varied perceptions among different populations. For instance, individuals with a greater sense of control over their environment tend to report higher comfort levels, suggesting that urban design can play a significant role in enhancing thermal experiences

Conclusion

In summary, this review stresses the importance of a holistic approach to evaluating outdoor thermal comfort. By combining objective and subjective methodologies and considering the intricate interplay of environmental, physiological, and psychological factors, urban planners and designers can create more comfortable and sustainable outdoor spaces. Future research should continue to explore these dynamics, developing strategies that effectively address the diverse needs of urban populations while fostering environments that promote thermal comfort and overall well-being. This integrated understanding of outdoor thermal comfort is essential for advancing urban planning practices in an era of climate change, where the demand for resilient and adaptive public spaces is increasingly urgent.

Abbreviation

TMRT: Mean Radiant Temperature.

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Author Contributions

Swetika Porwal: Conceptualization, Writing, Study Design, Manuscript Draft, Shailendra K. Mandal: Review, Refine, Subhrajit Banerjee: Review, Refine.

Conflict of Interest

The authors declare that there is no conflict of interests regarding the study or this article.

Ethics Approval

This review did not involve any original research with human participants or animals; therefore, ethical approval was not required. All sources and studies referenced have been cited properly to ensure transparency and integrity.

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