MANZAR, *18*(75), 28-37 / 2026
DOI: 10.22034/manzar.2025.538692.2370

Persian translation of this paper entitled:
تحلیل عددی تأثیر الگوی چیدمان و کشیدگی ساختمان‌ها در بلوک‌های مسکونی
مستقر در مجاورت شریان‌های ترافیکی بر کیفیت هوا در فضای باز بین ساختمان‌ها
is also published in this issue of journal.

Original Research Article

Numerical Analysis of the Impact of Building Layout Patterns and Elongation in Residential Blocks Adjacent to Traffic Arteries on Outdoor Air Quality between Buildings

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Received: 04/08/2025 Accepted: 15/10/2025 Available online: 22/06/2026

Abstract | The circulation of motor vehicles is one of the defining features of urban life in contemporary cities. However, particulate matter produced by fuel combustion in vehicle engines is considered one of the most significant contributors to air pollution in metropolitan areas. These particles are carried by wind into surrounding spaces, leading to a decline in air quality in built environments located adjacent to heavily trafficked urban arteries. It appears that by selecting appropriate building forms in such areas, it is possible not only to improve natural ventilation but also to partially prevent the penetration of pollutants into the open spaces of these complexes. This study investigates the impact of building layout configuration and elongation patterns in residential complexes located near heavily trafficked urban highways on air quality within the open spaces between them. To assess air quality, three parameters were used: wind speed, mean age of air, and the concentration of accumulated pollutants in the central open space between buildings. To extract case-study samples, three building elongation patterns were initially considered: a square pattern, a rectangular pattern elongated perpendicular to the prevailing wind direction, and a rectangular pattern elongated parallel to the prevailing wind direction. Each form was then arranged in six different layout configurations.

Ultimately, 18 case-study samples were generated, each containing a fixed central open space of 225 square meters as the study area. All case studies were assumed to be located 35 meters from an urban highway considered as the source of pollutant emissions. The findings indicate that increasing spatial enclosure through a centralized layout pattern in residential complexes, although reducing pollutant concentration in the central open space, significantly decreases ventilation quality in these areas. Additionally, increasing permeability along façades facing pollutant sources can facilitate the transfer of pollutant particles into the open spaces between buildings. Therefore, elongating building blocks perpendicular to the prevailing wind direction is one of the factors that can help prevent pollutants from entering the leeward open spaces behind them.

Keywords | *Residential complex layout pattern, building elongation, air quality, open space, CFD simulation.*

Introduction| Today, apartment living has become a common lifestyle in cities. Due to limited private open spaces in such dwellings, residents are compelled to use public open areas. One type of such space is the open courtyards within residential complexes. Improving the qualitative aspects of these spaces can increase their use, thereby enhancing vitality in residential environments (Saadatjou & Saligheh, 2021).

People's presence and continued use of urban open spaces depend on different factors, among which environmental comfort is crucial. Thermal comfort is influenced by

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several factors, including temperature, humidity, and wind (Yin et al., 2015; Hadianpour et al., 2019). Urban wind flow is mainly affected by building form and layout (Yousefian et al., 2017; Fatahi et al., 2021). Changes in density, spacing, height, form, and street geometry influence urban wind patterns (Pilechiha et al., 2020). Similarly, the arrangement of blocks within a complex can influence wind flow and, consequently, ventilation patterns in open spaces (Jiang et al., 2020; Eskandari et al., 2017).

In addition to comfort, air quality significantly influences people's presence in open spaces (Li et al., 2009). Airborne pollutant concentration is one of the most important indicators of air quality (Xie et al., 2005; Hassan, 2020). Pollutants such as NO_2, CO, SO_2, etc., generated from sources like factories and power plants, are carried by wind into urban areas (Barwise & Kumar, 2020). This increases pollutant levels in open urban spaces, raising pollution indices. Although wind improves natural ventilation, in neighborhoods located near pollution sources, it may increase pollutant concentrations between buildings (Liang et al., 2020).

Vehicular traffic is a major source of airborne pollutants (Baralis et al., 2016). Vehicle exhaust contains various pollutant particles dispersed across urban spaces, especially along major roads such as urban highways. Residential complexes adjacent to highways are therefore more exposed to pollution. This problem worsens when the prevailing wind is perpendicular to the highway and directed toward the residential fabric.

Thus, strategies that maintain natural ventilation while preventing pollutant intrusion are essential. Since building form and layout strongly influence wind flow, this study analyzes these factors in hypothetical complexes located near a highway. Three basic building forms were considered: square form (S-pattern), rectangular form elongated perpendicular to prevailing wind (H-pattern), and rectangular form elongated parallel to prevailing wind (V-pattern). Each form was analyzed in six layout patterns using CFD simulations to evaluate ventilation and pollutant concentration in the central open space (constant across all cases). The study sought to answer the following research question.

How do building elongation and layout patterns in a residential complex adjacent to a highway influence airflow speed and the concentration of accumulated pollutants in its central open space?

Literature Review

The research background of the present study can be examined from two perspectives: (a)Studies related to airflow within open spaces between buildings, (b) Studies concerning airborne pollutants originating from external sources in the spaces between buildings. The following section reviews several relevant studies addressing the role of building form and layout patterns on ventilation flow within the outdoor spaces separating them.

In a study conducted by Jiang et al. (2019) in Wuhan, the influence of residential block layout patterns on pedestrian-level surrounding airflow and associated thermal comfort was evaluated. Their findings indicated that a linear arrangement pattern, by creating airflow corridors, increased wind speed by 0. 3 m/s. However, a stepped arrangement aligned with the prevailing wind direction increased wind speed by 0. 4 m/s. In another study carried out by Ying et al. (2020) in Hangzhou, the role of various centralized block layout patterns on the passing airflow in their open spaces was investigated. They concluded that the layout pattern of the buildings has a significant effect on wind speed and the behavior of airflow around the buildings. Their results indicated that a clustered arrangement of blocks and an increased number of courtyards perform more efficiently than a single continuous central courtyard.

Saadatjoo and Saligheh (2021) were among the researchers who emphasized the role of building block arrangement on natural ventilation within the open spaces between them. In their study, they selected ten case samples, including one base case and nine variants with different layouts, and analyzed airflow passing between them using CFD simulations. Their results demonstrated that reducing the distance between blocks increases wind speed, whereas increasing the spacing reduces wind speed within the open areas. In another study, Saadatjou (2021) examined the effect of façade recesses on urban wind performance. A neighborhood unit consisting of nine mid-rise building blocks was simulated in a CFD environment, and various recess configurations were applied to the central building. The findings showed that applying recesses to the central building increased wind speed around the building by 48.33%. Regarding the role of building form and layout patterns on pollutant concentration in the open spaces between buildings, the following studies can be noted: In the study by Yang et al. (2020), the influence of urban form on pollutant dispersion within inter-building spaces in high-density urban centers was examined. They assessed the effects of variations in building height, volume, form, and density on pollutant dispersion between buildings. Their results showed that although these variables significantly affect airflow patterns and pollutant distribution, the accumulation of pollutants around high-rise buildings is considerably greater than in other parts of the site.

Li et al. (2005) investigated air quality in an urban street canyon and examined the impact of building configuration along the canyon on pedestrian-level air quality. They found that high-speed winds in windward step-up canyons improve air quality relative to leeward step-up canyons. Conversely, under low-wind conditions, air quality in leeward step-up canyons is better than in windward step-up canyons. In another study, Cui et al. (2021) examined the effects of building arrangement and height variation in two street canyons with symmetric and asymmetric (stepped) configurations on airflow and pollutant dispersion. Their findings indicated that pollutant dispersion in symmetrically shaped canyons is significantly lower than in asymmetric (stepped) canyons.

A review of the aforementioned studies indicates that although the effects of different building layout patterns on passing airflow have been examined in numerous investigations, the simultaneous impact of these patterns on ventilation quality and pollutant dispersion within the open spaces between buildings has not yet been comprehensively assessed. Accordingly, the present study evaluates the influence of building elongation and layout patterns in residential complexes situated adjacent to a pollution source on air quality within the open spaces between them.

Research Methodology

As previously noted, the principal objective of the present study is to evaluate the effects of building elongation and layout configuration within a residential complex situated adjacent to an urban highway (considered as the pollutant emission source) on air quality within its central open space. Accordingly, building elongation and layout pattern within the complex were defined as the independent variables, while air quality in the open space between buildings serves as the dependent variable.

To assess air quality, three indicators were employed: air velocity, air age, and the concentration of pollutants accumulated within the open space at the center of the complex. The research method was based on simulation using Computational Fluid Dynamics (CFD). The following sections describe additional methodological components.

• An introduction to case study studies

As explained earlier, two factors—building form and layout pattern—were considered as independent variables in this study. With respect to building form, three elongation patterns were defined as the base configurations: square form (S-pattern), rectangular form elongated perpendicular to the prevailing wind (H-pattern), and rectangular form elongated parallel to the prevailing wind (V-pattern). In the next step, each of these geometric patterns was incorporated into six distinct layout configurations, as illustrated in Fig. 1, resulting in a total of 18 case samples. The layouts associated with the square form were labeled Case-S 01 to Case-S06; those related to the perpendicular-elongated rectangular form were labeled Case-H 01 to Case-H06; and finally, the cases derived from the parallel-elongated rectangular form were labeled Case-V 01 to Case-V06.

Each case consists of a residential complex comprising eight building blocks, each with a floor area of 100 m^2 and a height of 10 m, arranged around a central open space measuring 225 m^2. The complexes are positioned 15 meters from an urban highway, which is considered the source of traffic-related air pollutants. The distance between the highway and the central open space (the study area) is 35 meters, and this value is kept constant across all case samples. Fig. 2 presents the plan of one of the complexes, illustrating the building dimensions, the location of the central open space, and its distance from the pollution source (Fig. 2).

• Computational domain, boundary conditions, and mesh

The computational domain used for analyzing the case samples in this study was defined based on the guidelines of Franke et al. (2011) and Tominaga et al. (2008). According to these guidelines, the domain dimensions should extend

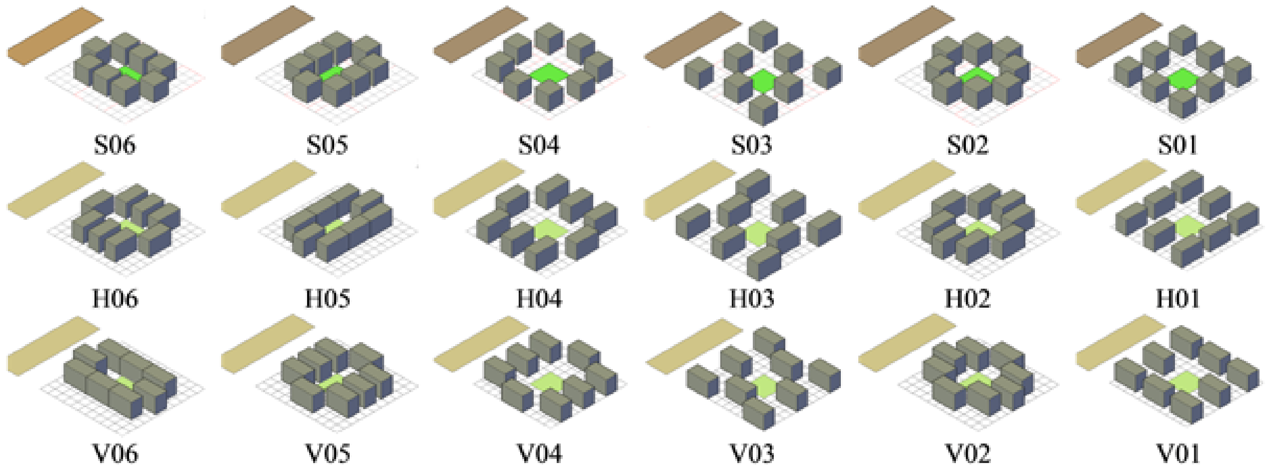

Fig. 1. Case study samples of the research. Source: Authors.

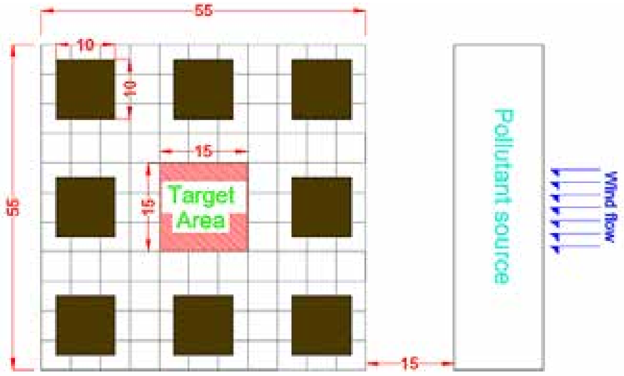

Fig. 2. Morphological features of the complex in one of the case study samples, including building dimensions, the location of the central open space, and the distance from the pollution. Source: Authors.

10H upstream, 20H downstream, and 10H on each lateral side, where H represents the height of the buildings. Given that the building height in all case samples is 10 meters, the dimensions of the computational domain were calculated as L × W × H = 385 × 255 × 110 m^3 (Fig. 3).

A computational mesh consisting of 1,064,479 cells was generated. The cells used in the mesh are predominantly prismatic and hexahedral, since hexahedral cells produce smaller shear errors and offer improved iterative convergence performance (Fig. 4).

In this study, Atmospheric Boundary Layer (ABL) characteristics under neutral stability conditions were employed in modeling the samples (Richards, 1986; Harris, 1981). Since the validation results provided in the reference study were based on two variables—air velocity and pollutant concentration—two separate models with different inlet wind speeds were used in this research as well. Accordingly, to evaluate air velocity and pollutant concentration, inlet velocities of 4. 6 m/s and 0. 78 m/s, respectively, were applied at the upstream boundary of the computational domain. In addition, a mass flow rate of 5 was imposed for the pollutant at the boundary conditions. A zero static pressure condition was specified at the outlet boundary. In this research, the steady three-dimensional RANS equations were solved in combination with the SST k–ω turbulence model. The solution procedure was performed in steady-state mode, and the simulated flow was considered incompressible. The SIMPLE algorithm was used for pressure–velocity coupling, and a fifth-order modified Petrov–Galerkin scheme was employed for discretizing the transport equations of the RANS model. The Average Residual Output (ARO) values for the converged solution were 10^{-5} m/s for the u-velocity field, 10^{-6} m/s for the v-velocity field, and 10^{-11} Pa for the pressure field.

- **Software validation**

Software validation for the present study was conducted based on the work of Bady et al. (2011). In that study, wind velocity and pollutant concentration were examined across four models representative of urban building configurations, among which Type (I) was selected for validation in this research. Measurements were performed at pedestrian height along the street canyon enclosed by Block Types A and B (Fig. 5). The physical model consisted of eight Type A blocks and two Type B blocks, all with an equal height of 9 meters, positioned at 1-meter intervals.

The wind tunnel used in the reference research measured 13 m in length, 2. 2 m in width, and 1. 8 m in height. The models were constructed from wood at a 1:100 scale and mounted on a rotating table inside the wind tunnel to allow assessment of different wind directions. In the validation study, six wind incidence angles were examined; however,

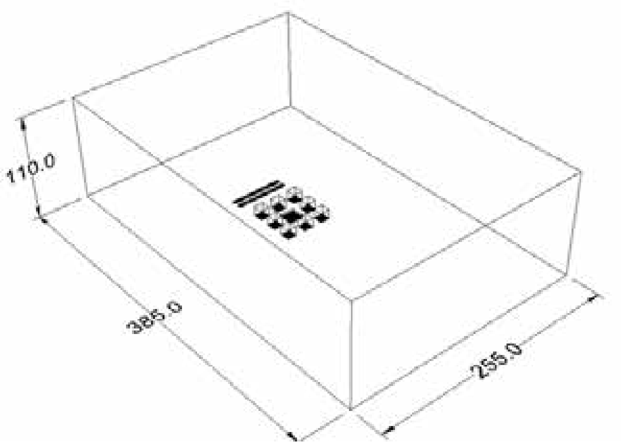

Fig. 3. Dimensions of the computational domain in the simulation of the case study samples. Source: Authors.

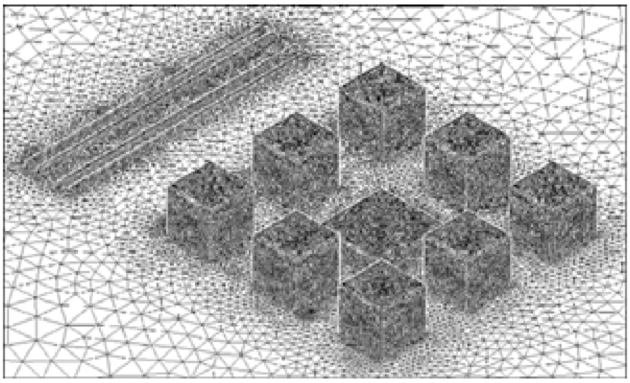

Fig. 4. Example of the mesh used in CFD simulations of the case study samples. Source: Authors.

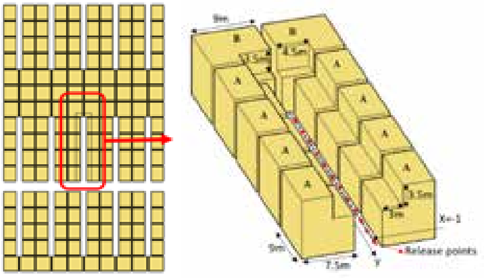

Fig. 5. Site plan and 3D model of the validation case Source: Bady et al., 2011.

in the present research, the validation simulations were carried out only under the 0° wind angle.

For wind speed and gas concentration measurements, reference velocities of 4. 6 m/s and 0. 78 m/s, respectively, were used. Ethylene gas (C_2H_4) with a concentration of 12,100 ppm served as the pollutant source (ASHRAE, 2022). The simulation results are presented in the form of wind speed and pollutant concentration profiles at a height of 1. 5 meters above ground level within the central area of the model (Fig. 6).

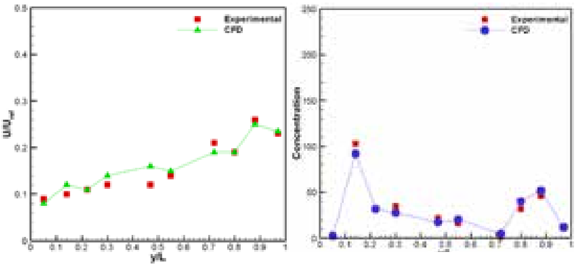

Fig. 6. Validation results comparing experimental data from Bady et al. (2011) with CFD results in the present study; right: validation of pollutant concentration, left: validation of wind speed. Source: Authors.

Findings

As previously noted, air quality within the open space between the residential complexes in the case studies was considered the dependent variable of the research. To analyze this, three indicators—air velocity, air age, and the concentration of accumulated pollutants within the space—were used. Accordingly, this section presents the results of the simulations for the case studies, organized by these indicators.

- **Air velocity analysis**

One of the climatic indicators employed in the assessment of air quality, particularly in relation to open urban spaces, is air velocity. A reduction in wind speed in an urban open space can lead to the accumulation of airborne pollutants and, consequently, a decline in user comfort. Figs. 7– 11 display the numerical values of average wind speed at a height of 1. 70 meters above ground level for the different layout patterns, and Fig. 12 illustrates the contour maps of wind speed at the same height for the case studies. Based on the diagrams above, the following points can be inferred.

-The highest average wind speed among the samples related to the S pattern occurs in Case-S03, with a value of 0. 61 m/s, and the lowest average speed occurs in Case-S05, with 0. 27 m/s (Fig. 7).

-The highest average wind speed among the samples related to the H pattern occurs in Case-H03, with a value of 0. 48 m/s, and the lowest average speed occurs in Case-H05, with 0. 19 m/s (Fig. 8).

-The highest average wind speed among the samples related to the V pattern occurs in Case-V03, with a value of 0. 71 m/s, and the lowest average speed occurs in Case-V06, with 0. 33 m/s (Fig. 9).

-Among all samples examined in this study, the highest average wind speed occurs in Case-V03, and the lowest average speed occurs in Case-H 05 (Fig. 10).

-In general, the average wind speed in the case studies belonging to the V pattern is the highest, while that of the H pattern is the lowest (Fig. 11).

- **Air age analysis**

Air age refers to the length of time air remains in an environment. Since the present study analyzes air quality in the open space

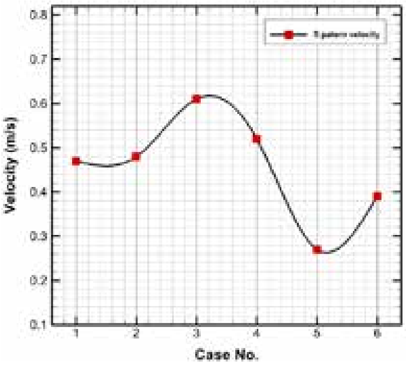

Fig. 7. Average wind speed in case studies of the S pattern. Source: Authors.

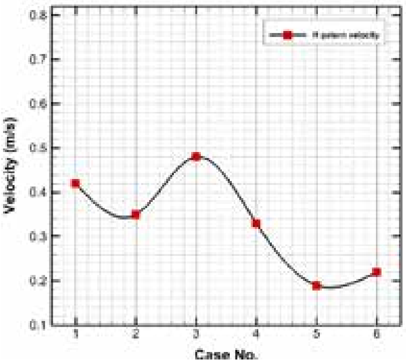

Fig. 8. Average wind speed in case studies of the H pattern. Source: Authors.

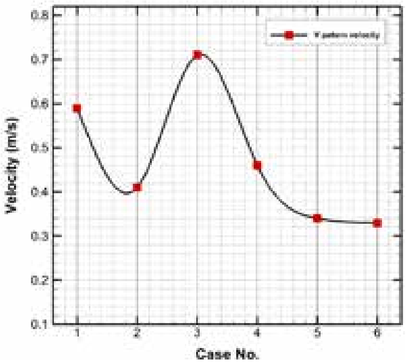

Fig. 9. Average wind speed in case studies of the V pattern. Source: Authors.

between residential building blocks, the layout pattern and spatial arrangement of the surrounding blocks can influence the residence time of air within these intermediate spaces. To evaluate this indicator in the study area, the mean air age up to a height of 1. 70 meters above ground level was examined. The results are presented in the diagrams shown in Figs. 13 to 17.

Based on the diagrams above, the following points can be inferred.

-The highest average pollutant concentration among the samples in the S pattern occurs in Case-S05, with 11,233 ppm, and the lowest value occurs in Case-S03, with 5,326 ppm (Fig. 18).

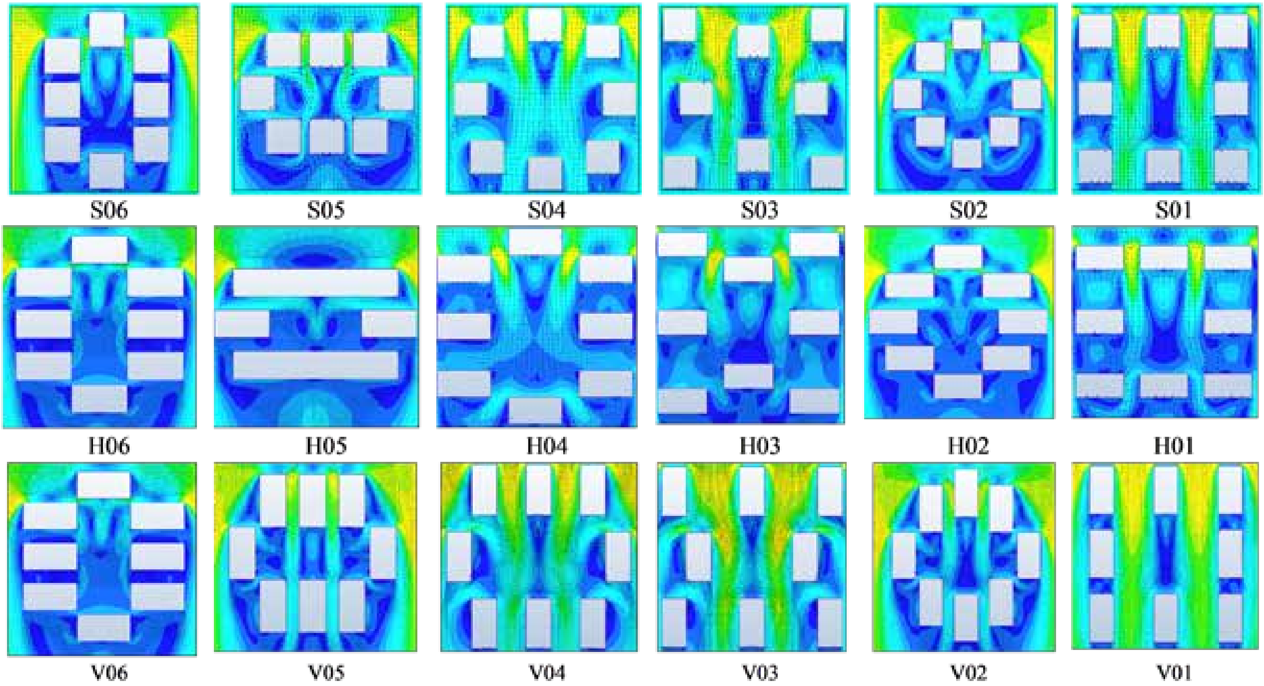

Fig. 12. Wind speed contours at 1.70 meters above ground level in the case study samples. Source: Authors.

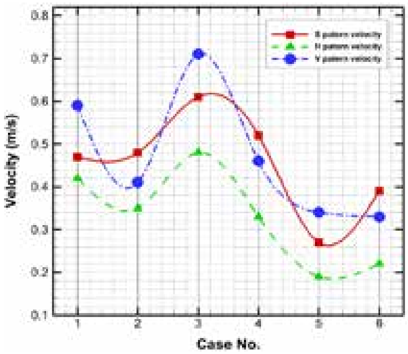

Fig. 10. Comparison of wind speed values across case studies in different patterns. Source: Authors.

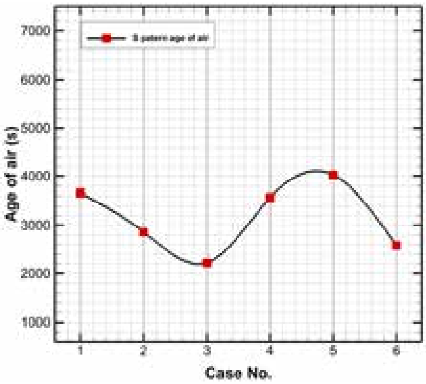

Fig. 13. Average air age in the case study samples of pattern S. Source: Authors.

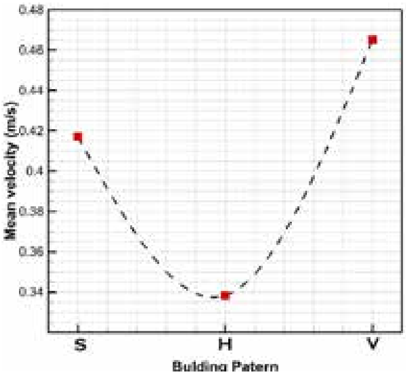

Fig. 11. Overall average wind speed in case studies across different patterns. Source: Authors.

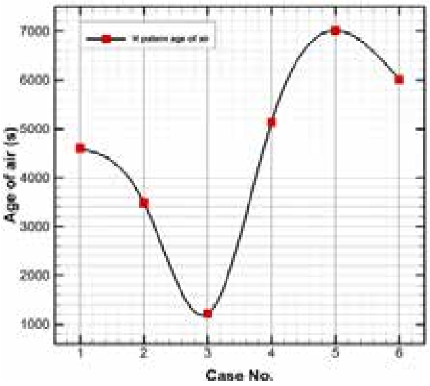

Fig. 14. Average air age in the case study samples of pattern H. Source: Authors.

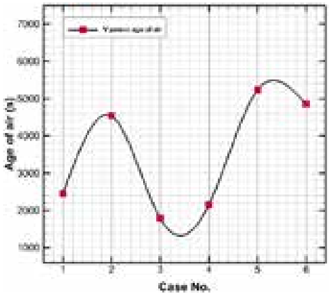

Fig. 15. Average air age in the case study samples of pattern V. Source: Authors.

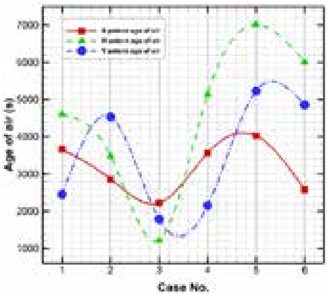

Fig. 16 .Comparison of air age values in case study samples across different patterns. Source: Authors.

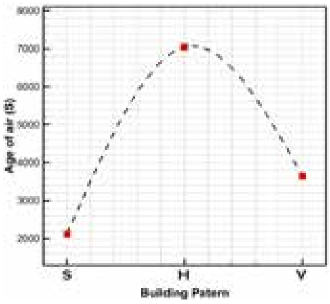

Fig. 17. Overall average air age in case study samples across different patterns. Source: Authors.

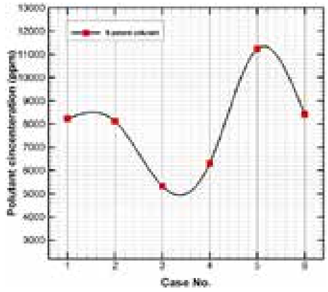

Fig. 18. Average pollutant concentration in pattern S. Source: Authors.

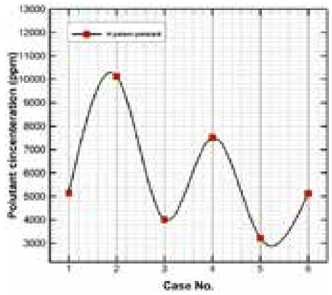

Fig. 19. Average pollutant concentration in pattern H. Source: Authors.

-The highest average pollutant concentration among the samples in the H pattern occurs in Case-H02, with 10,123 ppm, and the lowest value occurs in Case-H05, with 3,212 ppm (Fig. 19).

-The highest average pollutant concentration among the samples in the V pattern occurs in Case-V05, with 9,423 ppm, and the lowest value occurs in Case-V03, with 4,463 ppm (Fig. 20).

-Among all samples analyzed in this study, the highest mean accumulation of pollutants occurs in Case-S05, while the lowest occurs in Case-H 05 (Fig. 21).

-Overall, the mean pollutant concentration is highest in the S pattern and lowest in the H pattern (Fig. 22).

Discussion

As mentioned earlier, the main objective of the present study is to analyze the impact of building form and elongation in a residential complex located adjacent to an urban highway on air quality in the open central space of the complex. Accordingly, three building elongation

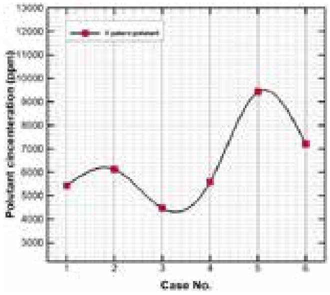

Fig. 20. Average pollutant concentration in pattern V. Source: Authors.

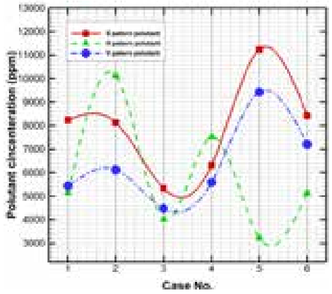

Fig. 21. Comparison of pollutant concentration values across case study samples in different patterns. Source: Authors.

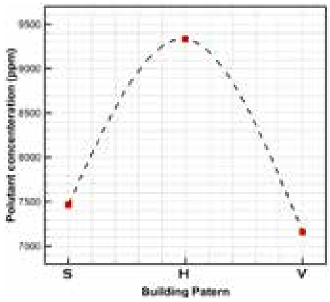

Fig. 22. Overall average pollutant concentration in case study samples across different patterns. Source: Authors.

patterns—square (S), rectangle elongated perpendicular to the prevailing wind (H), and rectangle elongated parallel to the prevailing wind (V)—each analyzed in six different layout configurations (Fig. 1), were considered as the study cases. Based on the quantitative results presented in the findings, the following observations can be made:

Air age and pollutant accumulation: An increase in air age in open spaces is directly associated with higher pollutant accumulation in that space. This trend is observed across all three building form patterns studied. In each case, samples with the highest air age also show the highest average pollutant concentrations, whereas samples with the lowest air age exhibit the lowest pollutant concentrations. This relationship is inversely related to air velocity; samples with higher air age generally correspond to lower air velocities, and vice versa.

-Spatial openness and enclosure: The layout patterns can be classified in terms of openness and enclosure. For instance, Case-03, Case-01, and Case-04 in all three patterns exhibit the highest spatial openness, while Case-05, Case-06, and Case- 02 show the greatest spatial enclosure. Analysis of the quantitative results reveals a significant relationship between spatial openness and the studied indices. Greater openness leads to increased air velocity, reduced air age, and consequently lower pollutant accumulation in the open space, whereas higher enclosure results in decreased air velocity, increased air age, and higher pollutant concentrations within the space.

Permeability of building facades facing the pollution source: The degree of permeability of facades facing the pollution source plays a critical role in air quality within open spaces. Reduced permeability on the windward facade significantly decreases pollutant intrusion into the central open space. This effect is evident in Case-H05, which exhibits the lowest pollutant concentration among all H-pattern cases and across all study cases. However, while reduced permeability limits pollutant entry, it also restricts airflow into the complex, resulting in lower air velocity and higher air age. Data for Case-H^{05} indicate the lowest average air velocity and the highest air age in its central space compared to other cases. Therefore, although pollutant ingress is minimized, ventilation is insufficient, making this case suboptimal from an air quality perspective.

Optimal air quality: Ideal air quality in open spaces is achieved when building form and layout both limit the entry of external pollutants into the central area and simultaneously allow effective natural ventilation between buildings. Based on the study cases, Case-H^{03} appears to provide a more favorable balance in terms of air quality indices. The elongation of the building blocks perpendicular to the pollutant flow partially blocks pollutant entry into the central space, while the spatial openness created by the arrangement of the blocks facilitates effective ventilation. Similarly, Case-S^{03} and Case-V^{03} also demonstrate reduced pollutant concentration and increased air velocity in the central space, suggesting their suitability as preferable configurations for air quality in the open spaces between complexes.

Conclusion

The presence and comfort of individuals in urban open spaces are influenced by various factors, among which air quality is one of the most critical. According to the existing literature, air quality encompasses multiple aspects, ranging from ventilation efficiency to the concentration of airborne pollutants. This issue becomes particularly significant in complexes located adjacent to pollution sources. One such source of urban pollution is highways, where a large number of vehicles operate daily, releasing exhaust gases that contribute substantially to air pollution in major cities. These gases carry particulate matter that can be transported by urban winds. When these suspended particles enter open spaces adjacent to highways, air quality indices deteriorate significantly. This is especially critical for open spaces within residential complexes situated near such traffic corridors.

However, building form and layout patterns can partially mitigate the infiltration of pollutants into the interstitial open spaces. Accordingly, the present study aimed to assess air quality in residential blocks with different forms and layout patterns located adjacent to an urban highway. Three building elongation patterns—square, rectangle elongated perpendicular to the prevailing wind, and rectangle elongated parallel to the prevailing wind—each in six different layout configurations, were considered as study cases near a highway (serving as the pollution source). A total of 18 case studies were simulated using CFD software, and three air quality indicators—air velocity, air age, and pollutant concentration in the central open space—were analyzed across all cases.

The key findings from these simulations are as follows:

-There is a significant relationship among the three indicators—air velocity, air age, and pollutant accumulation—in the open spaces between complexes adjacent to urban highways. Specifically, an increase in air velocity leads to a reduction in air age and, consequently, lower pollutant accumulation in these spaces, and vice versa.

-Increased spatial enclosure due to centralized layout patterns in residential complexes reduces pollutant concentrations in the central open space. However, this configuration negatively impacts ventilation indicators—air velocity decreases, and air age increases in the central space due to limited wind penetration. Therefore, while increased enclosure can lower pollutant concentrations, it simultaneously reduces ventilation quality, making it a less desirable option from the perspective of overall air quality.

-Enhanced permeability of building facades facing pollution sources may facilitate the transport of pollutants into interstitial open spaces. Consequently, elongation of building blocks perpendicular to the prevailing wind can serve as an effective strategy to prevent pollutant penetration into the leeward space. Nonetheless, this elongation must not obstruct adequate ventilation. Therefore, the layout of building blocks should be designed to ensure proper air circulation in the interstitial open spaces, balancing pollutant protection with sufficient ventilation.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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HOW TO CITE THIS ARTICLE

Sharifi, R., Heidari, A., Keshmiri, H., & Shamodini, A. (2026). Numerical Analysis of the Impact of Building Layout Patterns and Elongation in Residential Blocks Adjacent to Traffic Arteries on Outdoor Air Quality between Buildings. *MANZAR, The Scientific Journal of Landscape, 18*(75), 28-37.

DOI: 10.22034/manzar.2025.538692.2370

URL: https://www.manzar-sj.com/article_237626.html?lang=en