Simulation of PM_{10} and $PM_{2.5}$ Pollutant Dispersion Based on Urban Morphology and the Computational Fluid Dynamics (CFD) Method

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Abstract

Air pollution is one of the most serious environmental problems in large cities, particularly in developing countries, where it has escalated into a major crisis that endangers public health. To better understand and manage this issue, Computational Fluid Dynamics (CFD) provides an effective tool for analyzing airflow and pollutant dispersion in complex urban settings. This study aims to examine how urban morphology affects ventilation efficiency and pollutant dispersion using three-dimensional (3D) modeling integrated with CFD simulation. The case study focuses on Mashhad, Iran's second-largest metropolis, within a 300-meter radius of the Avini Air Quality Monitoring Station. First, a detailed 3D model of the study area was created using geospatial building data, including height and geometry. Then, the dispersion of $PM_{2.5}$ and PM_{10} particles was simulated in the CFD environment based on actual air quality data and prevailing wind conditions. The Residence Time Index (RTI) was calculated to represent the ability of the built environment to retain pollutants. Model validation was performed through comparison with results from a reference study, confirming good agreement and reliability. The findings indicate that areas with higher building density and lower wind velocity tend to trap more pollutants, leading to increased particle accumulation. Variations in building height and differences between PM_{10} and $PM_{2.5}$ behavior also influence dispersion patterns. Overall, integrating 3D urban modeling with CFD analysis provides a robust approach to understanding pollutant dynamics in urban areas and supports sustainable planning strategies aimed at improving air quality.

1. Introduction

Environmental concerns are among the most pressing challenges of our time and play a central role in shaping the global discourse on sustainability. Neglecting these issues poses serious threats to sustainable development at both local and global scales (Zangooei & Asadollahfardi, 2017). In Iran, a combination of factors including low-cost energy, outdated infrastructure, technological stagnation, rapid population growth, and urbanization has contributed to escalating energy consumption. Consequently, emissions from fossil fuel combustion have increased significantly, exacerbating the country's environmental problems. This pollution not only affects ecosystems but also directly impacts human health, particularly in urban areas where pollution levels are typically higher.

Particulate matter (PM), one of the most harmful forms of air pollution, has been identified as a major contributor to various chronic diseases, including cardiovascular and respiratory disorders. Managing PM pollution has therefore become a critical aspect of controlling urban air quality. Studies have consistently shown that the impacts of particulate pollution extend beyond short-term health consequences, leading to long- term public health burdens and increased healthcare costs. Accordingly, developing effective strategies for air pollution control, especially in urban environments, is essential for promoting public health and sustainability (Mahmoudzadeh et al., 2023).

A growing body of research focuses on spatial analyses to better understand pollutant distribution and impacts. These analyses provide insights into the sources, concentrations, and environmental and health effects of pollutants in urban settings. The primary advantage of spatial analysis is its ability to reveal pollution patterns across different geographical regions, enabling more targeted interventions. This approach allows researchers to identify areas with high pollution levels and evaluate the local sources contributing to environmental degradation.

Understanding spatial distribution is crucial, as it not only helps pinpoint contamination sources but also sheds light on the physical and environmental conditions facilitating pollutant dispersion.

Various techniques and methodologies are employed in spatial analyses, each with specific advantages and limitations. Advanced computational models have proven effective in simulating complex pollution dynamics. In particular, computational fluid dynamics (CFD) has emerged as a valuable tool for understanding interactions among pollutants, urban form, and environmental conditions. Urban morphology, especially the arrangement and design of buildings, plays a pivotal role in influencing pollutant dispersion across urban

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landscapes. The relationship between urban form and air pollution is complex, with factors such as local wind patterns, building height, and spatial arrangement affecting pollutant movement. Effective urban planning can therefore significantly mitigate pollution levels and improve air quality in cities (Yang et al., 2020).

Computational Fluid Dynamics (CFD) is a sophisticated tool that allows researchers to simulate airflow and pollutant dispersion in urban environments. By using CFD, urban planners and environmental engineers can model the flow of air and particulate matter across different terrains and urban structures, providing valuable insights into pollution patterns.

CFD relies on complex mathematical algorithms to simulate fluid dynamics, including air and gas flow, heat transfer, and chemical reactions, through computer-based numerical simulations (Versteeg & Malalasekera, 2007). CFD simulations are especially valuable for examining the relationship between urban geometry and pollutant dispersion. By accurately modeling wind flow and pollutant dynamics, researchers can visualize how environmental features such as building height, street orientation, and the arrangement of open spaces impact air quality.

The influence of urban morphology on pollutant dispersion has been well documented. For example, Azizi and Javanmardi (2016) and Badach et al. (2022) used CFD to assess how urban layout affects the distribution of airborne pollutants. Their studies demonstrated CFD's potential to provide detailed insights into the mechanisms behind air pollution dispersion, informing urban planning and pollution control strategies.

Research has consistently highlighted the importance of urban physical features such as building density, height, shape, and permeability in shaping local airflow patterns. These features significantly influence pollutant movement, impacting air quality and public health. In dense urban areas, buildings can act as barriers, either blocking or redirecting wind flow, thereby affecting pollutant dispersion.

Yuan et al. (2014) showed that building permeability and geometric configurations can notably alter pollution dispersion patterns, particularly in densely populated areas. These findings underscore the critical role of urban morphology in shaping air quality, suggesting that city design that considers airflow and ventilation can help mitigate pollution.

Wind direction and building arrangement are also key factors in local ventilation dynamics. Iqbal and Chan (2016) demonstrated that building layout and prevailing wind angles can create stagnant air zones or eddy flows, which trap pollutants and exacerbate pollution levels. Effective urban planning that accounts for these factors can improve ventilation and reduce the accumulation of air pollutants.

Recently, integrating Geographic Information Systems (GIS) with CFD has further enhanced the ability to model wind flow and pollutant dispersion. Li et al. (2019) developed a method that combines GIS and CFD to process large-scale urban data more efficiently, improving both simulation speed and accuracy. This integration significantly enhances the prediction of pollution hotspots and the development of effective mitigation strategies.

At the micro-scale level, land-use and urban space design play a crucial role in controlling pollution. Jana et al. (2020) demonstrated that CFD simulations can propose alternative urban design scenarios to enhance local ventilation and reduce pollution. Their work showed that thoughtful planning, including building spacing, green areas, and open spaces, can create favorable conditions for pollutant dispersion and natural air circulation.

Similarly, Kaseb et al. (2020) used CFD with evolutionary algorithms to optimize building configurations in Tehran. Their study indicated that integrating morphological analysis with CFD simulations can identify buildings contributing to pollution entrapment and suggest design modifications to improve ventilation and air quality. This approach, combining computational modeling with morphological analysis, shows significant promise for enhancing urban air quality.

Chang et al. (2021) further investigated wind pattern effects on pollutant dispersion, particularly concerning "twisted winds" or changes in wind direction at higher elevations. Their research demonstrated that such wind shifts substantially affect air movement between buildings and, consequently, pollutant dispersion, emphasizing the importance of understanding wind dynamics in urban design for pollution control.

Mashhad, Iran's second-largest city and one of its most densely populated urban centers, faces significant air pollution challenges. With a population of approximately 2.987 million as of the 2016 census and an influx of 20 to 30 million domestic and international pilgrims annually, the city experiences high population density, traffic volumes, and industrial activity, all exacerbating air pollution (Esmaeili & Amini, 2022). Its geographic and climatic conditions further amplify pollution impacts, making Mashhad an ideal case study for exploring the relationship between urban design and air quality.

Considering Mashhad's rapid urbanization, high population density, and significant tourist traffic, this study focused on the area surrounding the Avini Air Quality Monitoring Station within a 300-meter buffer zone. This area serves as a representative site for assessing local air pollution, ventilation conditions, and potential mitigation interventions. By employing advanced CFD simulations and analyzing pollutant dispersion patterns, this research aims to provide insights into how urban morphology and planning strategies can improve air quality in Mashhad.

2. Methodology

The research procedure was structured into four main phases to provide a systematic and coherent approach for achieving the study objectives. The first phase involved collecting relevant data from various organizations to establish a comprehensive understanding of the study area.

This was followed by the construction and reconstruction of a three-dimensional (3D) model, which served as a detailed representation of the urban environment. The third phase focused on conducting CFD simulations to examine airflow patterns and pollutant dispersion within the modeled area, providing insights into the interactions between urban form and air quality. Finally, the simulation results were validated to ensure the reliability and accuracy of the findings.

Together, these phases created a robust methodological framework that supports a rigorous analysis of the complex relationships between urban morphology, environmental conditions, and air pollution dynamics.

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2.1 Data Collection

The first phase of this study focused on establishing a comprehensive database for the simulation domain, which encompassed a 300-meter radius surrounding the Avini Air Quality Monitoring Station. All necessary data required for both three-dimensional (3D) modeling and numerical simulation were systematically collected to ensure the accuracy and reliability of subsequent analyses.

For the 3D modeling stage, detailed urban data were obtained from relevant municipal organizations. These data included the building polygon layer, building footprints, heights, number of floors, and land-use characteristics. Collecting these parameters was essential to accurately reconstruct the urban environment and represent the physical morphology of the study area.

In parallel, to implement the numerical simulations and define the model input parameters, real-world data on particulate matter concentrations, specifically PM_{10} and $PM_{2.5}$, were acquired. Additional information regarding the physical properties of the particulate matter, such as particle size distribution and density, was also gathered to ensure realistic representation within the simulation.

Furthermore, wind-related data, including prevailing wind speed and direction, were collected from the air quality monitoring station. These meteorological parameters were critical for accurately modeling airflow patterns within the numerical domain and for ensuring that the simulation reflects actual environmental conditions. Incorporating this high-resolution data allowed the study to capture the interactions between urban morphology, airflow dynamics, and pollutant dispersion with greater fidelity.

2.2 3D Model Construction and Simplification

In the second phase, following the systematic collection of all necessary urban and environmental data, the process of 3D model construction was initiated. Information processing and model development were conducted using a combination of ArcGIS©, SolidWorks©, and Rhino© software platforms, which enabled the accurate reconstruction of each individual structure within the study area. This step ensured that the spatial arrangement, building heights, footprints, and overall urban morphology were faithfully represented in the 3D environment.

To manage the computational demands of high-resolution simulations and to improve the efficiency of CFD analyses, targeted simplifications were applied during the modeling process. Specifically, non-essential geometric details that were unlikely to have a significant influence on airflow and pollutant dispersion were selectively removed. This approach allowed for a substantial reduction in computational volume while maintaining the geometrical fidelity and realism required for reliable simulation results (Antoniou et al., 2017; Ding & Lam, 2019; Zhang et al., 2021; Maing, 2022).

The careful construction and refinement of the 3D model are crucial because airflow patterns within the urban canopy are a primary factor influencing the transport and distribution of particulate matter. Preserving key morphological features, such as building height variations, street orientations, and open spaces, ensures that the CFD simulations can realistically capture complex interactions between urban form and air movement. Enhancing the geometrical accuracy of the 3D model is therefore a fundamental step toward producing valid simulation outcomes and supporting evidence-based decision-making in urban air quality management.

Figure 1 illustrates the final 3D model of the 300-meter buffer zone surrounding the Avini Air Quality Monitoring Station, highlighting the detailed representation of the urban environment and the simplifications applied to optimize computational performance.

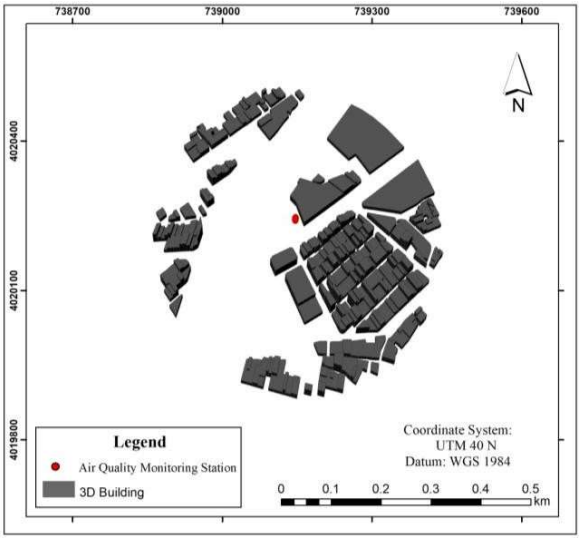

Figure 1. 3D model of the 300-meter buffer around the Avini Air Quality Monitoring Station

2.3 CFD Simulation

In the third stage, the simulation process was conducted using ANSYS Fluent©. This software was selected as the primary tool due to its advanced capabilities in mesh generation, implementation of complex physical models, and scripting options for customizing the simulation workflow (Versteeg & Malalasekera, 2007).

The CFD simulation began by importing the 3D model of the study area into the software and generating the computational mesh. A three-dimensional mesh with higher resolution near building surfaces and streets was employed to ensure accurate representation of flow behavior in boundary regions. The computational domain was defined with dimensions of 2000×1200×500 m, based on the average building heights in the area. Boundary conditions, including inlets, outlets, walls, and pollutant sources, were set to balance numerical accuracy and computational efficiency.

Parameters related to the prevailing wind speed and direction, along with the physical characteristics of PM_{10} and $PM_{2.5}$ pollutant particles, were incorporated into the model to realistically reproduce pollutant dispersion within the simulated environment. The choice of solver and turbulence model was a critical step in this study. The Reynolds-Averaged Navier–Stokes (RANS) equations, combined with the standard k-ϵ turbulence model, were employed due to their proven capability to reproduce turbulent flow behavior, their satisfactory numerical accuracy, high computational efficiency, and established performance in similar air pollution dispersion

studies (Chen et al., 2017; Lin, Hang, Li, Luo, & Sandberg, 2014; Peng et al., 2019).

To assess ventilation quality and pollutant dispersion, the RTI was also utilized. This index indicates the average residence time of pollutant particles at each point within the computational domain and enables the identification of areas with poor ventilation and high pollutant accumulation. By combining RTI with flow velocity and trajectory data, a comprehensive picture of airflow behavior and pollutant dispersion in the urban fabric was obtained. Equation1 shows the formula of the RTI index.

$$RTI = N_{escaped} / N_{total} \quad (1)$$

Where N = Number of Particles
Escaped = Particles Separated
Total = Total Number of Particles

Finally, after defining all parameters and boundary conditions, the numerical solution process was initiated and continued until convergence of the results was achieved.

2.4 Validation

In the final phase of this study, the methodology proposed by Badach et al. (2022) was adopted as the reference framework for validating the CFD simulation model. This approach provided a robust and systematic basis for assessing the accuracy and reliability of the simulated airflow and pollutant dispersion patterns. Specifically, the RTI values obtained from the current simulation were compared against those reported in the reference study, enabling a quantitative evaluation of model performance.

The reference study offers a comprehensive validation procedure, including detailed specifications of simulation parameters, boundary conditions, and assessment metrics. These procedures are grounded in internationally recognized standards, including those established by the Architectural Institute of Japan (AIJ) and the guidelines recommended by COST Action 732, ensuring methodological rigor and consistency. By following this framework, the study ensured that the CFD model was validated in accordance with best practices in urban air quality modeling.

To replicate the validation process, the P4 air quality monitoring station analyzed in the reference study was selected as a benchmark. The construction of its 3D geometry and the configuration of simulation parameters were reproduced meticulously, ensuring comparability between the current simulation and the reference results. Model validation was then performed by systematically comparing the RTI values derived from the current CFD simulations with those reported by Badach et al. (2022). This comparison not only confirmed the accuracy of the simulation framework but also highlighted the capability of the developed model to reliably represent pollutant behavior and airflow dynamics in complex urban environments.

The validation phase therefore provides a critical step in establishing the credibility of the CFD simulations and reinforces confidence in the subsequent analyses and conclusions derived from the model. By adhering to standardized validation procedures, the study ensures that the results are both scientifically robust and applicable to practical urban air quality management scenarios.

3. Results and Discussion

The present study employed an integrated approach combining 3D urban modeling with CFD simulations to examine airflow patterns and the dispersion behavior of particulate matter (PM_{10} and $PM_{2.5}$) within the study area. By utilizing a geometrically accurate 3D model of the urban environment, which incorporated building heights, footprints, street orientations, and open spaces, the simulations were able to capture the complex interactions between urban morphology, local wind dynamics, and pollutant transport with high spatial precision. The results presented in the following sections provide a detailed analysis and interpretation of the simulation outcomes.

Particular attention is given to the identification of key wind flow patterns, areas prone to pollutant accumulation, and the influence of urban form on airflow and dispersion dynamics. These insights offer a comprehensive understanding of how urban design and building configurations can affect air quality, highlighting areas where intervention strategies may be most effective. The systematic analysis of the CFD results allows for evidence-based evaluation of pollutant behavior and provides valuable guidance for developing urban planning strategies aimed at improving environmental quality and public health.

Figure 2(a) illustrates the concentration distribution of PM_{10} particles, and Figure 2(b) shows that of $PM_{2.5}$ particles. For both pollutants, the RTI was calculated to evaluate ventilation quality across different areas. The RTI represents the average residence time of particles within the environment; values close to one indicate effective ventilation and rapid particle removal, whereas values near zero correspond to prolonged particle retention and accumulation. The computed RTI values for PM_{10} and $PM_{2.5}$ were 0.57 and 0.74, respectively.

Although the initial number of particles injected was identical for both pollutants, the results revealed differences in the ratio of trapped-to-escaped particles, with PM_{10} exhibiting higher concentration and accumulation than $PM_{2.5}$. This difference is primarily attributed to variations in particle size and mass, which lead to distinct aerodynamic behaviors within the airflow. Coarser particles, such as PM_{10}, tend to settle and accumulate in lower wind speed regions due to their higher mass and inertia, while finer particles, such as $PM_{2.5}$, remain suspended for longer durations and are easily transported to higher elevations by turbulent vortices. Furthermore, building height and geometry play a significant role in ventilation efficiency and particle retention, as specific urban morphologies can either enhance air circulation and pollutant removal or increase stagnation and particle trapping in poorly ventilated areas.

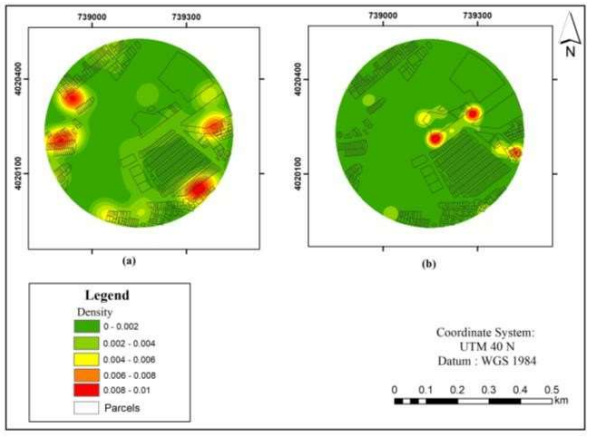

Figure 2. Density maps, PM_{10} (a), $PM_{2.5}$ (b)

Figure 3 depicts the trajectories of the pollutant particles. The results clearly show that particle accumulation occurs mainly in the spaces between buildings and in areas characterized by reduced wind speed. In these zones, the restricted airflow generates localized vortices and recirculation zones, which trap pollutants and lead to particle stagnation.

The persistence of these vortices limits pollutant removal by slowing down the rate of air exchange and increasing the residence time of particles near the ground. The strength and extent of these recirculating flows depend strongly on variations in building heights and the ratio of available open space. Areas with tall or irregularly spaced buildings tend to produce asymmetric and turbulent flow patterns, whereas more uniform layouts often result in weaker ventilation. Consequently, leeward façades and narrow streets experience higher pollutant concentrations, as the exchange with cleaner air aloft is reduced.

Overall, these findings highlight how the geometry of the urban fabric directly influences local airflow behavior and pollutant dispersion efficiency. Understanding these aerodynamic mechanisms provides valuable guidance for improving natural ventilation and mitigating air pollution hotspots in dense urban areas.

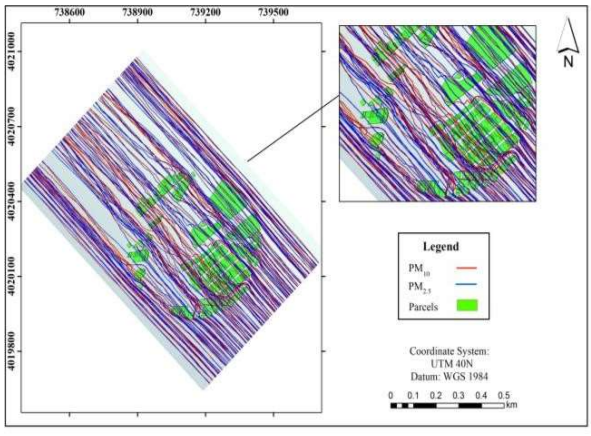

Figure 3. Streamline flow of PM_{10} and $PM_{2.5}$

Figure 4 illustrates the wind speed and direction across the study area. The average wind speed at the Avini Air Quality Monitoring Station is 0.56 m/s, with the prevailing wind originating from the southeast. As observed, areas within the study domain where wind speed decreases, often due to the obstruction of airflow by buildings or enclosed courtyards, exhibit a higher tendency for pollutant particle accumulation. These findings highlight that urban physical characteristics, particularly building height, spacing, and footprint, play a decisive role in shaping natural ventilation patterns and influencing pollutant dispersion.

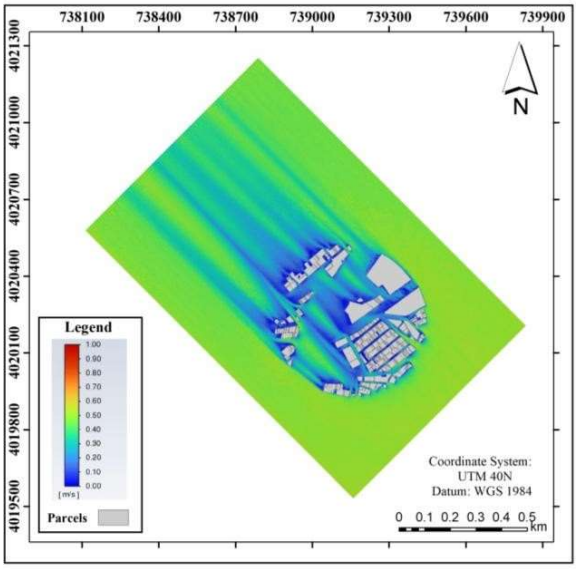

Figure 4. Speed and direction of simulated wind

These findings underscore the critical influence of urban form on local ventilation efficiency and pollutant retention. Such insights are essential for guiding urban design strategies aimed at mitigating air pollution hotspots, optimizing building configurations, and promoting sustainable ventilation performance in compact urban fabrics.

Finally, the study by Badach et al. (2022) was used as a standard reference for validating the simulation results. For this purpose, the reference study conditions were reconstructed, and the simulation was reproduced for the P4 air quality monitoring station, which was analyzed in the reference article.

The comparison of RTI values between the current simulation and the reference study showed a discrepancy of less than 5 percent. Specifically, the RTI for P4 under westerly geographical wind conditions was 0.87 in the reference study and 0.84 in the present study. This high level of agreement effectively confirms the accuracy of the simulation methodology and validates the findings of the current research.

4. Conclusion

The findings of this study indicate that integrating three-dimensional (3D) urban modeling with Computational Fluid Dynamics (CFD) simulations provides a highly effective and reliable framework for analyzing and understanding urban air quality. The 3D model accurately represents the physical structure and morphological characteristics of the urban environment, including building heights, footprints, and spatial

arrangement, while CFD simulations solve the governing fluid flow and pollutant transport equations, offering detailed insights into airflow behavior and pollutant dispersion patterns.

In this research, a 3D urban model was developed using building height and area data, and the effects of urban morphology on wind flow and the dispersion of PM_{10} and $PM_{2.5}$ particles were systematically evaluated. The CFD-based approach allows for the tracking of pollutant particles, identification of areas with high pollutant concentrations, and recognition of zones at elevated risk, providing a valuable tool for urban planners and environmental managers to design effective air quality management strategies.

Despite its clear advantages, this methodology has certain limitations. High-resolution CFD simulations demand substantial computational resources, which may limit their scalability for larger urban domains or long-term studies. Additionally, the accuracy of simulation results heavily depends on the quality and resolution of input data, including detailed urban geometries, local meteorological conditions, and pollutant emission parameters.

Future research is recommended to address these limitations by exploring diverse urban design scenarios, incorporating variable climatic and meteorological conditions, and employing complementary indices to assess urban ventilation and pollution dispersion. Such comprehensive approaches can enhance the predictive capability of urban air quality simulations, inform more sustainable planning practices, and contribute to healthier and more resilient urban environments.

References

Antoniou, N., Montazeri, H., Wigo, H., Neophytou, M.K.A.K.-A., Blocken, B., Sandberg, M., 2017. CFD and wind-tunnel analysis of outdoor ventilation in a real compact heterogeneous urban area: Evaluation using "air delay".*Building and Environment*,126,355–372. doi.org/10.1016/j.buildenv.2017.10.013.

Asadollahfardi, G., Zangooei, H., 2017. Prediction of PM_{10} air pollution in Mashhad city using MLP artificial neural networks and Markov chain model. *Applied Research in Geographical Sciences*, 17(47),39–59. dor.isc.ac/dor/20.1001.1.22287736.1396.17.47.8.0. [in Persian].

Badach, J., Wojnowski, W., Gębicki, J., 2023. Spatial aspects of urban air quality management: Estimating the impact of micro-scale urban form on pollution dispersion. *Computers, Environment and Urban Systems*, 99, 101890. doi.org/10.1016/j.compenvurbsys.2022.101890.

Chen, L., Hang, J., Sandberg, M., Claesson, L., Di Sabatino, S., Wigo, H., 2017. The impacts of building height variations and building packing densities on flow adjustment and city breathability in idealized urban models. *Building and Environment*,118,344–361. doi.org/10.1016/j.buildenv.2017.03.042.

Ding, C., Lam, K.P., 2019. Data-driven model for cross ventilation potential in high-density cities based on coupled CFD simulation and machine learning. *Building and Environment*,165,106394. doi.org/10.1016/j.buildenv.2019.106394.

Esmaeili, R., Amini, F., 2022. Spatial analysis of air pollutants Carbon Monoxide in Mashhad. *Journal of Environmental Research*, 13(25), 250–266. doi: 10.22034/eiap.2022.158590. [in Persian].

Lin, M., Hang, J., Li, Y., Luo, Z., Sandberg, M., 2014. Quantitative ventilation assessments of idealized urban canopy layers with various urban layouts and the same building packing density. *Building and Environment*, 79, 152–167. doi.org/10.1016/j.buildenv.2014.05.008.

Mahmoudzadeh, H., Heydari, R., Valizadeh, N., 2024. Investigating health indicators of air quality and its relationship with changes in the green spaces land use (the case study of Tabriz metropolitan). *Remote Sensing and GIS Applications in Environmental Sciences*,3(9),1–37. Doi: 10.22034/rsgi.2024.60092.1060.

Maing, M., 2022. Superblock transformation in Seoul megacity: Effects of block densification on urban ventilation patterns. *Landscape and Urban Planning*, 222, Article 104401. doi.org/10.1016/j.landurbplan.2022.104401.

Peng, Y., Gao, Z., Buccolieri, R., Ding, W., 2019. An investigation of the quantitative correlation between urban morphology parameters and outdoor ventilation efficiency indices.*Atmosphere*,10(1),33. doi.org/10.3390/atmos10010033.

Versteeg, H.K., Malalasekera, W., 2007. *An introduction to computational fluid dynamics: The finite volume method* (2nd ed.). Pearson Education.

Zhang, S., Kwok, K.C.S., Liu, H., Jiang, Y., Dong, K., Wang, B., 2021. A CFD study of wind assessment in urban topology with complex wind flow. *Sustainable Cities and Society*, 71, Article 103006. doi.org/10.1016/j.scs.2021.103006.