

A Multiscale Morphological–Aerodynamic Framework for Urban Air Quality: Explaining the Mechanisms Linking Urban Form to Pollutant Transport and Human Exposure

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Detailed abstract

Introduction

Urban air pollution is one of the major environmental challenges facing contemporary cities, with significant consequences for public health, environmental quality, and human well-being. Urban air quality is not determined solely by pollutant emissions; rather, it results from interactions among emission sources, meteorological conditions, urban spatial structure, landscape elements, pollutant transport processes, and patterns of human exposure. Therefore, although emission reduction remains essential, understanding how urban form affects pollutant transport, dilution, redistribution, accumulation, and removal is also important for environmental planning and design.

Urban morphology plays a critical role in these processes because the physical configuration of the built environment modifies airflow and pollutant transport. Building density and height, street geometry, block configuration, spatial openness, surface roughness, street orientation, and building setbacks can influence aerodynamic resistance, turbulence, horizontal transport, vertical exchange, and pollutant residence time. These relationships are particularly important in street canyons and dense urban environments, where built form, airflow, emission sources, and pedestrian-level receptors interact directly.

Previous studies have investigated these relationships using numerical simulations, field measurements, spatial analyses, and environmental assessments. However, the literature remains fragmented because many studies focus on a single spatial scale, individual morphological indicators, or isolated performance metrics. Aerodynamic studies often emphasize wind speed or ventilation, while landscape studies may focus on vegetation performance. Human-exposure studies further demonstrate that ambient pollutant concentration alone does not necessarily represent actual exposure.

Improved airflow therefore does not automatically produce lower pollutant concentrations at every location, while lower average concentrations do not necessarily imply reduced human exposure. Exposure also depends on receptor location, breathing height, duration of presence, and activity patterns. Accordingly, the relationship between urban morphology and air quality should be interpreted through an integrated chain connecting emission sources, transport pathways, pollutant concentration distribution, and human receptors.

This study consequently aims to develop a multiscale morphological–aerodynamic framework explaining how urban form and landscape elements affect pollutant transport, concentration distribution, and human exposure, thereby providing an analytical basis for evidence-based urban planning, design, and landscape interventions.

Materials and Methods

This applied study adopts an integrative literature review with a critical synthesis approach. This method enables evidence from theoretical studies, empirical investigations, numerical simulations, and spatial-data-based research to be integrated. The review was intended not merely to summarize previous findings, but to identify recurring patterns, differences, contextual dependencies, and mechanisms governing relationships among urban morphology, aerodynamic processes, pollutant dispersion, landscape characteristics, and human exposure.

Relevant literature was searched in Scopus, Web of Science, ScienceDirect, Google Scholar, SID, and Magiran. The literature covered three main domains: urban morphology and aerodynamic mechanisms; urban landscape and green infrastructure; and environmental quality and human exposure.

Selected studies were examined according to spatial scale, research method, morphological variables, landscape elements, transport mechanisms, and environmental and human outcomes. Evidence was organized and critically synthesized to identify relationships among physical drivers, aerodynamic processes, pollutant behavior, and receptor conditions.

The analytical structure distinguishes three interconnected spatial levels: the urban or macro scale, the neighborhood and urban-fabric or intermediate scale, and the street, building, and pedestrian or micro scale. Aerodynamic processes and source–receptor relationships connect these levels. The conceptual framework was ultimately organized around emission sources, transport mechanisms, pollutant concentration distribution, and human exposure.

Findings

The findings indicate that the relationship between urban morphology and air quality is multifactorial, nonlinear, context-dependent, and multiscale. No single morphological characteristic independently explains urban air-quality performance. Environmental outcomes emerge from interactions among spatial scale, urban configuration, meteorological conditions, emission characteristics, landscape elements, pollutant properties, and receptor location.

At the macro scale, urban development patterns, land-use distribution, transportation networks, emission-source distribution, topography, and large-scale surface roughness influence background pollution and general airflow conditions. The larger spatial structure therefore establishes the context within which neighborhood- and street-level processes operate.

At the intermediate scale, street networks, block geometry, building density, frontal area, continuity of open spaces, surface roughness, and variations in building height regulate airflow guidance, resistance, and exchange within the urban fabric. Changes in block organization and urban permeability can consequently modify ventilation capacity and pollutant-dispersion patterns.

At the micro scale, street aspect ratio, orientation, building height, façade geometry, setbacks, roof configuration, intersections, and landscape elements directly influence local airflow. These variables affect vortex formation, horizontal transport, vertical exchange, turbulent mixing, and localized pollutant distribution. Their effects, however, depend on wind conditions, source location, surrounding geometry, and environmental context.

The synthesis further demonstrates the importance of distinguishing among emission load, transport and removal capacity, pollutant concentration, and human exposure. Indicators such as wind speed and air exchange rate describe ventilation capacity but cannot independently represent actual air-quality performance. Increased airflow may redistribute pollutants instead of removing them from areas occupied by human receptors. Environmental assessment should therefore simultaneously consider sources, transport pathways, concentration patterns, and receptor characteristics.

Landscape elements and green infrastructure also influence urban environmental performance. Vegetation can modify pollutant deposition, thermal conditions, aerodynamic resistance, and airflow patterns. However, its effectiveness depends on spatial arrangement, density, geometry, surrounding built form, and meteorological conditions. Green infrastructure should therefore be evaluated as an integrated component of urban morphology rather than as an independent solution.

The proposed framework conceptualizes urban air quality as an interconnected process in which emission load and background pollution represent system inputs; airflow supply at the macro scale, flow guidance and resistance at the intermediate scale, and horizontal transport, vertical exchange, and turbulent mixing at the micro scale operate as intermediate mechanisms; while pollutant concentration distribution and human exposure represent the main environmental and human outcomes.

Discussion and Conclusion

The findings demonstrate that evaluating the environmental performance of urban form requires moving beyond direct relationships between individual morphological indicators and pollutant concentrations. Urban morphology should instead be understood as part of a broader environmental system in which physical configuration modifies aerodynamic processes and consequently affects pollutant transport, redistribution, residence time, removal, and human exposure.

A major implication is that ventilation performance and air-quality performance are not equivalent. Improvements in wind speed or air exchange may facilitate pollutant removal in one location while redistributing pollution toward another urban space or receptor. Likewise, reductions in average pollutant concentrations do not necessarily result in lower exposure for all urban users. Reliable assessment therefore requires identifying where pollutants originate, how they move, where they accumulate or leave the system, and where human receptors are located.

The framework also has practical implications for urban planning, urban design, and landscape architecture. Rather than seeking a universally optimal urban form, interventions should balance emission reduction, ventilation and pollutant-removal capacity, organization of open spaces, green infrastructure, and reduction of exposure among sensitive receptors. Urban development patterns, neighborhood permeability, street-canyon geometry, building configuration, and landscape interventions should therefore be evaluated as interconnected components.

The reviewed literature also presents limitations because studies differ in spatial scale, methodology, climatic conditions, pollutant type, and performance indicators. These differences restrict the development of universal quantitative relationships. In addition, much existing evidence relies on numerical simulations and controlled conditions, while direct assessment of human exposure remains comparatively limited.

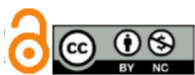
Future research should develop multiscale models connecting city, neighborhood, and street levels; expand multi-height monitoring and personal-exposure assessment using mobile sensors; and employ multiple environmental performance indicators rather than relying solely on wind speed or air change rate.

Overall, urban air quality results from interactions among spatial structure, pollutant-transport processes, landscape characteristics, emission conditions, and human behavior. Urban planning and landscape design should therefore move from isolated assessments toward an integrated “emission source–transport pathway–concentration distribution–human receptor” approach. The proposed multiscale morphological–aerodynamic framework provides a conceptual basis for evaluating urban design scenarios and developing environmentally responsive strategies to improve air quality and reduce human exposure.

Declarations

The authors declare that the scientific analysis, selection and interpretation of the reviewed literature, critical synthesis of findings, and development of the conceptual framework were conducted by the authors. Artificial intelligence tools were used for language editing, improvement of the writing process, and the preparation of figures and diagrams. ChatGPT (OpenAI) was used as the artificial intelligence tool.

Keywords: Urban Morphology; Urban Air Quality; Pollutant Dispersion; Human Exposure; Urban Ventilation; Street Canyon; Aerodynamic Processes; Green Infrastructure; Critical Synthesis



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