International Research Journal on Advanced Engineering and Management
https://goldncloudpublications.com
https://doi.org/10.47392/IRJAEM.2025.0033

e ISSN: 2584-2854
Volume: 03
Issue:02 February 2025
Page No: 194-202

Exploring the Interplay Between Urban Morphology and Microclimate in Urban Heat Island Formation

Deepti Pande Rana[1], *Abhinav Tripathi*[2], *Samreen Siraj Siddiqui*[3], *Sidra Sabahat*[4], *Rituparna Chattopadhaya*[5], *Sayan Munshi*[6]

[1,2,3]*Associate Professor, Amity School of Architecture and Planning, Amity University Uttar Pradesh, Lucknow campus, India.*

[4]*Assistant Professor, Integral University, Uttar Pradesh, Lucknow, India.*

[5]*Assistant Professor, Lovely Professional University, Phagwara, Punjab, India.*

[6]*Assistant Professor, Amity School of Architecture and Planning, Amity University, Kolkata, India.*

Email ID: *dprana@lko.amity.edu*[1], *sssiddiqui@lko.amity.edu*[2], *atripathi3@lko.amity.edu*[3], *sidras@iul.ac.in*[4], *sonairisha@gmail.com*[5], *sayanmunshi.m@gmail.com*[6]

Abstract

It has been observed that the formation of urban heat islands depends on a lot of factors like meteorological conditions and specific characteristics of a city. Among the major contributors to the creation of an urban heat island are urban parameters like the usage of materials of low albedo, design of urban geometry, high population density, and presence of anthropogenic heat sources together aggravating the problem. The phenomenon of urban climate is becoming more and more complex at both local and global levels due to its multiple interconnected variables. Such elements include the built environment, strategies for urban design, urban morphology, building density, coverage with vegetation, height and orientation of buildings, distance between buildings, exposure to sunlight on road surfaces, and wind patterns. Each of these factors plays a critical role in determining the thermal dynamics of urban areas. For example, street-level wind velocities can significantly influence the development of a city's thermal microclimate by either facilitating or hindering the dispersal of heat. The interaction of these factors results in the amplification of heat retention within the urban environment, often leading to a noticeable temperature difference compared to surrounding rural areas. The objective of this paper is to examine and synthesize earlier studies about the relationship between the shape of urban morphology and its influence on the microclimate, especially with regard to the development of urban heat islands. The better the dynamics at play are understood, the better urban planners and environmental scientists can address and mitigate the effects of urban heat islands.

Keywords: *Urban Heat Islands, Urban Morphology, Microclimate, Anthropogenic Heat, Meteorological Factors, Urban Climate*

1. Introduction

Cities are the core of economic and population growth, as such, mainly facilitated by the new areas developed within their boundaries, due to increasing population, economic activities, and infrastructural developments in those areas. However, this increase causes higher temperatures in urban areas, therefore bringing about differences in the microclimates of the urban areas. The urban environment mainly influences the city's microclimate through factors such as layout and shapes, population density, water supply, and types of surfaces. These generally affect the retention and distribution of heat in city spaces, especially in open areas (Shishegar, 2013). Oke's parametric model of urban heat islands brings to the fore a direct relationship between population density and growing urban temperatures. In other words, as cities expand in terms of both population and built-up areas, the strength of the urban heat island effect strengthens, affecting the environmental outcome negatively. This is because increased urbanization is usually accompanied by more heat entrapment within the dense infrastructure, including buildings, roads, and pavements. Therefore, temperatures in urban areas are significantly higher than in the rural environment. Furthermore, this warming effect drastically results in increased energy demands as buildings need more during hot temperatures and significantly more during cold temperatures to warm and heat more respectively (Oke, 1981). This cycle of increasing temperatures and higher energy consumption calls for attention to urban heat islands in sustainable city planning and energy management. Various research studies have been done on outdoor thermal comfort, impacts of urban canyon building heights, and their relevant objectives and analysis techniques in different parts of the world [1-4]. Some of the key studies in this field are those by Oke (1981), Bärring et al. (1985), Kusaka and Kimura (2004), Takebayashi and Moriyama (2012), Allegrini et al. (2012), Shishegar (2013), Dallman et al. (2014), Gál (2014), Haizhu et al. (2020), M'Saouri El Bat et al. (2020), and Mughal et al. (2020), among others. Each of them is specialized on other aspects of urban morphology, building height, and their influence on the urban microclimate, bringing forward different research findings into how the built environment influences outdoor comfort levels. This paper reviews and synthesizes all existing literature and current evidence relating to the morphology of urban buildings and their geometric characteristics in association with urban microclimates, shown in Figure 1.

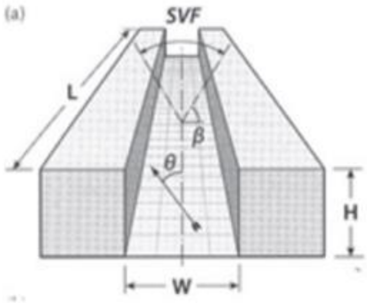


Figure 1 **L, B & H in the Canyon and its SVF**

There is a focus on understanding the outdoor thermal comfort of urban road canyons, which has effects due to airflow, exposure to sunlight, and directional variations within these factors in the urban road canyon environment. This white paper is a synthesis of the research at hand and seeks to offer a deeper understanding of how the urban design affects thermal comfort in public spaces and dynamic interactions between building geometry and environmental conditions with human comfort. The concept of the Urban Street Canyon is primarily defined by the relationship between the height and width of the canyon, commonly referred to as the Height/Width (H/W) ratio. An Urban Street Canyon is typically formed by the alignment of streets, sidewalks, or two parallel, vertically oriented structures that extend indefinitely, creating an open space within an urban environment. Shishegar (2013) divided urban road canyons into three categories by their aspect ratio: uniform road canyons, shallow road canyons, and deep road canyons. They are differentiated according to the walls' aspect ratio. Uniform canyons have an aspect ratio of 1, shallow canyons an aspect ratio of less than 0.5, and deep canyons are distinguished by an aspect ratio greater than 2, shown in Figure 2 [5-8].

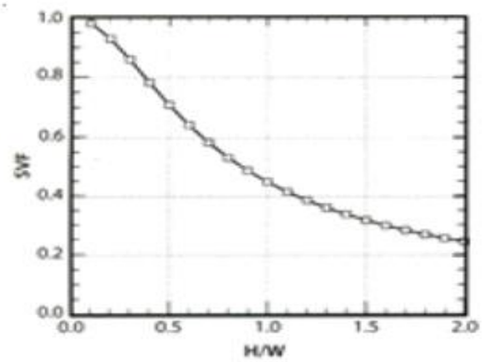


Figure 2 **Relationship of H/W & SV**

Another term describing an urban canyon type is a leeward canyon wall-the downwind-facing slope of a canyon where it provides an unhindered flow on its roof in air rising between building rows and flows up under it (Letzel et al., 2008). Besides Canyon Length-L-denotes canyon size and groups into several subclasses regarding the relative dimension of L against the urban road canyon's height. According to Shishegar (2013), short canyons have an L/H ratio of 3, medium-length canyons have an L/H ratio of 5, and long canyons have an L/H ratio of 7. These categories help in the understanding of different spatial and environmental characteristics that impact the microclimate within urban road canyons. Figures 1 and 2 show some examples of these canyons in an urban road environment, which gives a picture of these various canyon types [9-12]. The impact of urban canyons on microclimates has been widely researched, and many scientists have pointed out their significant role in local environmental conditions. Oke's work (1981) states that urban canyons are the primary factors in determining the microclimate of cities. The surfaces within these canyons, combined with the vegetation, are in a constant cycle of absorbing and reflecting heat, which contributes to the transfer of heat within the environment. It takes the entire cooling cycle, in metropolitan places after dusk more extended, when compared with countryside regions due to this intensifying of urban heat island effects. Bärring et al. (1985) discuss the sky view factor and the nocturnal conditions of urban canyon in Malmo, Sweden, where they discussed the impact on the formation of temperature patterns differentially across city streets due to the layout and geographical arrangement of streets. Here, it shows that the effect of urban form is very decisive in the way thermal dynamics are carried out in an urban environment.Moreover, Allegrini et al (2012) further proved that the urban street canyon's microclimate plays a major role in building energy use, especially in heating and cooling. This implies that if energy efficiency is considered in the design of a city, it must have knowledge about the thermal response of urban spaces. Morgati et al. (2018) has conducted research work in the Mediterranean region, where urban morphology indices have been applied to analyse the potential solar energy. That work further presented the intersection of both urban design and environmental factors - especially related to energy optimization. In 2014, Ann Dallman and colleagues have discussed how factors of resilience impact heat circulation in an urban canyon in changing environmental conditions. The researchers presented two scenarios for their study. The first was naturally heated walls that were not significantly affected by thermal input from the ground surface. The second scenario analyzed the temperature conditions of a 2D canyon using theoretical models. This research work provided much insight into the dynamic nature of heat flow in urban canyons. A great study that deserves mentioning was made by Bakarman and Chang in 2015, to discuss the thermal performance of deep urban canyons against shallow canyons with two different scenarios for Riyadh in Saudi Arabia: the hot desert. The investigated two canyons were an older deep one, with H/W = 2, against a modern and more shallow canyon, with an H/W of 0.42. Their results showed that the orientation of the roadway (NS-SW) and the H/W ratio within the canyon had a strong impact on ambient air temperature. The study demonstrated that with decreasing H/W ratio, the strength of the urban heat island effect increased, and ambient air temperatures were 5% warmer in shallow canyons compared to the surrounding rural areas. In addition, the shallow canyons were found to be 15% warmer than the surrounding countryside, thus underlining the significant role of urban canyon geometry in shaping local microclimates. These studies collectively portray the complex relationship between urban form, heat distribution, and energy dynamics in the city. All these relationships form a basis upon which strategies must be developed in order to combat the effects of urban heat islands and improve urban sustainability and resilience. Understanding wind flow in urban canyons is critical for the management of dispersion of heat and pollutants.

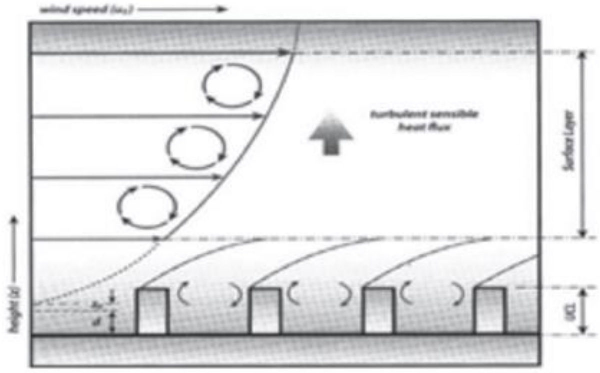
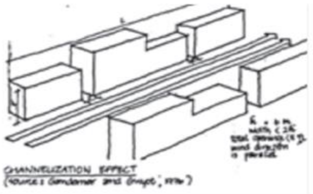
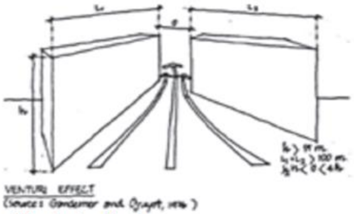


Figure 3 The Removal of Sensible Heat from a Built-Up Urban Surface by Wind Turbulence

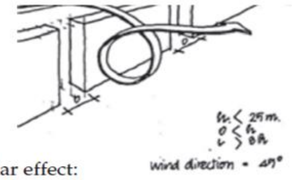
The design of the built environment significantly affects the wind movement within such urban spaces; hence, there are considerations with regards to streets and buildings arrangements. Some major factors such as wind speed and direction are used in the regulation of airflow within the urban canyon. As various studies have pointed out, the elements that contribute to how wind flows through urban canyons include the presence of vegetation, the height, shape, and size of buildings, the scale and configuration of openings, and the prevailing wind direction. In urban areas, wind turbulence aids in the removal of sensible heat from surfaces, especially those that are highly built up. This is depicted in Figure 3, which shows how wind turbulence aids in the dissipation of heat from urban surfaces. The principles of fluid dynamics, such as channelization, the Venturi effect, and the Bar effect, can be applied to better understand the movement of wind in these urban canyons. These principles can explain how wind is funneled through narrow urban spaces and enhance or reduce heat and pollutant dispersal, as demonstrated in Figure 4. The dynamics of these factors can provide useful insight into the way urban design impacts air quality, thermal comfort, and the overall urban microclimate. Channelization Effect: In urban canyons, wind tends to follow the direction of the canyon itself and this is called channelization effect. The channelization effect is very efficient in removing the pollutants from the space; however, it might create uncomfortable conditions for the occupants of the space.



Channelisation effect:



Venturi effect:



Bar effect:

Figure 4 **Effects of Wind Movement for Dispersing Heat and Pollutants**

The strength of this impact depends on several factors, including the wind speed, the total length of the canyon as well as average width, and height. Combined, these elements help in establishing how effectively the wind can traverse the canyon to flush off contaminants as highlighted by Das (2013). Venturi Effect. This is caused by the presence of wind flowing through narrow opening areas within a canyon. Due to this factor, the flow velocity increases, producing a funnel-like effect. Since the wind flows faster, people will find this environment uncomfortable because of the accelerated speed. Nonetheless, it contributes greatly to enhancing the dispersion process of pollutants in the air. The extent of the Venturi effect is determined by many factors including width, length, height, and the size of openings in the canyon. This characteristic is where the size that the wind speed is amplified impacts how well it carries the pollutants away as shown by Das (2013). Bar Effect: Air flows past the leeward side of a street canyon at an angle of about 45 degrees, in the bar effect. The combined effect is brought about by several factors, which include the width, length, and average height of the walls of a canyon, and the size of the openings of a canyon. These variables play a significant role in shaping how the air moves through the canyon and how effectively it disperses heat and pollutants (Das, 2013). The aspect ratio is the ratio between the height and width of the canyon. Such a ratio enables one to recognize different airflow patterns, including isolated roughness flow, wake interference flow, and skimming flow as depicted in Figure 5. Isolated roughness flow is established when the air currents along the windward and leeward directions do not interfere with each other. This mostly occurs because wind is diverted along a barrier or an obstruction. Shishegar (2013) explained such an occurrence. In addition to the Bar effect, other factors that influence how airflow behaves within the urban canyon include the specific roadway pattern, wind direction, canyon geometry, building spacing, presence of vegetation, and local wind speed. All these elements can modify the wind dynamics within the canopy layer, producing different patterns of airflow that impact thermal comfort and pollution dispersion. Figures 6, 7, and 8 represent the various wind flow patterns produced by these factors, which would be very effective in visualizing the way wind movement is affected by the urban environment.

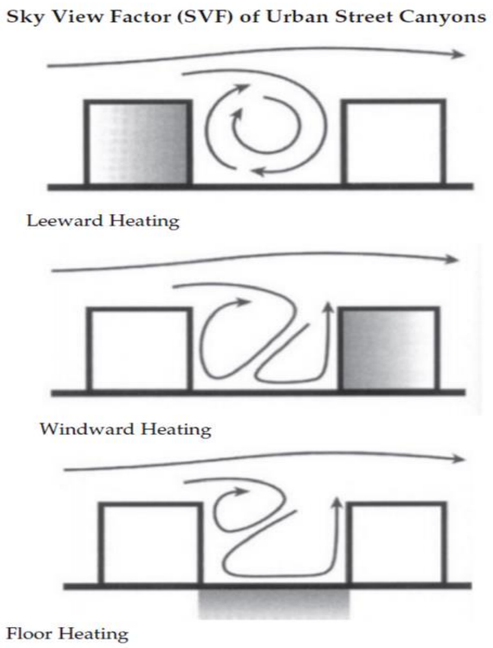


Figure 5 **Wind Flow Pattern Based on Heating at Different Sides of the Canyon**

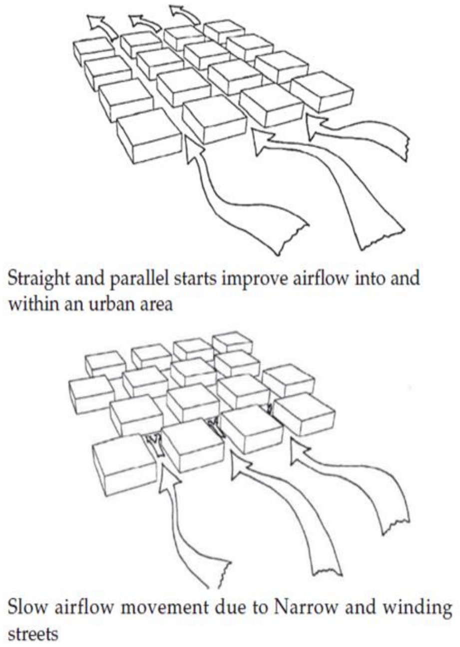


Figure 6 **Street Design and Orientation Influence the Design of Wind Penetration into the City**

Wei et al. (2016) reported that obstructions in the sky can delay ground cooling significantly during clear, calm evenings. These obstructions prevent the efficient release of heat from the ground, leading to higher nighttime temperatures. Oke (1988) further explored this relationship, suggesting that in basic urban canyons, the height-to-width ratio of the canyon is directly linked to the sky view factor (SVF). The SVF is the fraction of the sky that is visible from a given point in the canyon and is an important factor in controlling the thermal regime of the area. Oke proposed a procedure for determining the SVF (Figure 6), (Figure 7). This procedure would take into consideration the geometry of radiation at the central point in the canyon cross-section, as indicated in Figure 8. Simply put, the SVF determines the ratio of radiation received or emitted by a flat surface against the total amount of radiation received or emitted from the entire hemispheric environment above the given point (Wei et al., 2016). Wai et al. (2016) conducted an investigation of the effect of various urban morphological parameters, such as building height, street width, and orientation, on the microclimate in an urban area. Their work sought to establish ideal ranges of parameters that could promote thermal comfort for pedestrians in cities. The significance of the research lies in its relevance to the relationship between city design and layout and human comfort in terms of temperature.

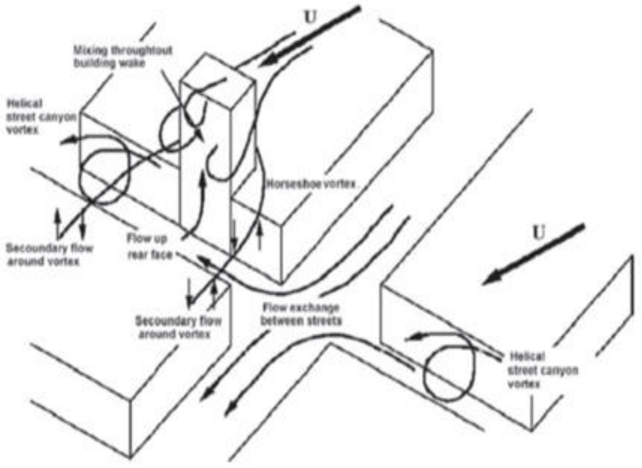


Figure 7 **Wind Flow Pattern at The Street node with Varying Shape Size, and Height of a Building**

Moreover, Chen and Ng (2009) applied the GIS-based approach in Hong Kong to analyze the SVF of street canyons and their implications on the intensity of the UHI effect. This study showed how urban canyon geometry relates to UHI intensity, using the variation of the sky view factor to understand the local temperature patterns and thus the overall thermal dynamics of the city.

2. Urban Density Parameters

The Space-mate tool is introduced by Pont, M.B.; it takes density indicators, incorporating different indications toward characterizing geometry in urban situations, as highlighted in Figure 9. For the definition of the urban environment through a set of key density variables-Floor Surface Index (FSI), Ground Space Index (GSI), Open Space Ratio (OSR)-and Layers, these are applied as major essential metrics that represent the method and prescription toward descriptions and characterizations of diverse situations in an urban environment. The Space-mate tool analyzes the FSI, GSI, OSR, and L to explain how the geometry of an urban site can be differentiated from others.

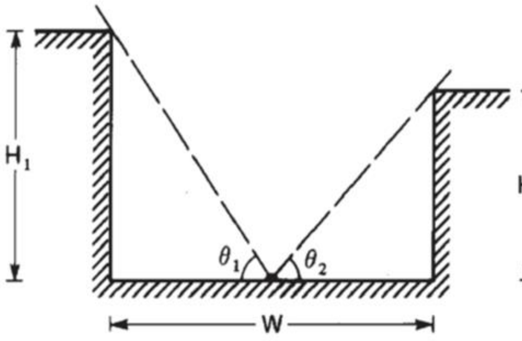


Figure 8 Geometry of an Unsymmetric Canyon flanked by Buildings 1 and 2

The FSI is the ratio of the total floor area of buildings to the area of land they occupy, while the GSI measures the proportion of ground space covered by buildings versus open areas. The OSR indicates the amount of open space relative to the built environment, and the Layers parameter considers the vertical aspect of urban development, such as the number of building floors or levels. These indicators, when combined in the Space-mate tool, enable a comprehensive understanding of urban density and its relationship to the form of the urban environment. Numerous studies have studied the influence of urban density on the UHI effect. Examples of researchers that have investigated the contribution of different factors of urban density to intensify heat in cities include Hu et al. (2016), Wei et al. (2016), Bagan et al. (2018), Kim and Guldmann (2014), and Singh and Singh (2018). Their research identifies the role of urban geometry and density in determining microclimates, with particular emphasis on the design and spatial arrangement of buildings that may be exacerbating or mitigating UHI effects. These studies emphasize the need to employ detailed urban density parameters to further understand and control the thermal dynamics of urban areas.

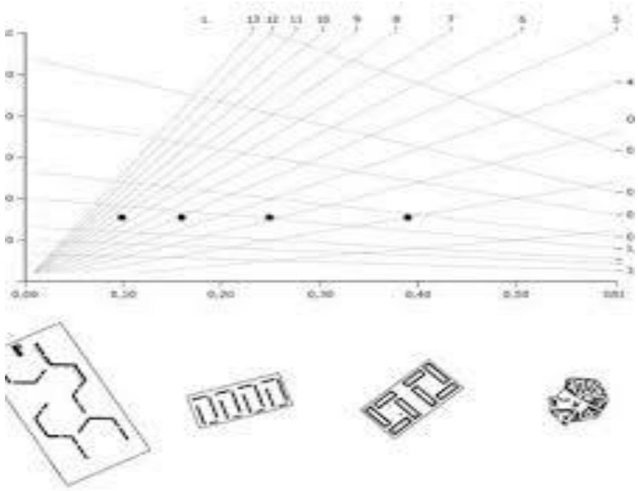


Figure 9 Illustrates How Pont, M.B., Defined and Characterized the Urban Geometry with a Variety of Density Indicators as Part of His Space-Mate Tool

Such a tool forms a framework of understanding an urban environment through the key density variables in the form of FSI, GSI, OSR, and L. These parameters can be used to describe and prescribe different urban environments by evaluating the spatial distribution and arrangement of buildings and open spaces. The FSI is the ratio of the total floor area of buildings to the land area they occupy, thus giving insight into how much space is used for built structures. The GSI measures the proportion of land covered by buildings in relation to open areas, thus giving a sense of the density of the built environment at ground level. OSR is the open space to the built-up areas, and thus it measures how much open space is accessible in the urban environment. The final one is Layers (L), which refers to the vertical dimension of urban development, including the number of floors or levels of buildings, adding to the density and spatial distribution of the urban landscape. Combining these indicators within the Space-mate tool helps to build an overall description of a site's geometry, allowing for differentiation among various urban areas based on their spatial and density characteristics. This tool enables planners and researchers to evaluate the specific characteristics of the urban environment and how their geometrical configurations influence such factors as heat distribution, airflow, and human comfort. Many researchers have assessed the effects of urban density on the UHI effect, including Hu et al. (2016), Wei et al. (2016), Bagan et al. (2018), Kim and Guldmann (2014), and Singh and Singh (2018). Others are studies on how part of the aspects of urban density, including distribution of buildings and open spaces, vertical development affects the temperature regulation for intensification of the UHI effect. The findings essentially show how understanding the aspect of urban geometry in trying to curb heat buildup enhances thermal comfort among city residents [13-15].

Conclusion

This study explores the impact of urbanization on microclimates, with a focus on the key factors determining the features of urban microclimates. By example, the research shows how street geometry and built form configuration, which form an integral part of the design of streets and cities, can affect environmental conditions at the local level. Properly planned street and urban design may either counter or enhance disadvantageous features, such as heat concentration and low air exchange. Indeed, the geometry of urban spaces will have a serious impact on not only two aspects but also significant elements: that is, air flow and the exposure to the sun. Thus, these have a direct role in how airflow occurs in a street, by which buildings warm up or cool down, as well as strengthen or weaken heat island effects throughout the urban morphology. The height-to-width (H/W) ratio, the length-to-width (L/W) ratio, and building density are particularly strong factors in deciding the intensity of the UHI effect. More intense H/W ratios, in which buildings are taller and more closely spaced, tend to retain more heat than lower ratios with wider streets and shorter buildings that allow for better airflow and sunlight exposure. Additionally, the density of buildings, or their occupancy levels, also contributes to the buildup of heat in urban spaces. The combination of these factors can either aggravate the UHI effect, leading to higher local temperatures, or help mitigate it by promoting better ventilation and increased shading. Maximization of the benefits of shading and reduction of the amount of direct sunlight that contributes to heat accumulation requires proper orientation of urban streets. Streets oriented in north/south, northeast/southwest, or northwest/southeast directions are the most effective for optimal shadowing across urban canyons, especially during the hottest times of the day. Orientation helps ensure buildings remain shaded, reducing the need for artificial cooling and improving outdoor comfort for pedestrians and residents. The third key element affecting the microclimate is wind flow in urban canyons. The sky view factor (SVF) which refers to the fraction of sky visible from ground level in an urban canyon plays a very essential role in determining wind flow and heat dissipation. With a high SVF, this implies more openness at street levels, thereby causing easier circulation of wind and lower concentrations of heat. Research has also found that the arrangement of the town and street patterns in an irregular or seemingly random pattern can be more efficient to create stronger airflow and better wind flow rather than uniform or grid-like street alignment. This could mean that horizontal randomness, such as changing direction and spacing, helps improve wind flow better than vertical randomness, or random building heights. There must be sufficient sunlight and natural ventilation access in designing urban canyons to achieve a healthy urban microclimate. The balance needed between sunlight, wind, and the distribution of heat is crucial to maintain a comfortable outdoor environment. Urban design is considered thought-provoking where sunlight, wind, and the distribution of heat interact with one another to lower the reliance on artificial heating and cooling, subsequently reducing energy consumption. Moreover, it may be useful in helping mitigate the effects of the urban heat island, often associated with unbearable living conditions, increased energy bills, and bad environmental effects. Lastly, the importance of integration of urban geometry and environmental factors in city planning should be put at the center. By keenly considering all aspects such as street orientation, building density, and wind flow, urban designers can design more resilient cities which become more energy efficient and comfortable places for residents in the face of climate change. The findings, therefore, mean that urban designs should be given priority both as functional and sustainable spaces that meet their challenges in response to urban heat, pollution, and the requirement for energy-saving. Through these measures, cities can become more livable, healthy, and sustainable in the face of growing urban populations and the effects of climate change.

References

[1]. Bagan, H., Li, H., Yang, Y., Takeuchi, W., & Yamagata, Y. (2018). Sensitivity of the subspace method for land cover classification. The Egyptian Journal of Remote Sensing and Space Science, 21(3), 383–389. https://doi.org/10.1016/j.ejrs.2017.12.003

[2]. Bakarman, M. A., & Chang, J. D. (2015). The Influence of Height/Width Ratio on Urban Heat Island in Hotarid Climates. Procedia Engineering, 118, 101–108. https://doi.org/10.1016/j.proeng.2015.08.408

[3]. Bärring, L., Mattsson, J. O., & Lindqvist, S. (1985). Canyon geometry, street temperatures, and urban heat island in Malmö, Sweden. Journal of Climatology, 5(4), 433–444. https://doi.org/10.1002/joc.3370050410

[4]. Chen, L., & Ng, E. (2009). Sky View Factor Analysis of Street Canyons and Its Implication for Urban Heat Island Intensity. ResearchGate, 7.

[5]. Dallman, A., Magnusson, S., Britter, R., Norford, L., Entekhabi, D., & Fernando, H. J. S. (2014). Conditions for thermal circulation in urban street canyons. Building and Environment, 80, 184–191. https://doi.org/10.1016/j.buildenv.2014.05.014

[6]. Das, D. (2013). Urban built forms investigations for interventions in urban environment case study Kolkata [Jadavpur University]. http://hdl.handle.net/10603/175828

[7]. Gál, C. V. (2014). The impact of built form on the urban microclimate at the scale of city blocks. 94th Annual Meeting of the American Meteorological Society (AMS) Jointly with the 11th Symposium on the Urban Environment, Atlanta, GA, 7.

[8]. Haizhu, Z., Neng, Z., & Qingqin, W. (2020). Modelling and simulation of the urban heat island effect in a tropical seaside city considering multiple street canyons. Indoor and Built Environment, 1420326X2093026. https://doi.org/10.1177/1420326X20930262

[9]. Hu, Y., White, M., & Ding, W. (2016). An Urban Form Experiment on Urban Heat Island Effect in High Density Area. Procedia Engineering, 169, 166–174. https://doi.org/10.1016/j.proeng.2016.10.020

[10]. Kim, J. P., & Guldmann, J. M. (2014). Land-Use Planning and the Urban Heat Island. Environment and Planning B: Planning and Design, 41(6), 1077–1099. https://doi.org/10.1068/b130091p

[11]. Kusaka, H., & Kimura, F. (2004). Thermal Effects of Urban Canyon Structure on the Nocturnal Heat Island: Numerical Experiment Using a Mesoscale Model Coupled with an Urban Canopy Model. Journal of Applied Meteorology, 43(12), 1899–1910. https://doi.org/10.1175/JAM2169.1

[12]. Letzel, M. O., Krane, M., & Raasch, S. (2008). High resolution urban large-eddy simulation studies from street canyon to neighbourhood scale. Atmospheric Environment, 42(38), 8770–8784.

https://doi.org/10.1016/j.atmosenv.2008.08.001

[13]. M’Saouri El Bat, A., Romani, Z., Bozonnet, E., & Draoui, A. (2020). Integration of a practical model to assess the local urban interactions in building energy simulation with a street canyon. Journal of Building Performance Simulation, 13(6), 720–739. https://doi.org/10.1080/19401493.2020.1818829

[14]. Mughal, M. O., Li, X.-X., & Norford, L. K. (2020). Urban heat island mitigation in Singapore: Evaluation using WRF/multilayer urban canopy model and local climate zones. Urban Climate, 34, 100714. https://doi.org/10.1016/j.uclim.2020.100714

[15]. Allegrini, J., Dorer, V., & Carmeliet, J. (2012). Influence of the urban microclimate in street canyons on the energy demand for space cooling and heating of buildings. Energy and Buildings, 55, 823–832. https://doi.org/10.1016/j.enbuild.2012.10.013