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Design Optimization with Building Forms and Their Effects on Outdoor Thermal Comfort: The Case of Composite Climate of Lucknow, India

Swetika Porwal [1,2*] , ***Shailendra K. Mandal*** [1] , ***Subhrajit Banerjee*** [3]

[1] *Department of Architecture and Planning, National Institute of Technology, Patna 800005, India*

[2] *Amity School of Architecture and Planning, Amity University Uttar Pradesh, Lucknow Campus, Lucknow 226028, India*

[3] *Faculty of Architecture and Planning, Dr. A.P.J. Abdul Kalam Technical University, Lucknow 226007, India*

ABSTRACT

The recent development in Lucknow shows that the amount of built mass may increase significantly soon, which may affect outdoor thermal comfort. This study aims to achieve a better alternative to the geometrical configuration of vertical surfaces that helps improve the outdoor thermal comfort level. The study primarily deals with the exploration of built forms by altering the planar forms, heights, and orientations to arrive at a better composition of vertical surfaces. 144 typologies were finally generated, which were then simulated in ENVI-met. The results show that, with the I-shaped typology it is difficult to reduce solar access, whereas in terms of ventilation, the typology performed better than L-shaped and C-shaped typologies. For this reason, the hours of solar access, as well as wind speed, should be seen together while developing the built-form typology. Urban neighborhoods can be designed with streets and open spaces oriented primarily to northeast-southwest and northwest-southeast directions which allow the open spaces to be thermally more comfortable than the rest of the orientation. This research highlights the importance of varying building heights to enhance thermal comfort. The findings provide valuable insights for composite climate cities like lucknow and can serve as a framework for future design strategies aimed at mitigating outdoor thermal discomfort. It is therefore important for planners, urban designers, and architects to design considering the minimal impact of the upcoming development on the thermal comfort level.

*CORRESPONDING AUTHOR:

Swetika Porwal, Department of Architecture and Planning, National Institute of Technology, Patna 800005, India; Amity School of Architecture and Planning, Amity University Uttar Pradesh, Lucknow Campus, Lucknow 226028, India; Email: swetikap.phd20.ar@nitp.ac.in or sporwal@lko.amity.edu

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1. Introduction

India being a developing nation is undergoing rapid urbanization. Cities expand their boundaries persistently due to the increasing population and migration. As most of the cities are expected to be built in the near future, there is scope for development with adequate thermal comfort levels [1]. Unplanned development in urban areas has worsened the microclimatic conditions. Urban geometry contributes both to occupants' thermal comfort and urban environment quality. The explorations with built geometry and optimization studies have been conducted globally. Ref. [2] studied the new town of Aswan for a hot and arid climate. The study analyzed the impact and variation of various morphologies on outdoor thermal comfort. The study [3] on design optimization of urban typologies for Syracuse discussed a framework for evaluating building energy performance and outdoor thermal comfort. Ref. [4] studied the role of urban morphology on outdoor thermal comfort for Al-Sharq City, Az Zarqa, and investigated the impact of urban form on outdoor thermal comfort in public spaces. The role of built geometry in microclimatic modification is studied by [5]. The in-depth review study [6] discussed the existing status of outdoor thermal comfort studies in India and highlighted the gaps present in the field. Based on the future directions given by the study, it can be said that there is a need for optimization studies for built morphologies, and future settlement is necessary.

The recent development in the city is guided by the development control regulations whereas there is no guidelines or reference for design concerning the thermal comfort level. The uncontrolled development in the city is worsening the microclimate and the outdoor thermal comfort level of the city. It is also observed from previous studies that the thermal comfort level worsens with the development of the built forms [1, 5, 7, 8]. The thermal comfort level in the city may worsen significantly. Therefore, it is important for planners, urban designers, and architects to design considering the minimal impact of the upcoming development on the thermal comfort level of the user.

This study aims to achieve a better alternative to the geometry of vertical surfaces that helps improve the outdoor thermal comfort level. One of the objectives of the study is to guide future developments in the city concerning the basic geometrical configurations such as height, orientation, and the spacing between the forms. The objective is also to improve the thermal comfort level of future development. The thermal comfort indices Tmrt and PET are focused on in this paper. Since the study deals with the upcoming development, geometrical explorations are considered by keeping materials constant to negate the effect due to materials.

2. Materials and Methods

2.1. Flowchart of the Study

Figure 1 shows the steps followed in this study. In the first step, the neighborhood with varying morphologies is selected. It was ensured that the selection of the neighborhood fulfills the objective of the study; for this reason, the recently developed neighborhood with varying geometry was selected. It was also ensured that the vertical surfaces enclosing the open spaces were uniform in character (materials and opening sizes). In the next step, the basic forms were extracted. Overall, three different forms were selected. In the next step, the exploration exercise was performed concerning variation in height and orientation. For each shape 48 options were generated, which were then simulated using ENVI-met**.** After simulation results were achieved and validated, analysis was performed for climatic and non-climatic parameters to differentiate and observe the variation amongst the morphological options.

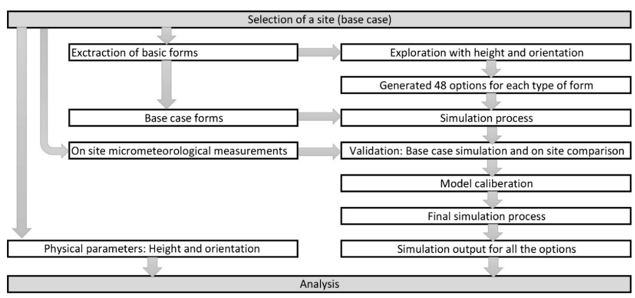

Figure 1. Flowchart of the study.

2.2. Site and Climate

The selected site belongs to the composite climate zone as per the climatic classification of India [9]. The city is characterized by extreme weather conditions. The city experiences cold winters for two to three months of the year and long summers with extreme temperatures in July and August [10]. The selected site is located near Arjunganj at Lucknow (49°97’17” E, 29°65’59” N). Lucknow is the capital city of Uttar Pradesh, India. The study by [11] investigated changing landscape patterns of the last five decades and found increased urban growth and land consumption and declined open spaces in the city. The increasing built mass can result in the decline of thermal comfort level [12]. It is therefore necessary to regulate the development in the city concerning the thermal comfort level. The site is selected in Lucknow since the city acts as a typical case of composite climate cities that are continuously growing. Although the development in the city is regularized by development control regulation, built mass is primarily regulated by the floor area ratio and height limitation. There are no such norms that control the development concerning the thermal comfort level. Unregulated geometry may significantly affect the wind flow, solar access, etc. to the open spaces.

The selected site (**Figure 2**) acts as the base case for this study. The site represents the typical character of the recent developments in the city in terms of the built form that includes height variations, orientations, open space structure, etc. The variety in the fraction of enclosures can be observed on the site. This character of the built environments also yields variety in the wind speed, wind direction, shaded and non-shaded spaces, hours of solar access, etc. It was also observed that there is not much variation in the material properties which may impact on thermal comfort level. Natural elements such as vegetation and water bodies can cause variations in the thermal comfort level. To understand the effect only from the built masses it was ensured that the thermal comfort level is not affected by vegetation, waterbodies, etc. and only the built forms are dominating.

2.3. Extraction of Basic Forms

The selection of the base case (existing site) started with the idea of having a typical site with various planar forms having various degrees of orientation and varying degrees of enclosures to the adjacent open space, which may cause variation in the thermal parameters. In the first step, the search operation started with Google Earth to identify the neighborhood with various typologies of the buildings. In the second step, an actual visit was conducted to the site to observe the variation in the building typologies. To select the site as a base case, it was also ensured that the buildings are of similar heights and materials so that it will be easier to create various possible options in terms of height variations and orientations.

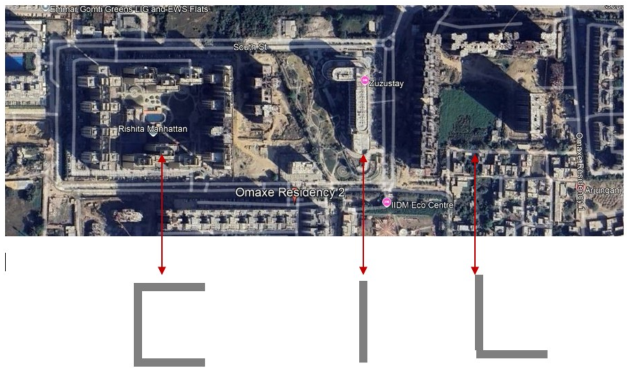

Figure 2. (**a**) Site selected as a base case, and (**b**) Basic forms extracted from the selected site.

The orientation is usually affected due to the context of the site, the adjacent streets, site boundaries, and spatial requirements whereas the heights are highly dependent on the permissible FAR (floor area ratio). Considering the possible variations in the orientations and heights, the explorations are done by altering the base case morphology. The exploration of forms is performed at three levels: 1) Building form in plan, 2) Orientations of the selected forms, and 3) Height variations of the forms with all the possible orientations.

In any urban area, the built form and its architecture take shape depending on the functional requirements, climatic conditions, site conditions, etc. The geometrical profile in the plan for those blocks can be anything and not just I, L, and C shaped. The geometrical profile of vertical surfaces can influence the adjacent open spaces. For example, T-shaped forms can be considered as two adjacent L-shaped forms. In this manner, most of the building forms can be simplified to basic geometries depending on the kind of enclosure. In terms of height, the directions they are enclosed from also determine the number of directions the open space is enclosed from. The quality of the enclosure may decide on the shadow pattern, hours of solar access, and the wind access, which may have a significant impact on the thermal parameters.

I-shaped forms represent the built forms having a linear configuration; they enclose the open space only from one direction, and the shade and shadow cast by these forms are often minimal and highly dependent on the orientation. For example, the I-shaped forms facing east or west may cause deeper shadows compared to the forms facing north or south. The wind passing along these forms can be uninterrupted. L-shaped forms represent the built forms enclosing the open space from two directions. Shade cast by these forms can be deepened for various orientations. These forms can also affect the wind flow pattern and wind velocity. Similarly, the shaded spaces caused by C-shaped forms can be much higher than L-shaped and I-shaped forms.

2.4. Form Exploration

The optimization studies are conducted by the studies [3, 4, 13, 14] at various parts of the world. For optimization, the form explorations are done in terms of the plan profile of the built mass, height, and orientation. The existing built morphology is usually simplified to a geometrical form. This study follows the methods adopted by the studies [13, 15] to abstract and simplify the built geometries.

For the exploration, three basic forms were extracted from the selected site (**Table 1**). The selection of these forms is also based on the number of sides they are enclosing the open space from. The nomenclature of these forms is based on their shapes in the plan. The first type is linear, which indicates the enclosure only from one side of the open space; this option is termed as I-shaped. In the second type, the form encloses the open space from two adjacent sides; this option is termed as L-shaped. In the third type, the form encloses the open space from three directions which is termed as C-shaped. Based on the commonly found building heights at the studied site, six different options for each type are applied (**Table 1**). The exploration was also done in terms of orientation. Eight different orientations based on the direction these forms are facing are applied to all six height options. The selected forms were observed to be 42 m in height and considered as the "base case" in this study. There is no specific height or orientation that is dominating, and the development is more or less unplanned. However, the maximum height, setbacks, ground coverage, etc., are in accordance with the development control regulations. The lowest height considered for the exploration is 15 m whereas the highest is 84 m (**Table 1**). Eighteen (3 × 6) different typologies were developed when height variations were applied to the base case. All these typologies were further explored with the orientations. This way, 48 options (6 different heights × 8 different orientations) were generated for each shape.

2.5. Micrometeorological Measurements

On-site measurements were conducted between 4th June 2023 and 10th June 2023 (one week). The measurements were collected at 60-second intervals. The month of the measurements was decided based on the yearly temperature trends [16]. The instrument was placed alternately in three different locations as per the typologies selected for the study. The mini weather station was used to conduct the basic climatic parameters Ta, Rh, Va, wind direction, and Tg. Several other Indian studies collected similar climatic data on-site [6].

Testo 608-H2 was used for the measurements of Ta and Rh. It has a temperature range of –10° to +70 degrees with an accuracy of +/–0.5° and a humidity range of +2 to +98 with an accuracy of +/–2%. The measurement interval for the instrument is 18 seconds. WS102 three-cup sensor was used for wind speed measurement that has a range of 0 to 70 m s–1 and an accuracy of +/–3%.

The instrument was placed considering several protocols. It was ensured that the duration of the campaign is such that the weather conditions are typically sunny, and the weather conditions were usual for the past 15 days so that there are no unusual readings in the instrument. While placing the instrument on the monitoring locations, it was ensured that the instrument was not affected by parameters such as shade (from trees and buildings). The instrument was placed at least 5 m away from the nearest wall and 1.5 m above the finished ground level. The protocols are in agreement with the previous studies [6, 17].

2.6. Simulation Tools Used for the Explorations

Since the study is about the explorations, the simulation tools help in creating the virtual environment and representation of the thermal parameters. In this study, ENVI-met (version 5.0.1) is used for the simulation. ENVI-met has

Table 1. Various scenarios of explored forms, and their nomenclature concerning height.

Height (m)	15	24	33	42 (Base Case)	63	84
I-shaped	I-1	I-2	I-3	I-4 (Base case)	I-5	I-6
L-shaped	L-1	L-2	L-3	L-4 (Base case)	L-5	L-6
C-shaped	C-1	C-2	C-3	C-4 (Base case)	C-5	C-6

proven to be capable of providing weather data close to real-time conditions[18], especially for the summer season[19]. This tool was often used by studies to simulate the urban environment[20–22]. Several studies[5, 6, 23–27] used ENVI-met for the analysis of outdoor thermal comfort, which shows the reliability of the software. The software can simulate the urban environment to evaluate important thermal indices such as PET and Tmrt, study[28] discussed the importance of using ENVI-met for Tmrt calculations. ENVI-met can also be used to estimate the effect of changing climate conditions in cities[17]. ENVI-met takes into account the interaction between the atmosphere, buildings, ground, and vegetation[29].

The ENVI-met model was constructed on the grid size of x = 60 m, y = 60 m, z = 60 m with the grid resolution of x = 3 m, y = 3 m, and z = 3 m. Since the thermal effect caused by the geometrical configuration is the focus of the study, the material input for the model was standardized for all the typologies. The materials and their physical characteristics were used as ENVI-met's default database. Simulation duration and the default parameters of the ENVI-met are in agreement with the other studies[30, 31] that used ENVI-met.

The simulations were run for 24 hours. The first seven hours of simulation are discarded from the study. The simulated output between 7 am and 6 pm is taken for analysis. The input parameters for the base case model were given from the micrometeorological measurements conducted on-site. The input of Ta, Tg, Va, and wind direction was given as per the on-site observations. Once the base case model was simulated, the output was taken for validation. After several calibrations to the base case model, the finally accepted model after validation was used for the analysis.

Due to the focus of the study being on built forms typologies and their effect on outdoor thermal comfort, other entities such as vegetation or other outdoor elements are not given importance and were not modeled. This may cause some variation in the simulation output. Due to the scarcity of vegetation at the base case site, the difference caused due to the vegetation must be very small. The ENVI-met model was then calibrated by adjusting the boundary conditions of the climate. **Figure 3** shows the example of the simulation output for the thermal indices Tmrt and PET.

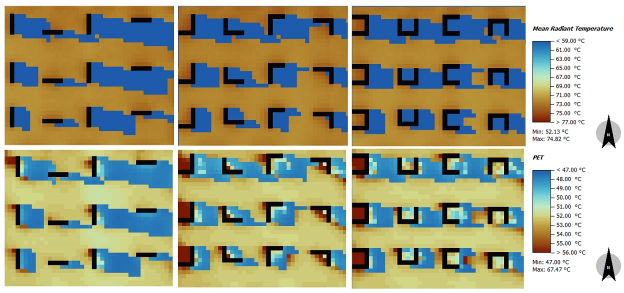

Figure 3. Simulation output sample showing T_{mrt} (**top row**) and PET (**bottom row**) at 4 pm. For the orientations of East, West, North, and South.

2.7. Validation

Since the results and the analysis are primarily based on the simulated outcome, it is necessary to validate the ENVI-met model with on-site measurements[32]. Several studies[30, 33, 34] performed the ENVI-met validation by comparing field measurements and simulation results. **Figure 4** shows the average difference between simulated and observed (measured) data. There are various methods used to validate simulated data. In this study, R2, RMSE, and d are used. These parameters for the validation are suggested by the study[35]. The mean difference at I, L, and C shapes typologies are 0.39, 0.46, and 0.52 respectively. R2 values at I, L, and C shapes typologies are 0.92, 0.88, and 0.86 respectively. RMSE at I, L, and C shapes typologies are 0.46, 0.50, and 0.59 respectively. d at I, L, and C-shaped typologies are 0.994, 0.993, and 0.99 respectively.

The simulation model needs to be calibrated before its outcome is used for further analysis. This study followed the calibration process[32]. The calibration involved several steps. After the first simulation output, drastic variation could be observed between observed values and simulated values. In the first step of calibration, the model domain size was readjusted by adding extra cells to the model space. It was observed that the variation persisted for the first few hours of the simulation output; for this reason, simulation duration was increased (starting from 00:00 hrs), which allowed the necessary fetch and valid outcome. Adjustments were also made in the climatic input, especially the Va, since the higher Va overestimated the simulated outcome. The values are accepted based on the earlier studies that discussed the accepted validation results[6].

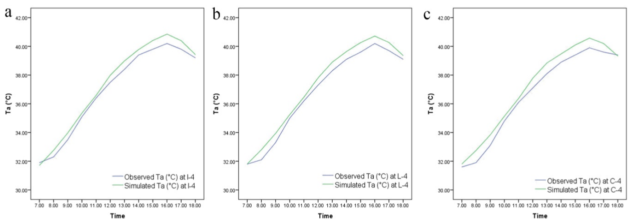

Figure 4. Validation of ENVI-met model for (**a**) I-shaped, (**b**) L-shaped, and (**c**) C-shaped typologies.

2.8. Outdoor Thermal Comfort Indices

There are numerous thermal comfort scales used to date. The selection of the right thermal comfort scale is dependent on the geographic region and climatic region. It also depends on the purpose of using the scale since different scales will give output for different thermal models. The study[6] conducted a literature review for outdoor thermal comfort in India and comprehensively discussed the thermal indices used by Indian studies. Accordingly, in this study, Ta, Tmrt, and PET are used for the thermal comfort analysis. Ta is the most popular index, which is usually understood by various professions it is also used in day-to-day life for understanding the weather situation. Mean radiant temperature (Tmrt) is also used in this study. It is commonly used in studies where the influence on thermal comfort due to radiation is prominent[36–40]. Since the studied location is in Lucknow, it makes sense to use Tmrt as one of the evaluation indices for thermal comfort. Physiological equivalent temperature (PET)[41] is a very common index used in Indian studies[8, 42, 43]. The index also gets affected due to various thermal parameters such as wind speed. For this reason, PET is also used in this study.

A line chart is used for identifying the average variation between the typologies and the variation as per the geometric change. Linear regression (R^2) is used to identify the relationship between geometrical parameters and thermal indices.

3. Results

The results are analyzed at three different scales: the average variation of thermal parameters among typologies, the variation of thermal parameters within a typology, and the variation of thermal comfort across typologies with similar morphological parameters such as height and orientation. The effect due to geometrical variation on thermal comfort is studied along with the effect of solar access and wind speed which are highly affected by the geometrical configuration of vertical surfaces.

3.1. Average Thermal Variation between the Typologies

Figure 5 shows the average variation of thermal parameters among all the typologies. The average is calculated by taking all the height and orientation scenarios for each typology. The average variation of Ta is negligible. The variation in terms of PET and Tmrt can be observed in **Figure 4**. It is noteworthy to see that contrasting results are obtained in terms of PET and Tmrt. The C-shaped typology shows the highest PET and lowest Tmrt. PET in the C-shaped typology is 4.35 °C higher than the I-shaped typology and 2.1 °C higher than the L-shaped typology. The possible reasons can be found in the subsequent sections of this study. During noon the maximum variation is observed in PET whereas minimal variation is observed in Tmrt. The variation in Tmrt can be observed during the harshest hours of the day (between 1 pm to 4 pm). Typology is 4.4 °C higher than the C-shaped typology and 2.13 °C higher than the L-shaped typology.

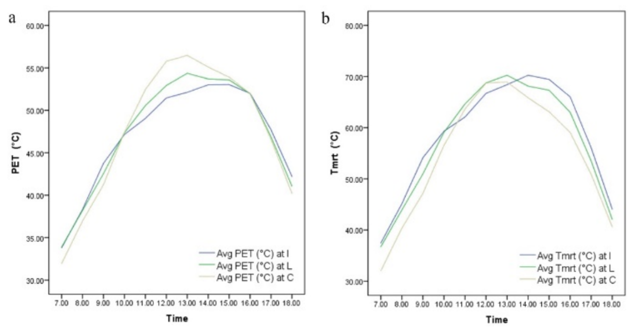

Figure 5. Average variation of (**a**) T_{mrt} and (**b**) PET.

3.2. Average Variation as per the Heights within the Typologies

Figure 6 shows the variation in all the typologies concerning heights. Since the variation of Ta is negligible, it is not considered for the analysis. The variation of T_{mrt} and PET is observed to be lesser in the case of I-shaped typologies. The variation in thermal parameters is higher as the day progresses up to 4 pm. At both the L-shaped and C-shaped typologies, distinct variation is observed as per the change in height of the block; the higher the block, the lesser the temperature. It can be said that the improvement in thermal comfort is possible by reducing the height-to-width ratio. The results are in agreement with the study done for the subtropical climate of Dhaka [44], which studied the height variations and found that the increased building height can significantly improve the thermal comfort level. Another study in Dhaka [45] found that the deep canyons showed a lower temperature than the average temperature shown on the meteorological station.

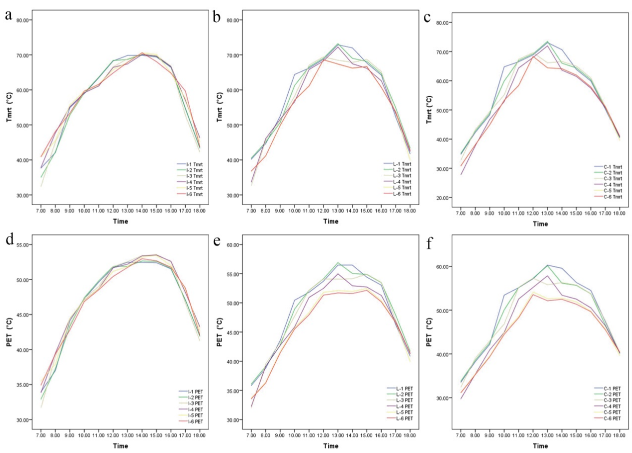

Figure 6. Thermal variation among various scenarios within the typologies: (**a**) I-shaped T_{mrt}, (**b**) L-shaped T_{mrt}, (**c**) C-shaped T_{mrt}, (**d**) I-shaped PET, (**e**) L-shaped PET, and (**f**) C-shaped PET.

In terms of I-shaped typologies, the height of the building block itself may not help improve thermal comfort, and orientation along with height is an important consideration. The base case (I-4) is higher than the rest of the typologies. I-1 showed the lowest PET with 0.93 °C less than the base case during the harshest hour (2 pm). The Tmrt at I-1 is observed to be the lowest with 0.24 °C lesser than the base case. It was also observed that Tmrt increased as height increased. In the case of L-shaped typologies, L-1 shows 3.55 °C higher PET than the base case. Gradual increases of PET from L-4 (base case) to L-1, L-5, and L-6 are observed. Tmrt at L-1 is 4.55 °C higher than the base case. The higher the built mass, the lesser the Tmrt. In the case of C-shaped typologies, C-1 shows 6.16 °C higher PET than the base case. The PET lowers gradually till C-6. Tmrt at C-1 is 7 °C higher than the base case.

3.3. Relationship between the Heights of Vertical Surfaces and Thermal Parameters with Respective Orientations

Table 2 shows the linear regression between thermal parameters and the height of the enclosing surfaces concerning the orientation of the vertical surfaces (the direction the vertical surfaces are facing).

I-shaped typologies showed a strong negative correlation with Tmrt for east and southeast surfaces. This means the higher the I-shaped typologies for these orientations, the lesser the Tmrt, whereas, a moderate positive correlation was observed for the west, northwest, and south-facing vertical surfaces. The increase in height negatively affects the thermal comfort level. For this reason, it can be said that in the case of I-shaped typologies, the focus should be on having higher east and southeast-facing surfaces than the rest of the vertical surfaces. This is due to the direct solar radiation received by the vertical surfaces during the afternoon hours. In the case of PET, the correlation was observed to be moderate with all the vertical surfaces. Only south-facing vertical surfaces showed a strong correlation. North-facing vertical surfaces resulted in poor correlation.

I-shaped typology showed a poor relationship for north and south-facing vertical surfaces but shows a good negative relationship with east-facing vertical surfaces and a positive relationship with west-facing vertical surfaces. It can be said that the east-facing vertical surfaces should be higher than the west-facing surfaces to improve the thermal comfort level. It can be said that the uniform heights may cause a negative effect on the thermal comfort level. This result is in agreement with the study [46] done for Dhaka that suggests the variety in the building heights may have a positive effect on the thermal comfort level. The effect of orientation on PET is studied by [47] and concluded that the E-W open space performs poorly even with the higher aspect ratio. Other Indian studies [1, 47] found similar results. The study [42] performed the optimization study for the street orientation and found that the streets N30°E and N60°E perform better during the harsher hours. The vertical surfaces facing NE, NW, and SE directions (except for SW) showed a good correlation. This can allow open spaces to orient NE-SW and SE-NW directions. Since the SW-facing vertical surface showed a poor relationship, the vertical surface against the SW, i.e.,

Table 2. Correlation coefficients between thermal coefficients and orientation.

Form	Parameter	N	E	W	S	NW	NE	SW	SE
I	T_a	0.01 (–)	0.78 (–)	0.92 (–)	0.23 (–)	0.83 (–)	0.57 (–)	0.83 (–)	0.80 (–)
	T_{mrt}	0.18 (+)	0.79 (–)	0.60 (+)	0.66 (+)	0.55 (+)	0.65 (+)	0.01 (–)	0.40 (–)
	PET	0.29 (+)	0.57 (–)	0.37 (+)	0.87 (+)	0.07 (+)	0.52 (+)	0.19 (–)	0.56 (–)
L	T_a	0.81 (–)	0.63 (–)	0.91 (–)	0.87 (–)	0.94 (–)	0.80 (–)	0.91 (–)	0.94 (–)
	T_{mrt}	0.04 (–)	0.49 (–)	0.74 (–)	0.48 (–)	0.61 (–)	0.83 (–)	0.77 (–)	0.83 (–)
	PET	0.44 (–)	0.86 (–)	0.54 (–)	0.77 (–)	0.81 (–)	0.92 (–)	0.81 (–)	0.83 (–)
C	T_a	0.95 (–)	0.89 (–)	0.96 (–)	0.94 (–)	0.97 (–)	0.82 (–)	0.75 (–)	0.85 (–)
	T_{mrt}	0.91 (–)	0.80 (–)	0.88 (–)	0.88 (–)	0.69 (–)	0.61 (–)	0.66 (–)	0.79 (–)
	PET	0.78 (–)	0.88 (–)	0.84 (–)	0.84 (–)	0.85 (–)	0.72 (–)	0.27 (–)	0.66 (–)

NE facing the vertical surface can be higher.

In the case of L-shaped typologies, all the vertical surfaces except for north facing showed a moderate negative to good negative correlation with Tmrt and PET. It can be said the vertical surfaces facing NE, NW, SE, and SW directions have better correlation compared to the vertical surfaces facing cardinal directions. For this reason, the easiest way to improve the thermal comfort level at L-shaped typologies is to orient the block at 45 degrees from the cardinal directions.

In the case of C-shaped typologies, a moderate negative to strong negative correlation is observed between all the typologies and the thermal indices. It can be because of the reduction in solar access, increased shaded area, and the shading to the vertical surfaces due to adjacent vertical surfaces. The height-to-width (H/W) ratio is highly dependent on the orientation, whereas there is no role of orientation in SVF, due to the degree of enclosure. The extent of the enclosure affects the thermal parameters [2, 48]. The study AA found a similar result where SVF showed a significant effect on thermal comfort variation than the SVF.

3.4. Effect of Solar Access

The effect of solar access can be seen in the thermal parameters Ta, Tmrt, and PET (**Figure 7**). The relationship between Ta and sun hours is poor to moderate whereas a moderate to good relationship could be observed between thermal parameters (Tmrt and PET) and sun hours. The relationship between thermal parameters and sun hours in the I-shaped typology is poor (R^2 = 0.28 for Tmrt), whereas L-shaped (R^2 = 0.68 with Tmrt, and R^2 = 0.44 with PET) and C-shaped typologies showed a good relationship (R2 = 0.78 with Tmrt, and R^2 = 0.60 with PET). It can be due to the number of sides enclosing the open spaces combined with height having a significant impact on solar access to that open space. The I-shaped typology casts a lesser amount of shade on the adjacent open space. The appropriate orientation must be followed to reduce the hours of solar access. For C-shaped typologies, height variation should be the focus rather than the orientation. The H/W ratio and orientation are the most impactful in the linear configuration of the open spaces [2]. East-west-oriented open spaces experience stressful conditions [28, 49]. It can be said that the typologies having more than two or three sides as enclosures to the adjacent open spaces help reduce the number of solar hours and improve thermal comfort. The effect of solar access is prominent on Tmrt and PET. Similar results are obtained in the previous studies [44, 50, 51].

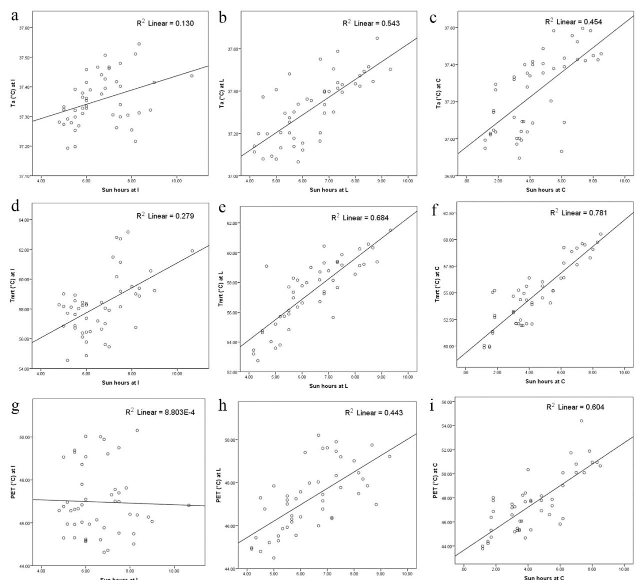

Figure 7. Linear regression between hours of solar access and thermal comfort: (**a**) Ta at I-shaped; (**b**) Ta at L-shaped; (**c**) Ta at C-shaped; (**d**) Tmrt at I-shaped; (**e**) Tmrt at L-shaped; (**f**) Tmrt at C-shaped; (**g**) PET at I-shaped; (**h**) PET at L-shaped; (**i**) PET at C-shaped.

The orientation of the streets dictates the orientation of the block [2]. Since the orientation of the building block affects the thermal comfort level, it is necessary to arrange the street consciously. Although various studies found that streets and open spaces oriented north-south performed better in thermal comfort, the N-S orientation also necessitates the E-W connecting streets that are poor in terms of thermal comfort level. Orienting the streets NW-SE and NE-SW can be the better option for thermal comfort on streets. This orientation will encourage the building blocks to orient 45° to cardinal directions. Subsequently, this orientation can reduce the hours of solar access while allowing the wind to flow. The heights of the buildings can be worked out if a suitable street orientation cannot be achieved.

3.5. Effect of Wind Speed

Figure 8 shows the correlation between wind speed (Va) and PET. Several studies [52–54] have identified that the relationship between Va and PET is more prominent than the relationship between Va and other parameters. Pearson correlation (two-tailed, $p = 0.01$) between Va and PET at I-shaped typology is $r = –0.70$, at L it is $r = –0.67$, at C it is $r = –0.574$. The correlation is poor between Va and Tmrt; at I-shaped typology it is $r = 0.54$, at L it is $r = 0.07$, at C it is $r = –0.15$. The linear relationship between Va and PET at I-shaped typology is the highest ($R^2 = 0.69$), followed by C-shaped typology ($R^2 = 0.54$) and L-shaped typology ($R^2 = 0.49$). The strong negative relationship I-shaped typology shows the importance of ventilation in outdoor spaces. It can be said that the building blocks and their vertical surfaces can be designed in such a way that maximum ventilation happens in the outdoor spaces which improves the thermal comfort level. A void in the windward direction can improve the thermal comfort level [45]. The vertical surfaces can be oriented obliquely to the wind direction [42] to enhance the thermal comfort level due to ventilation.

Wind plays a significant role in determining the outdoor thermal comfort level in urban areas [40]. The change in the orientation and height significantly affects the wind speed and flow pattern [45]. A study by [55] explored the orientations of the selected case and observed the varying effects of the wind speed on thermal comfort level. A study conducted by [37] in the composite climate of Sonipat, India, found that higher wind speed improved the thermal comfort level.

L-shaped and C-shaped typologies showed a moderate relationship between Va and PET (**Figure 8**), whereas the relationship between solar access and Tmrt is better in this typology (**Figure 7**). On the other hand, as the number of enclosures is increased, the Tmrt index improves. It is observed that with the I-shaped typology, it is difficult to reduce the solar access, whereas in terms of ventilation, the typology performed better than L-shaped and C-shaped typologies. For this reason, the hours of solar access, as well as wind speed, should be seen together while developing the built-form typology. The result coincides with the study [4] that suggested the combined effect of shading and wind for thermal comfort improvement.

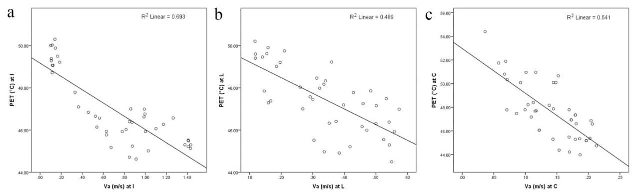

Figure 8. Linear regression between PET and Va at (**a**) I-shaped, (**b**) L-shaped, and (**c**) C-shaped forms.

4. Conclusions

This study aimed to optimize geometrical configurations of vertical surfaces to improve outdoor thermal comfort. It focuses on modifying the heights and orientations of built forms to create better compositions of vertical surfaces. 144 options for three basic forms—I-shaped, L-shaped and C-shaped—were analyzed using ENVI-met simulations to evaluate thermal comfort indices Tmrt and PET.

Key findings include contrasting results between PET and Tmrt, with C-shaped morphologies having the highest PET and lowest Tmrt. For I-shaped morphologies the building height alone did not enhance the thermal comfort. Higher built masses improved thermal comfort, and varying building heights is advisable. L-shaped forms showed better thermal performance when oriented to non-cardinal directions such as northeast and northwest.

I-shaped typologies cast less shade, making it challenging to reduce solar access, but they performed better in ventilation. C-shaped buildings performed well for all the orientations. The study found that streets and open spaces oriented NE-SW or SE-NW could reduce solar access and enhance wind flow. The sky view factor was more relevant than the height-to-width ratio for three-sided enclosures.

Limitations include the study's inapplicability to the existing built environment or material-based explorations. It also does not account for measures like vegetation or water bodies. However, the findings are valuable for developing composite climates, particularly in Lucknow and can serve as a benchmark for future studies.

Author Contributions

Every author actively contributed to this study, providing valuable contributions. All the authors commented on earlier drafts of the manuscript. Additionally, each author thoroughly reviewed and consented to the final version of the manuscript.

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Not applicable.

Data Availability Statement

The data that support the findings of this study are the software simulated data and it is available on request from the corresponding author.

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Conflicts of Interest

No conflict of interest was observed by the authors while conducting the research.

List of Abbreviations

Ta	Ambient temperature
Rh	Relative humidity
Va	Wind speed
Tg	Globe temperature
Tmrt	Mean radiant temperature
PET	Physiological equivalent temperature
H/W	Height to width ratio
SVF	Sky view factor

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