

# Investigating the Impact of High-Rise Buildings on Urban Wind Patterns, Pollution Dispersion

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The construction of several high-rise buildings has been a response to the rapid urbanization experienced in Indian cities, with implications for air quality and wind flow patterns. Setting aside the impacts of the urban heat island effect, which exist in some of India's urban centers because of dense development, this study seeks to analyze the relative influences of building density, height, and spacing on wind movement and pollution dispersion through a design/build study using the wind tunnel. Data for five cities— New Delhi, Kanpur, Patna, Lucknow, Varanasi— were obtained from air quality index (AQI) platforms and remote sensing methods based on density, building height, with PM<sub>2.5</sub> conditions ranging between 85150  $\mu\text{g}/\text{m}^3$ , and respective average wind speeds of 8-15 km/h, and building heights with relative inter-building spacing of 1535 meters. Three cities, with varying building intensities - Navi Mumbai (low density), Lokhandwala (medium density), and Gurugram (high density) - were selected for the scaled models testing. Building layouts of each of those three cities were used in scaled models that were 3D printed at a 1:300 scale using SolidWorks, FlashForge Adventurer 3, and PLA. The models were placed inside a custom-built wind tunnel with a size of 1.5 m  $\times$  0.6m  $\times$  0.9m designed to simulate wind speeds between 25.777.1 m/s across the wind tunnel, relating to realistic urban wind speeds of 1015 km/h in real-world applications. The models also simulated the dispersion of controlled powder tracers designed to mimic PM<sub>2.5</sub> under identical wind angles of 0° and 45°. The numbers show that Gurugram had the most pollutants, especially when spacing was less than 20 m (although we found no difference in pollutants up to individual spacing distances). The spacing for Navi Mumbai was better than Gurugram, so the wind was able to continue to disperse 30-40 meters past the buildings. Lokhandwala had lower distances at 45 or even 90 degrees. Pollution dispersion possibly took places best in the 25-35 meter spacing area. In general, this study provides practical information for urban planners suggesting that if zoning ordinances can be changed to modify distances between buildings, or the orientation of buildings especially in high-density areas, could lead to delays in the accumulation of pollution pathways. This study though was limited to having only scaled models and operating in a wind tunnel, that could basically guarantee consistency for testing conditions, while real world circumstances are impacted by other factors like surface roughness, variability in atmospheric conditions and microclimate.

**Keywords:** Urban air pollution, PM<sub>2.5</sub> dispersion, building density, wind tunnel testing, inter-building spacing

## Introduction

The rapid expansion of urban areas had resulted in the construction of large numbers of tall buildings, which had changed wind patterns and air quality in these regions. This urban growth had led to increased pollution from automobiles and industries concentrated in cities. High-rise buildings had also contributed to the pollution problem by influencing air movement and causing stagnation near ground level, particularly in congested urban zones. Prior research had suggested that tall buildings altered near-ground atmospheric processes, thereby affecting the dispersion of pollutants. For instance, A. Shirzadi, H. Fattahi, A. Rajabi, and R. Zand-Parsa in their study "Air pollution in the vicinity of skyscrapers: experimental and numerical analysis"<sup>1</sup> had examined the influence of skyscrapers on pollution accumulation and turbulence generation in dense urban regions.

To study these effects in detail, researchers had utilized specially designed wind tunnels and 3D-printed city models to simulate real urban environments. Using a geometric scale of 1:300, representative cityscapes had been built inside controlled experimental setups. Wind flow had been examined from various orientations (0°, 45°, and 90° building angles) and wind speeds (1015 km/h) to analyze how urban density impacted contaminant dispersion and airflow. These experiments had allowed precise control over environmental parameters, offering insights into how building form and spacing influenced air circulation and pollutant concentrations. H.D. Lim, Y. Zhao, T. Kataoka, and H. Uehara, in their paper "Pollutant dispersion by tall buildings: laboratory experiments and Large-Eddy Simulation"<sup>2</sup>, had demonstrated the effectiveness of combined wind tunnel tests and LES simulations in studying pollutant transport dynamics around tall structures.

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Alternative solutions had also been explored to mitigate the challenges caused by vertical urban expansion. Urban planners had increasingly considered increasing building porosity and incorporating green infrastructure to improve air movement. Additionally, regulating building heights and spacing had been proposed to enhance wind circulation and pollutant dispersion. For example, J.P. Vidanpathirana, D.K.W. Yuen, and R.W. Yeung in their work "Morphological impacts on urban air pollution dispersion"<sup>3</sup> had emphasized how spacing between buildings significantly affected pollution mitigation. Furthermore, architectural developments like green roofs and vertical gardens had helped reduce air pollution by trapping pollutants and supporting passive ventilation. This approach had been echoed by Y. Chen, S. Wang, J. Xie, and J. Jiang in their paper "Influence of 3D building configurations and tree plantings on urban pollutant dispersion"<sup>4</sup>.

Therefore, the present study adopted a mixed-methods approach—combining field data collection with experimental simulations—to examine the effect of building height and wind speed on urban pollution levels. Cities with low, medium, and high pollution rates had been selected for this analysis. Wind tunnel models had been constructed to simulate urban environments under various wind speeds and angles. Pollution loads were monitored in different model zones to evaluate how deeply pollutants penetrated and accumulated.

This research was highly relevant to urban planners. It had provided a clearer understanding of how vertical expansion altered a city's wind dynamics and pollution patterns. The study had offered actionable techniques for developing sustainable urban designs that prioritized air quality and public health amid rapid urbanization. These conclusions had aligned with the findings of F. Li, Z. He, C. Liu, and Y. Lin, who in their work "Optimization of urban design to reduce PM<sub>2.5</sub> pollution"<sup>5</sup> had proposed practical solutions to mitigate PM<sub>2.5</sub> concentrations through improved city layouts.

## Literature Review

The research by Shirzadi et al. tackled the problems related to the analysis of air pollution in urban areas in the vicinity of skyscrapers. Emissions from vehicles in thick urban environments, particularly near road intersections, resulted in sky-high concentrations of pollutants. This raised major health concerns. Moreover, the researcher noted the influence of urban buildings on pollution distribution: irregular shapes and the existence of smaller structures near the skyscrapers ushered in turbulence, further complicating the dispersal of pollutants through the air. On the other hand, the lack of a sufficient number of experimental tests was the main issue; due to this, the models that were applied were not validated<sup>1</sup>. Elsa Aristodemou et al. worked on the application of the Large Eddy Simulation (LES) method combined with wind tunnel experiments in this approach to the

computational fluid dynamics (CFD) problem. Using these two methods together, it was possible to model the transportation of pollutants and conduct experimental validation. In the analytical part, two studies were considered with two main objects: an independent tall building and another one standing among lower ones. In conclusion to this, it could be said that the buildings around modifiers at higher levels led to higher emissions. Finally, it was inferred that the maximum concentration was at two-thirds the height of the high-rise, which was five times higher than in the isolated situation. It was duly noted that the top-level inhabitants were in danger of high pollution. Moreover, the study also stated that the transport of air pollutants was a complicated process and that turbulent diffusion among components made it even harder<sup>6</sup>.

The study by Ding et al. examined the impact of air movement and pollutant spread in city areas through the fluctuation in the building heights and widths. The paper concerned the negative side effects of pollutants gathering near buildings, particularly high-rise buildings, on the environment. Relying on the Production-Limited Eddy Simulation (PLES) technique, they performed threat modeling of airflow experiments and contaminants around separated buildings. The tests of the models used different building sizes, and they were validated with some experimental data from Tokyo Polytechnic University<sup>7</sup>.

He et al. investigated the interrelationship between high-rise urban forms and wind environments in Macau with the dense Area Preta reclamation area. The paper discussed important problems such as inadequate ventilation, urban heat islands, and the dangers of typhoon winds in high-density residential areas. Through PHOENICS computational fluid dynamics software, the researchers mimicked the wind conditions during both regular days (seasonal monsoons) and extreme weather events (typhoons). The study analyzed the impacts of building sizes, street designs, and urban canyon directions by supplementing with field survey data and local urban planning standards<sup>8</sup>.

This study by Vidanpathirana et al. dealt with air pollution problems in high-populated urban environments and referred to several fast-developing cities, such as Colombo in Sri Lanka. It pointed out pollution issues due to the lack of ventilation and traffic emissions that worsened the air quality in the areas with dense building clusters. They focused on identifying how building morphology affects urban air pollution dispersion. By examining factors such as wind flow and the role of buildings as obstacles, the research aimed to give a new perspective on reducing pollution in future development plans. Furthermore, the study also indicated a knowledge gap in implementing urban forms and planning strategies that could lead to optimal improvements in the efficiency of ventilation<sup>3</sup>.

Chen et al. delved into the problem of urban air pollution and focused on the role of 3D building configurations and tree plantings in pollutant dispersion and building intake fractions. The study underlined the issues of pollutant buildup and air quality

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management inefficiency arising from poorly designed urban areas, which intensified the environmental problems. CFD simulations were employed to model the effect of various building geometries and vegetation layouts on airflow and pollutant behavior in urban areas. The researchers came up with elaborate simulations to find out how these factors affected the pollution spread and pollution concentration around the intake points of the buildings<sup>4</sup>.

Fan Li et al. addressed the challenges associated with urban air quality, referring to the dispersion of PM<sub>2.5</sub> pollutants in Shijiazhuang City, China. The principal issue on which researchers focused was to find the optimal urban designs to diminish air pollution concentrations and improve public health conditions. To find solutions to these problems, they tried to come up with approaches to strategically rearrange roads and trees in the city to enhance the wind velocity and reduce the pollution effects. In solving this problem, the scientists made use of Computational Fluid Dynamics (CFD) methods, with the standard k- $\epsilon$  model and the Disperse Phase Model (DPM). The research discussed how city arrangement designs could be improved so that they decreased pollutant levels and increased ventilation in cities<sup>9</sup>.

Lim et al. addressed the air pollution distribution problem in the study of tall buildings in urban areas. The results were that these buildings played a part in airflow and pollutant spreading, which had been affected by buildings in the surrounding areas. The project aimed to highlight the influence of the tower through the sky-high congestion of air which were the “rooftop shear layers” impacting both vertical upleash and pollutants transportation<sup>2</sup>.

Aristodemou et al. were trying to solve the problem of skyscrapers that not only disturbed the air flows but also became the source of pollutant dispersion in the cities. The ever-rising number of skyscrapers in cities had given rise to new energy flow, which in turn had implications for the effectiveness of air quality management across the urban landscape, which was vital for urban planning and air quality management activities. Their interest lay in the perception of those buildings and the spatial diversity derived from airflow modifications, especially in the centers of our cities<sup>10</sup>.

The study by Yang et al., with their colleagues, was about the growing problem of air pollution stagnation in high-density urban areas and the tremendous consequences for human health and urban liveliness. The research demonstrated that various types of urban forms (i.e. building height, orientation, and density) impacted the wind flow pattern, which then affected the exhaust emissions. Ineffectively ventilated urban areas, represented by calm wind zones or virtual formations, were one of the main contributing factors to the accumulation of air pollutants in such environments. These findings highlighted the need for strategic urban planning to mitigate pollution-related health risks<sup>11</sup>.

Yu et al. investigated the air pollutant diffusion behavior

near high-rise buildings with different angles of wind incidence, pointing out the importance of wind direction on pollutant concentrations and distribution. Their study showed that buildings could either block or channel the wind flow depending on the wind angle, thereby impacting the pollution levels near pedestrian areas. This research emphasized the need for precise modeling and wind tunnel testing to optimize urban planning decisions<sup>12</sup>.

Hertwig et al. studied the variability of physical meteorology in urban areas at different scales and its implications for air quality. The researchers highlighted the effect of urban morphology on local meteorological conditions, influencing pollution dispersion. Their study underscored the importance of considering multiple spatial scales when assessing urban air quality and designing mitigation strategies<sup>13</sup>. Kuo et al. explored pedestrian-level wind fields in street canyons downstream of parallel high-rise buildings. The study revealed how building arrangements affected airflow at pedestrian heights, influencing comfort and pollutant dispersion. Understanding these wind patterns could inform the design of more livable urban environments<sup>14</sup>.

Liu et al. performed wind tunnel tests to investigate indoor air pollutant dispersion and cross-contamination around typical high-rise residential buildings. Their research provided insights into pollutant transmission pathways in indoor and adjacent outdoor environments, crucial for designing healthier residential buildings<sup>15</sup>.

## Methodology

### City Data Collection

The research began by carefully investigating the availability of updated data about the chosen cities regarding density, pollution, and wind which was the reference point of the study. With city maps, the local AQIs of the areas, and the data platforms of the government or private meteorological services, data regarding the main indicators was obtained for many urban zones. Metrics such as average wind speeds, pollution levels (PM<sub>2.5</sub>), building heights (both the tallest and the shortest), and distances between the buildings were recorded. Historical and contextual studies like Yang et al.<sup>11</sup> and Huang et al.<sup>16</sup> provided background information to ensure the parameters chosen matched globally recognized research standards. High-resolution 3D remote sensing imagery, along with urban planning datasets derived from satellite-based building footprint maps and elevation models, were utilized to analyze city structures. Supplementary data from CPCBs hourly PM<sub>2.5</sub> pollution records and wind patterns were also integrated. Table 1 highlights Indian cities with high pollution levels and a dense concentration of high-rise buildings.

The decision on the selection of cities was driven by the different urban densities, wind patterns, and pollution dispersion

**Table 1** The Indian city with high pollution and high-rise buildings

City	Average Pollution Rate (PM2.5)	Average Wind Speed	Average Height of Buildings	Height of Tallest Building	Height of Shortest Building	Average Distance Between Buildings	Tallest Building Name	Source
New Delhi	120–150 $\mu\text{g}/\text{m}^3$	10–15 km/h	20–40 meters	43 meters	~10 meters	20–35 meters	Leela Palace	World Air Quality
Kanpur	110–140 $\mu\text{g}/\text{m}^3$	10–12 km/h	15–25 meters	35 meters	~10 meters	15–25 meters	Motijheel Apartments	AQI Kanpur
Patna	100–130 $\mu\text{g}/\text{m}^3$	8–10 km/h	20–30 meters	45 meters	~12 meters	20–30 meters	Takht Sri Harmandir Ji Patna Sahib	AQI Patna
Lucknow	90–120 $\mu\text{g}/\text{m}^3$	8–12 km/h	20–35 meters	55 meters	~10 meters	20–35 meters	Sahara City Homes	AQI Lucknow
Varanasi	85–115 $\mu\text{g}/\text{m}^3$	8–10 km/h	15–25 meters	50 meters	~10 meters	15–25 meters	Ramada Plaza JHV	AQI Varanasi

characteristics to give a complete picture of the environmental impacts of high-rise buildings. Navi Mumbai, Lokhandwala, and Gurugram were the three cities selected to represent low, medium, and high urban densities, respectively. Navi Mumbai with an average building height of 3040 meters and a relatively large span between buildings provided information about the relative wind speed. Lokhandwala, a city known for medium-density urbanization and architecture with an average height of 2535 meters, was used to test turbulence and pollution dispersion. Gurugram is characterized by its high-density areas and tall buildings with a height range of 30-50 meters, and a minimum inter-building spacing space, thus showing the problems of pollutant retention and urban heat island formation.

### 3D Printing of the City Model

To conduct an exact experimental analysis of the data, highly accurate, scaled 3D models of the selected city zones were built using advanced 3D printing technology. Figure 1 shows this model. The first stage of the experiment was to model the setup using 3D design software. PLA was used in this method of urban features to demonstrate practical examples of durability and precision operations. After printing the models at the given scale, their design remained the same as the real ones. The 3D models of this kind were the backbone for carrying out experiments in a wind tunnel with proper supervision, thus enabling wind flow modifications and pollutant movement to be observed in different urban densities. This approach guaranteed that in confidently controlled situations real urban cases were displayed correctly.

### Wind Tunnel Design

The wind tunnel section shown in Figure 2, has been scaled down in order to study the effect of high-rise buildings on urban wind flow and the dispersion of pollution. The scaling process was made feasible by adopting the full-scale dimensions of commonly used high-rise buildings whose representative heights and widths are based on city construction standards. Scaled building models got their heights and widths properly lowered so that they could be accommodated within the wind tunnel dimensions by using a scaling factor of 1:11. For the wall

effects to be minimized during testing, a safety factor of 1/3 was included in the test section dimensions. The test section's width and height of 1.5m and 0.6m, respectively, were fixed, providing a cross-sectional area of  $0.225\text{m}^2$ . The length of the test section was fixed at 0.9m which would give a testing length enough considering the scaled dimensions of the buildings.

The volumetric flow rate was determined from an airspeed interval of 25.7 to 77.1 m/s with an average of 50 m/s, which is out of the consideration of urban wind speeds and turbulence intensities. The corresponding flow rate is 247.5 cubic meters per second, which is the same as 524,422.8 cubic feet per minute (CFM). Two configurations for the fan placement were examined and for experimental result powder was randomly dispersed manually by placing the fan in the inlet, to generate turbulence or at the outlet to ensure the continuity of the laminar flow without any fluctuations. The latter option was selected to minimize the turbulence and thus reduce the use of flow dynamic controls. To attain flow uniformity, honeycomb straighteners, and mesh screens were designed with a cell diameter-to-length ratio (L/D) of 10 and a pressure drop coefficient of 0.2.

The contraction portion of the device has been constructed specifically to ensure faster traveling of air and less friction with the test section. A contraction ratio (CR) of 3 to 6 was employed along with a half-angle of  $8^\circ$ ; thus, besides the axis, cones are characterized by half of cone angles which may range between 5 and 9. Thus, in this layout, the length of the contraction section would be about 2 m. The shut-off areas of the contraction were adjusted correspondingly to the dimensions of 1.5 m by 0.6 m of the test section. Here the diffuser is credited with the recovery of the static pressure and in order to achieve this, its  $4^\circ$  expansion angle has been taken advantage of to suppress separation. The length was calculated by contraction ratio which was 5, and they acquired the cross-section of the exit part with the enlarged diameter of  $0.45\text{m}^2$ . 0.8 m was found to be the suitable length. The introduction of the grilled surfaces makes the flow uniform by inducing a pressure drop of 0.05 Pa for each surface, with a total pressure reduction of 0.12 Pa from the honeycomb straightener. These design aspects represent the fact that the test section is capable of a scaling factor, preservation of even fluidity, and pressure dissipation through the test section. The testing results of all three cities are explained in the next section of the paper.



Fig. 1 City 3D printed for the actual wind tunnel test

## Results and Discussion

### Wind Dispersion Patterns Across Cities

The wind tunnel experiment conducted across Navi Mumbai, Lokhandwala, and Gurugram offered insight into how wind interacts with different urban densities. The key parameters observed included wind speed, time duration, and the resulting height and width of the wind spread, along with impacts on heat retention and CO<sub>2</sub> trapping. From the data: Navi Mumbai, a city with relatively low urban density and wider building spacing, allowed for greater wind spread. At 15 km/h, wind spread increased to 20 m height and 35 m width, indicating effective natural ventilation and minimal heat accumulation. Lokhandwala, representing medium density, experienced moderate wind dispersion. At a higher wind speed of 12 km/h, width increased to 30 m, but the height remained 10 m, suggesting lateral spread was possible, but vertical dispersion was restricted, likely due to urban form. Gurugram, with high-density clusters and tall buildings, exhibited poor wind dispersion initially. Even at 15 km/h, though height and width reached 25 m and 35 m respectively, these values reflected limited efficiency in pollutant clearing due to the enclosed urban fabric, leading to higher CO<sub>2</sub> trapping and surface heat accumulation.

### Particulate Dispersion and Retention

The dispersion of particulate matter was evaluated by measuring the amount of powder spread, its concentration near buildings, and the total area of dispersion. This method provided quantitative support for how different city configurations influence pollutant spread. Since the size of powder particles resembles aerosol particle size hence powder particles exhibit similar dispersion properties.

### Observations:

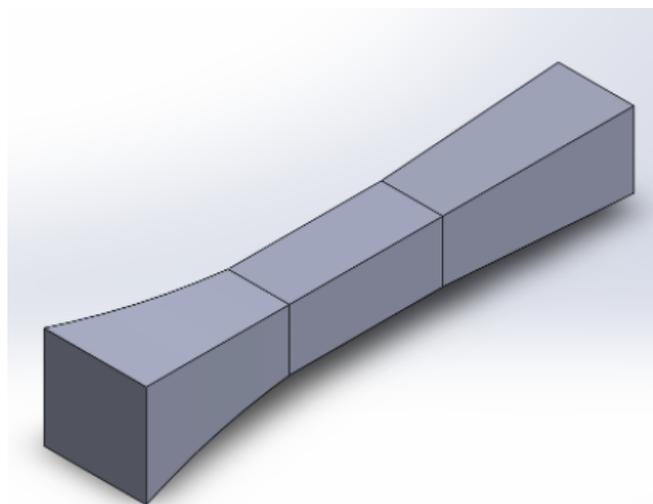
- **Wind speed** had a direct impact on dispersion area: in **Navi Mumbai**, a wind speed increase from 12 to 15 km/h expanded the dispersion area from **15 m<sup>2</sup> to 18 m<sup>2</sup>**, reducing near-building concentration from **0.3 to 0.25 g/m<sup>2</sup>**.
- **Urban density** influenced pollutant retention. **Gurugram**, despite higher wind speeds, had elevated pollutant concentrations (**0.5 → 0.45 g/m<sup>2</sup>**) due to limited ventilation caused by closely spaced high-rise buildings. The data shows how dense building forms can trap pollutants even under favorable wind conditions.
- In **Lokhandwala**, a moderate configuration, powder spread reduced from **12 g to 9 g**, and concentration near buildings fell from **0.4 to 0.35 g/m<sup>2</sup>** as wind speed increased. Dispersion area improved from **20 to 23 m<sup>2</sup>**, showcasing that modestly spaced urban forms provide better pollutant clearing than tightly packed clusters.

Table 2 Particulate Matter Data Insight

City	Wind Speed (km/h)	Time Interval (Sec)	Powder Spread (g)	Concentration Near Buildings (g/m <sup>2</sup> )	Total Dispersion Area (m <sup>2</sup> )
Navi Mumbai	12	10	10	0.3	15
	15	20	8	0.25	18
Lokhandwala	10	15	12	0.4	20
	12	25	9	0.35	23
Gurugram	10	20	15	0.5	25
	15	30	11	0.45	30

### Powder Dispersion Measurement

As shown in figure Post-experiment image processing was used to quantify the area of powder settlement across different urban model configurations. Binary thresholding isolated white



A CAD model of the Wind Tunnel Design



B Actual Wind tunnel made for the testing

Fig. 2 The wind tunnel CAD model and the actual Model.

pixel regions from top-view images, representing settled powder (analogous to PM2.5). The percentage of powder-covered surface area, denoted as  $P_{retained}$  was calculated for each case.

To interpret pollutant behavior, the following parameters were used:

### Pollutant Retention Index

$$R^* = \frac{P_{retained}}{P_{max}}$$

### Ventilation Effectiveness Score

$$\eta = 1 - R^*$$

### Empirical PM2.5 Concentration Relation

$$C_{PM2.5} \propto \frac{P_{retained}}{A_{effective}}$$

Where:

$P_{retained}$  : Powder-covered area (%)

$P_{max}$ : Maximum observed powder coverage (7.4%)

$\eta$ : Relative indicator of airflow efficiency

$A_{effective}$  : Urban area participating in ventilation

$C_{PM2.5}$ : Expected pollutant concentration in real-world scenarios

Table 3 Powder Spread and Derived Metrics for Urban Cases

Case Type	Pertained (%)	R*	$\eta$	Interpretation
Medium-Density	7.4	1	0	Significant pollutant retention; poor ventilation
High-Density	3.4	0.46	0.54	Moderate airflow; better dispersion under test wind

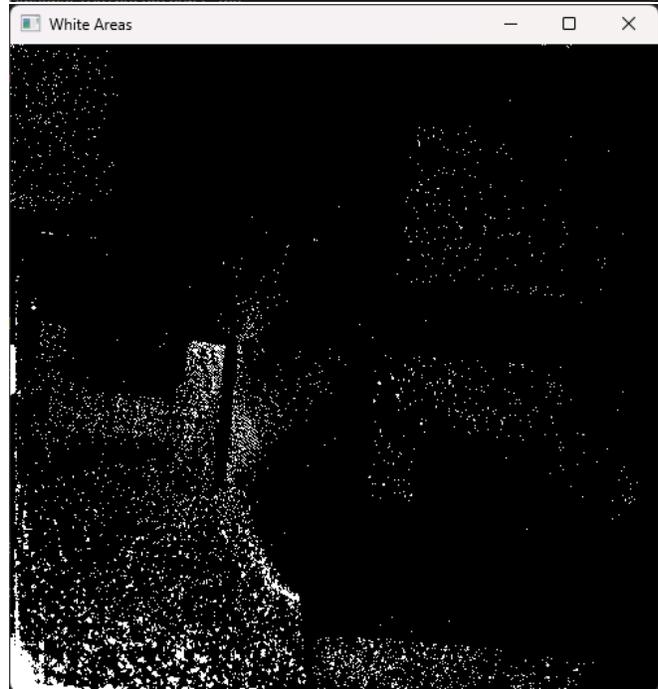
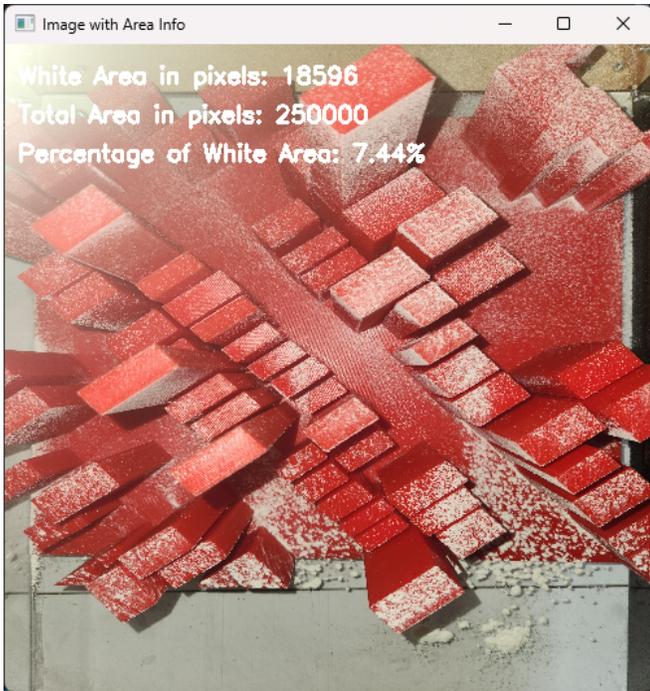
### Summary of Impacts

The integrated analysis confirms three central findings:

1. **Higher wind speeds consistently improve horizontal pollutant dispersion**, evidenced by increased spread area in all cities. However, without adequate building spacing and lower urban density, this benefit is greatly diminished.
2. **High-density urban environments, such as Gurugram, show greater accumulation of pollutants**, higher heat retention, and lower efficiency in natural air circulation, even when wind conditions are optimized.
3. **Moderate-density zones like Lokhandwala strike a middle ground**, offering partial pollutant clearing and moderate thermal behavior, suggesting that optimized zoning and building arrangement can balance urban growth with environmental quality.

### Conclusion

This research has offered a detailed understanding of how urban density, building configuration, and spatial planning impact wind behavior, pollutant dispersion, ecological balance, and heat retention within cities. Through wind tunnel experiments using scaled 3D models of three distinct urban layouts—Navi Mumbai (low-density), Lokhandwala (medium-density), and Gurugram (high-density)—the study has highlighted the crucial role of strategic architectural planning in mitigating environmental stressors.



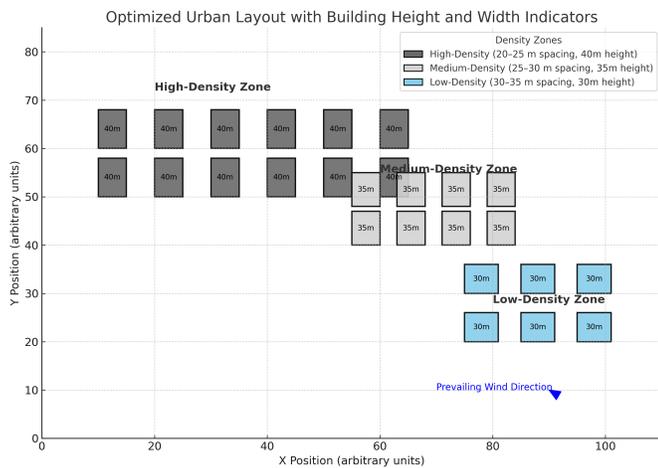
(a) Medium Density Prototype and black and white image after the experiment

(b) Low Density Prototype and black and white image after the experiment

Fig. 3

Figure 4 indicates figures of optimal building spacing for good air flow. The series of experiments was conducted to check by keeping the building at there actual spacing in real

time, also by increasing the distance between the building and by decreasing the distance. In case of low-density areas such as Navi Mumbai, where there was space between 3035 meters



**Fig. 4** The optimum distance between the buildings for better wind flow

between buildings and it was staggered in layout, the wind flow was smooth and not turbulent. This helped the pollutants disperse better and minimized CO<sub>2</sub> retention and heat absorption. For example, with an increase in wind speed from 12 to 15 km/h, the dispersion area was increased from 15 to 18 m<sup>2</sup>, and pollutant concentration closer to buildings decreased from 0.3 to 0.25 g/m<sup>2</sup>.

Medium-density developments like Lokhandwala, with 2530 meter inter-building distances and moderate building heights, found a balance. Airflow was stable enough but some turbulence was noted, especially at higher wind velocities. Pollution and ecological disturbance levels were moderate; however, staggered patterns still provided satisfactory pollutant dilution as well as airflow continuity.

Conversely, the high-density urban setting of Gurugram—with spacings between buildings of 2025 meters and building heights of 40 meters—exhibited higher turbulence and pollutant trapping. Near-field pollutant concentration around buildings rose to 0.5 g/m<sup>2</sup> at 10 km/h, with the dispersion area increasing to 30 m<sup>2</sup> at 15 km/h. The urban heat island effect grew stronger because of inefficient heat dissipation.

In general, the research reiterates that ideal urban design—incorporating spacings of 2530 meters or more, building heights of less than 40 meters, and orienting streets with the direction of prevailing winds—can remarkably improve wind distribution, prevent pollution deposition, promote ecological integrity, and alleviate urban warming. These findings provide useful lessons for future urban planning strategies towards creating climate-resilient and environmentally sustainable cities.

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