Understanding the effect of built-up and green spaces upon air quality at multiple spatial scales: A systematic literature review

Citation for the original published paper (version of record):
Wu, C., Eldesoky, A., Morello, E. (2025). Understanding the effect of built-up and green spaces upon air quality at multiple spatial
scales: A systematic literature review. Landscape and Urban Planning, 257.
http://dx.doi.org/10.1016/j.landurbplan.2025.105304

Landscape and Urban Planning 257 (2025) 105304

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Understanding the effect of built-up and green spaces upon air quality at multiple spatial scales: A systematic literature review

Chenling Wu [a,*], Ahmed Hazem Eldesoky [a,b], Eugenio Morello [a]

[a] Laboratorio di Simulazione Urbana Fausto Curti, Department of Architecture and Urban Studies (DASTU), Politecnico of Milan, via Bonardi, 3, Milan 20133, Italy
[b] Spatial Morphology Group (SMoG), Department of Architecture and Civil Engineering, Chalmers University of Technology, Sven Hultins Gata 6, SE-412 96 Gothenburg, Sweden

HIGHLIGHTS

- A taxonomy of built-up and green space indicators affecting air quality was developed.
- Effects of built-up and green spaces on air quality across different scales are compiled.
- Research emphasises air pollution phenomena over processes and outcomes.
- Green spaces, at micro- to meso-scale, do not necessarily enhance air quality.
- Vegetation planting interventions should consider the surrounding built-up areas.

ABSTRACT

Understanding how to design and plan built-up and green spaces in cities is essential for achieving optimal outdoor air quality. While several studies have investigated how different indicators of built-up and green spaces impact air quality across various spatial scales (macro, meso, and micro), the findings and evidence remain fragmented and largely inaccessible to urban designers, planners, and policymakers. To bridge this gap, we conducted a systematic literature review of 61 peer-reviewed publications to: (1) provide an overview of the literature addressing the impacts of built-up and green spaces on air quality, including key areas of investigation (emission, dispersion, deposition, exposure, etc.), the pollutants studied (particulates, gases), and the quantitative methods used (numerical, physical, and empirical models); (2) develop a taxonomy of built-up and green space indicators that influence air quality at different spatial scales, such as urban canyon aspect ratios, vegetation size, and land-use and land-cover compositions; and (3) synthesize quantitative evidence on how these indicators affect air quality (positively, negatively, insignificantly, or variously) across scales. The taxonomy and synthesized evidence offer actionable, evidence-based insights for urban planning, design, and policy to improve air quality at different spatial scales. Additionally, the review highlights several under-explored areas for future air quality research, such as the impact of vegetation configuration.

1. Introduction

Air pollution is a major global health risk, causing around 4.2 million premature deaths yearly (WHO, 2024). Cities, home to over half the world's population, are the first to bear the cost of air pollution. Air pollution can be recognised across a range of spatial scales. At the macro-scale, the impact of the density of built-up and green spaces on air quality is controversial (Berghauser Pont et al., 2021). On the one hand, dense cities contribute to lower emissions by encouraging high residential densities with mixed land uses, which decreases car dependency and traffic-related emissions (Yuan et al., 2017). On the other hand, dense cities can result in higher population-weighted exposures to air pollution (Carozzi and Roth, 2023). A dispersed and polycentric urban form has been shown to be associated with better air quality (She et al., 2017). This can be attributed to decentralising emission sources and enhancing pollutant dispersion by providing more green and open spaces. At the micro-scale, air pollution is often associated with decreased wind flow and natural ventilation, especially in urban canyons (Voordeckers et al., 2021b). Although vegetation is often recognised as a measure to mitigate urban air pollution at this scale, it can also lead to negative consequences. For example, trees with big canopies can obstruct wind flow, reduce ventilation, and lead to higher pollutant concentrations (Janhäll, 2015).

In urban planning and design practice, the aforementioned

* Corresponding author at: Laboratorio di Simulazione Urbana Fausto Curti, Department of Architecture and Urban Studies (DASTU), Politecnico of Milan, via Bonardi, 3, Milan 20133, Italy.

E-mail addresses: chenling.wu@polimi.it (C. Wu), ahmed.eldesoky@chalmers.se (A.H. Eldesoky), eugenio.morello@polimi.it (E. Morello).

https://doi.org/10.1016/j.landurbplan.2025.105304
Received 10 April 2024; Received in revised form 12 November 2024; Accepted 16 January 2025
Available online 11 February 2025

controversy has resulted in a limited understanding of how to plan and design built-up and green spaces to achieve maximum air quality potential in cities. In this paper, we argue that there are at least three factors underlying this controversy, which are often hard to address in a single study.

Firstly, there are various areas of air quality investigation, such as emission, concentration, and exposure. This means that the same urban intervention (e.g., expansion of green infrastructure) might have different, even opposite, implications for the different areas of air quality investigation. Existing reviews often examined one or two areas in isolation (Abhijith et al., 2017; Janhäll, 2015). One recent study indicated that expanding green infrastructure can alleviate urban air pollution to a certain extent but cannot compensate for the injustices caused by pollution exposure (Jennings et al., 2021). Therefore, thinking through all areas of air quality investigation is crucial to informing policymakers, urban planners, and designers in decision-making.

Secondly, previous studies examining the impact of built-up and/or green spaces on air quality have focused on reducing air pollution through one of two main approaches: (1) the optimisation of built-up (or urban form) indicators such as land use mix (Li et al., 2023b); and (2) the planning and design of green infrastructure, such as urban forests (Han et al., 2020) with a focus on vegetation characteristics such as plant species (Barwise and Kumar, 2020; Diener and Mudu, 2021). However, none of these studies have integrated both built-up and green spaces in their investigations. This integration is important because while urban green spaces provide significant environmental, health, and socio-economic benefits, including air pollution reduction (Kumar et al., 2019; Riondato et al., 2020), their effectiveness depends on the surrounding built-up space. For example, in open road environments, trees with low and wide porosity canopies lead to pollutant reductions in the downwind direction (Abhijith et al., 2017). However, in urban canyons, trees with big canopies can deteriorate air quality (Janhäll, 2015).

Thirdly, different urban interventions can have different impacts on air quality depending on the scale. For example, Venter et al. (2024) found that while vegetation can have positive effects on air quality at the city scale, it can exacerbate air pollution at the street-level. However, previous studies have mainly focused only on one scale or urban unit. One commonly studied urban unit is the urban canyon, which is recognised as a bottleneck area due to traffic emissions and lack of dispersion (Huang et al., 2021; Tomson et al., 2021; Voordeckers et al., 2021b). Therefore, a better understanding of the characteristics of built-up and green spaces at different scales is essential for developing urban interventions that effectively improve air quality.

Based on the above background, the aim of this paper is twofold. Firstly, better understand how built-up and green spaces (through a variety of indicators that describe their characteristics such as size, spatial structure, configuration, etc.) are linked to air quality. Secondly, support urban planning decision-making at different scales by synthesizing scientific evidence about the impacts of different indicators of built-up and green spaces on air quality.

To achieve these aims, this paper systematically reviews and provides an overview of the scientific literature that addresses the impact of built-up and green spaces on air quality. This paper is structured as follows. Section 2 explains the review method, followed by a detailed analysis of the review results in Section 3. In Section 4, we discuss the results, implications for future research, and proposals for implementing urban interventions (planning, design, and policy). Finally, Section 5 presents the conclusions.

2. Review method

The systematic review included three main steps (Fig. 1). Firstly, relevant publications were retrieved from a multidisciplinary scientific database (Section 2.1). Secondly, irrelevant publications were filtered out (Section 2.2). Thirdly, the current state of the art of the included publications was reviewed, and the final sample of publications was analysed in depth using a predefined analytical method (Section 2.3).

2.1. Publications search procedure

We searched for relevant scientific publications in the Scopus

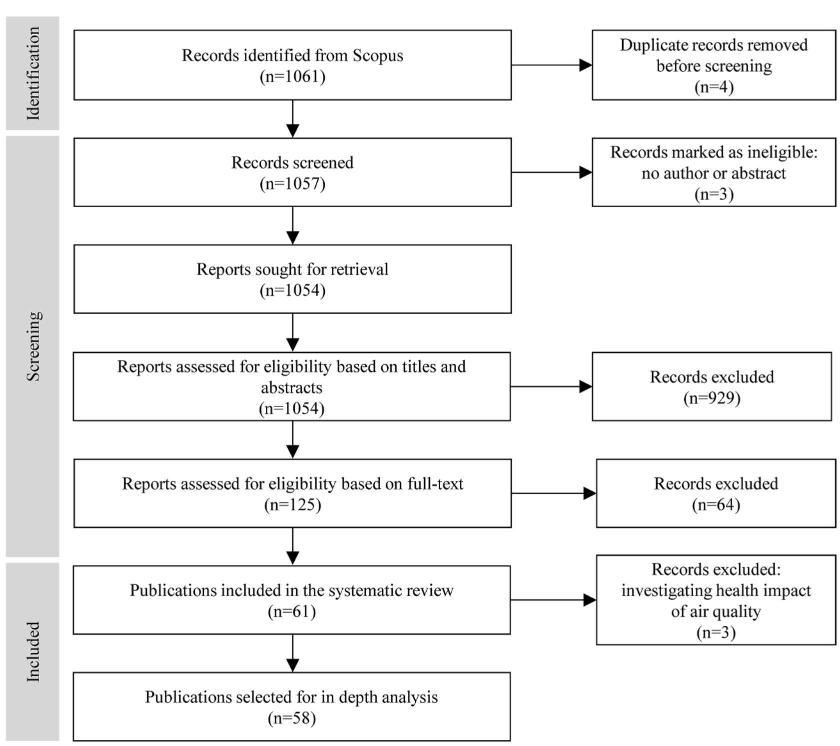

Fig. 1. A flow diagram of the systematic review process.

database. A query composed of three sets of keywords related to (1) built-up spaces, (2) green spaces, and (3) air quality was used (Table S1). The search was performed on February 26, 2023, on the title, abstract, and keywords fields. The search was restricted to publications written in English, published from the start of the database coverage to 26 February 2023. It resulted in 1061 publications, from which duplicates (n = 4) and records without authors or abstracts (n = 3) were removed.

2.2. Inclusion and exclusion criteria

Two inclusion and exclusion criteria were applied to the retrieved publications. Firstly, we included only publications that studied the impact of the built environment on outdoor air quality. By built environment, we refer to "the human-made space in which people live, work, and recreate on a day-to-day basis. It includes the buildings and spaces we create or modify" (Roof and Oleru, 2008: 24). Buildings, green spaces, water, and other facilities (e.g., transportation facilities such as streets and parking spaces) are main elements of the built environment (Seyedrezaei et al., 2023). Therefore, irrelevant publications, for example focusing on vegetation for urban biomonitoring (Hofman et al., 2013) or the micro-morphological characteristics (e.g., leaf surface) of specific tree species (Zhao et al., 2019) were excluded.

Secondly, since this paper aims to synthesize empirical evidence about the impacts of built-up and green spaces on air quality, the publications should use quantitative methods. Therefore, publications about literature reviews, method development, qualitative research, and viewpoints were excluded. Based on the criteria above, 61 publications (Table S2) were selected for the systematic literature review and analysis of the full text.

2.3. Extraction and analysis of data and synthesis of evidence

As a first step, spreadsheets were used to classify the 61 publications based on different areas of air quality investigation (emission, deposition, dispersion, etc., defined later in Section 3.1.1), different pollutants discussed, and various quantitative methods used (Table S3). This is an important step because, besides it provides an overview of the current state of the art, it also ensures a deep understanding of the impacts of built-up and green space indicators on air quality. The first author reviewed and classified publications independently. Whenever it was difficult to designate a classification for a publication because of the complexity or lack of information, the three authors discussed it to reach an agreement. More specifically, we proposed areas of air quality investigation based on the conceptual frameworks provided by previous studies (Oke et. al., 2017: 295; Schweitzer and Zhou, 2010), with the addition of the specific areas investigated by publications we reviewed. Air pollutants were classified according to their physical state of matter (particulate matter or gas). The different quantitative analytical methods used to investigate the impact of built-up and green spaces on air quality were classified into three major groups: numerical models, physical models, and empirical models (Oke et al., 2017: 44).

Then, three publications investigating the health impacts of air quality, such as the prevalence and incidence of some diseases that might be caused by intaking air pollutants (e.g., asthma and lung cancer), were further excluded (Table S3). This is because the impact of built-up and green spaces on health is complex and, besides air pollution, this impact can be mediated by other factors, such as physical activity, walkability, and accessibility to health-related services. Moreover, a few recent reviews have addressed this issue (Hankey and Marshall, 2017; Qiu et al., 2021). Next, the 58 publications were examined to identify the indicators of built-up and green space and their impact on air quality. However, considering that air pollution occurs at different spatial scales, the results were synthesised based on three common horizontal scales: micro (up to 100 x100 m); meso (from 100 × 100 m to 10 × 10 km), and macro (10 × 10 km and larger) (Oke et al., 2017: 17). Furthermore, each of these scales was classified into different urban units. By urban units, we mean "the hierarchical scale sequence of physical features that when amalgamated resemble the urban form. The smallest units are facets (walls, roofs), several of which create urban elements (buildings, trees), which combine to form urban blocks, which together form neighborhoods and many neighborhoods represent a synthetic city" (Oke et al., 2017: 484).

Then, to understand the impact of each indicator on air quality, we classified the examined or reported impact of indicators of built-up and green spaces on air quality in each study as either significant (positive/negative relationship), insignificant, or various depending on the context. A positive relationship means that when the assessed value of the indicators of built-up and green spaces increases, the measured or simulated air pollution value decreases, corresponding to better air quality and vice versa. On the other hand, a statistically insignificant relationship means there was a weak relationship between the indicators of built-up and green spaces and air quality, or there was not enough data. Various relationships mean that the relationship between the indicators of built-up and green spaces and air quality varies in different contexts. Finally, the percentage of evidence pieces (rather than the percentage of studies) reported by the 58 publications were summarised. We aimed to present the findings in a communicable way for designers, planners, and policymakers, showing the overall impact of the built-up and green space indicators on air quality (considering different areas of air quality investigation and air pollutants). Therefore, if one publication addressed more than one area of air quality investigation (e.g., emission, concentration) or various pollutants, it provided more than one piece of evidence to the analysis.

3. Results

3.1. An overview of the current state of the art

3.1.1. Areas of air quality investigation

The review showed that there are at least eight areas of investigation related to the air quality (Table 1). These can be generally organised into three categories: processes, phenomena, and outcomes. The air pollution processes are the mechanisms and activities that lead to (1) emission, (2) dispersion, and (3) deposition. Air pollution phenomena are observable events and occurrences related to air quality (e.g., reduced visibility). They are measured by (4) pollutant concentration, (5) atmospheric

Table 1
Categories of areas of air quality investigation and their definitions.

Category	Area of air quality investigation	Definition
Processes	Emission	Pollutants originating from anthropogenic and natural sources are released into the atmosphere (Oke et al., 2017: 298).
	Dispersion	Pollutants are transported by airflow (Oke et al., 2017: 299).
	Deposition	Pollutants are transported by turbulent mixing to surfaces like vegetation leaves (Oke et al., 2017: 301).
Phenomena	Concentration	Overall levels of pollutants in the atmospheric environment (Schweitzer and Zhou, 2010).
	Atmospheric visibility	The horizontal opacity of the atmosphere at the point of observation (Fu et al., 2018).
	Urban particulate matter island effect	The phenomenon of higher pollutant concentrations in urban areas is gradually fading into surrounding areas (Huang et al., 2019).
Outcomes	Exposure	The level of interaction between individuals and pollutants present in the air (Schweitzer and Zhou, 2010).
	Health impacts	The health outcomes of the human body with the impact of intaking pollutants (Schweitzer and Zhou, 2010).

visibility, and (6) urban particulate matter island effect. When pollutants exist in the atmosphere for sufficient concentration or periods of time, they can lead to adverse outcomes. The outcomes of air pollution include (7) exposure and (8) health impacts.

As shown in Fig. 2, air pollution phenomena were the most studied category of the areas of air quality investigation in the selected 61 publications, accounting for 63% of all publications. This was followed by the processes (23%) and outcomes (14%). Specifically, the most studied areas of air quality investigation was concentration, followed by dispersion (12%), atmospheric visibility (11%), exposure (8%), deposition (6%), health impact (6%), emission (5%), and urban particulate matter island effect (2%).

3.1.2. Examined air pollutants

As for air pollutants, Fig. 3 shows that gaseous pollutants were the most investigated, accounting for 56%, while particulate pollutants were the second most studied at 44%. The most studied pollutant overall was fine particulate matter ($PM_{2.5}$), accounting for 27% of the reviewed publications, probably because of its well-documented health impacts and significant presence in urban environments (Feng et al., 2016). Besides $PM_{2.5}$, the most frequent air pollutants investigated by the publications we reviewed included coarse particulate matter (PM_{10}), Nitrogen Dioxide (NO_2), Sulfur Dioxide (SO_2), Carbon Monoxide (CO), and Ozone (O_3). This is because these pollutants are measured to calculate air quality index (AQI), which are used to communicate with the public about air quality. Black carbon and greenhouse gases (GHGs), such as CH_4 and N_2O, were the least studied pollutants.

3.1.3. Quantitative methods

Our systematic review showed that empirical models were the most applied methods, accounting for 76% of all publications (Fig. 4). This was followed by numerical models (22%) and physical models (2%).

Considering that previous studies have examined quantitive methods in more detail (see, e.g., Lin et al., 2019; Zhang et al., 2023), here we focused more on the different methods in relation to their applicability in the planning practice. Fig. 5 shows the relationship between different analytical methods (middle), their scales of application (left), and areas of air quality investigation (right) in the reviewed publications. Most empirical models were applied by publications at the macro- and meso-scale, and only a few publications used empirical models at the micro-scale. Empirical models were used to study all eight areas of air quality investigation. Numerical models were mainly applied by publications we reviewed at the micro-scale because they are computationally expensive. They addressed dispersion, deposition, concentration, and exposure to air pollution. Only one publication we reviewed (Gromke and Ruck, 2012) discussed the impact of built-up and green spaces on air pollution dispersion at the micro-scale using wind tunnel experiments, which is an example of a physical model.

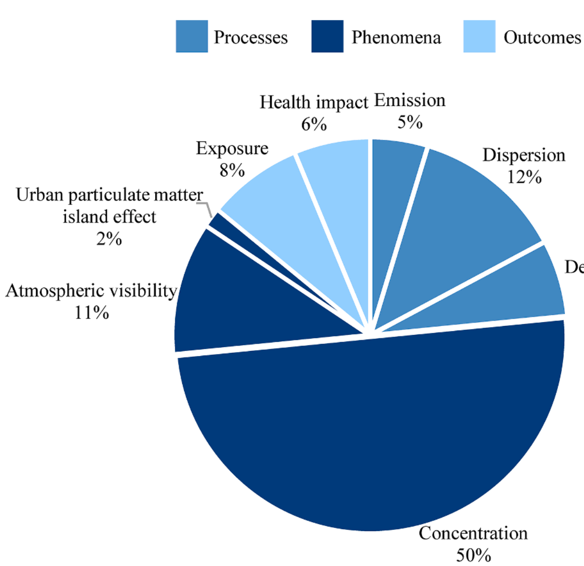

Fig. 2. Frequency of occurrence of areas of air quality investigation in the reviewed publications. Percentages show the frequency of each area's occurrence, considering that multiple areas may have been investigated within the same publication.

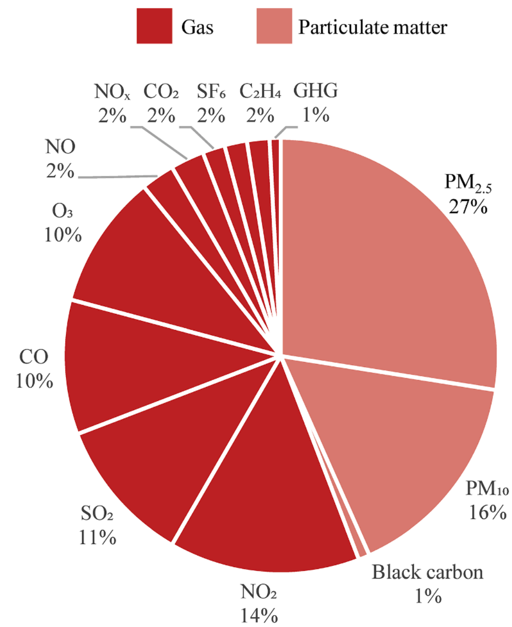

Fig. 3. Frequency of occurrence of different air pollutants in the reviewed publications. Percentages show the frequency of each pollutant's occurrence, considering that multiple pollutants may have been investigated within the same publication.

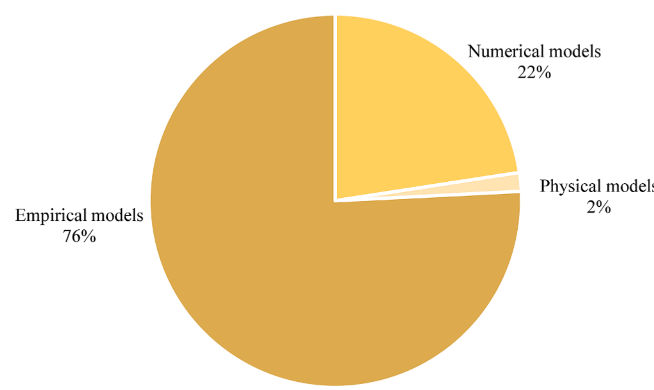

Fig. 4. Frequency of occurrence of applied quantitative methods in the reviewed publications. Percentages show the frequency of each method's occurrence, considering that multiple methods may have been investigated within the same publication.

3.2. Indicators of built-up and green spaces and their impact on air quality across spatial scales

The main results of this systematic literature review are: (1) an original taxonomy identifying the indicators of built-up and green spaces that influence air quality across multiple spatial scales; and (2) the synthesis of scientific evidence about their impact on air quality.

Table 2 shows the classification of spatial scales, urban units, elements, and indicators (or groups of indicators) of built-up and green

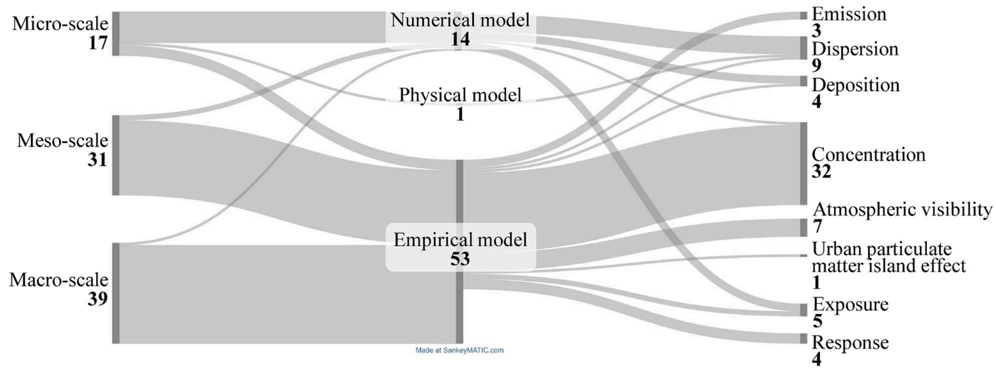

Fig. 5. Connections between scale of built-up and green spaces (left), quantitative methods (middle), and areas of air quality investigation (right).

Table 2
Classification of scales, urban units, elements, group of indicators, and indicator(s) of built-up and green spaces (Readapted from Oke et al., 2017: 19). The asterisk (*) refers to a group of indicators. The full list of indicators, sub-indicators, references, and their definitions are provided in Table S4.

Scale	Unit	Specific characteristics of (or elements that define) each unit			Group of indicators	Indicators
		Built elements	**Green elements**	**Other relevant elements/ characteristics**		
Micro-scale	**Facet**	Roof, wall	Green roof, green wall	–	–	Percentage of the vegetation cover on roofs and walls of buildings
	Urban canyon	Street, flanking buildings	Street vegetation (tree and hedge)	Flanking roadside wall, parked car	–	Aspect ratio
					View factor	Sky view factor, building view factor, green view factor
					Vegetation size	Vegetation height, trunk height, hedge length, canopy width, canopy dimension
					Canopy characteristic	Leaf area index, leaf area density, canopy porosity*
					Vegetation configuration	Tree spacing, tree stand density, vegetation relative position
					–	Vegetation canopy coverage percentage
					–	Flanking roadside wall height
					–	The angle of parked cars
Meso-scale	**Block**	Cluster of buildings	Green land use zones (e.g. green space, park, wood, and green belt)	–	Building configuration	Building height*, building width, spacing between buildings, total building area, average building volume, the standard deviation of building height*
					Block layout	Block enclosure*, roughness of buildings and vegetation*
					Block density	Building density*,green space density*
	Neighborhood	Built land use zones (e.g. residential, industrial)		–	Neighborhood composition	Area and density of different types of land use zones
					–	Green space accessibility
					Transportation networks	Road length*, road connectivity*
					Spatial mixing degree of different land uses	Land use mix degree*, land use evenness
Macro-scale	**City and urban agglomeration**	Urban and built-up land covers	Forest, open shrub, grass, and farm land covers	Population, bare soil and water land covers	Dwelling size	Total population, rural population, population density*
					City composition	Area and density of different types of land covers
					Spatial mixing degree of different land covers	Land cover mix degree, land cover evenness*
					Degree of clustering	Degree of clustering of different types of land covers
					Fragmentation and isolation	Fragmentation and isolation of different types of land covers
					Shape complexity	Shape complexity of different types of land covers
					Shape elongation	Shape elongation of different types of land covers

spaces. Due to space limitations, the full list of sub-indicators and their definitions are provided in Table S4. The impact of the indicators of built-up and green spaces on air quality is discussed per scale in the following sub-sections and summarised in Tables 3, 4, and 5. As outlined in Section 2.2.3, the tables show the overall impact of each indicator (negative, positive, insignificant, or various) based on the percentage of evidence pieces collected from the 58 publications. However, it should be noted that in some cases, the overall impact was calculated only based on evidence from one or a few publications. Therefore, the tables also include a column showing the number of pieces of evidence used to

Table 3
The impact of indicators of built-up and green spaces on air quality at the micro-scale. N denotes the number of evidence pieces that the percentage reported is calculated upon (one paper can contain multiple pieces of evidence). The asterisk (*) refers to a group of indicators.

(a)

	Indicators of built-up and green spaces	Impact of indicators of built-up and green spaces on air quality				N.
		Negative	Insignificant	Various	Positive	
Facet	Percentage of the vegetation cover on roofs and walls of buildings	0%	0%	33%	67%	3
Urban canyon	Aspect ratio	-44%	26%	30%	0%	27
	View factor					
	Sky view factor	-100%	0%	0%	0%	1
	Building view factor	0%	100%	0%	0%	1
	Green view factor	0%	0%	0%	100%	2
	Vegetation size					
	Vegetation height	0%	0%	100%	0%	2
	Trunk height	0%	100%	0%	0%	1
	Hedge length	-100%	0%	0%	0%	2
	Canopy width	0%	0%	100%	0%	1
	Canopy dimension	-100%	0%	0%	0%	1
	Canopy characteristic					
	Leaf area index	-38%	62%	0%	0%	13
	Leaf area density	-25%	0%	75%	0%	8
	Canopy porosity*	0%	50%	0%	50%	4
	Vegetation configuration					
	Tree spacing	0%	0%	0%	100%	2
	Tree stand density	-50%	50%	0%	0%	4
	Vegetation canopy coverage percentage	-25%	0%	0%	75%	4
	Flanking roadside wall height	0%	0%	0%	100%	1

(b)

	Indicators of built-up and green spaces	Positive impact of indicators of built-up and green spaces on air quality	N.
Urban canyon	Vegetation configuration		
	Vegetation relative position	Double-rows 17%; Windward 17%; Leeward 33%; Centre 33%	7
	The angle of parked cars	Parallel to the street 50%; Perpendicular to the street 50%	2

calculate each percentage. While these indicators could have been removed from the analysis, we opted to retain them to highlight areas where future research is needed to provide more evidence. In any case, the reported evidence of these indicators should be interpreted with caution. Table S5 provides the detailed impacts of these indicators on different areas of air quality investigation and air pollutants.

Fig. 6 shows that the macro-scale was the most frequent scale studied (42%). The city and urban agglomeration was the only unit investigated at the macro-scale. The meso-scale comprised neighborhoods and blocks, accounting for 29% and 10% of the selected publications, respectively. The micro-scale was the least studied scale, accounting for 19% of the 58 publications. Urban canyons and facets were the two units belonging to this scale, making up 17% and 2% of all the publications, respectively. The following sub-sections discuss the indicators of built-up and green spaces and their impact on air quality at each of these scales (with their urban units), drawing insights from the reviewed publications.

3.2.1. Micro-scale

3.2.1.1. Facet. The facet unit can be recognised by its directional aspect (Oke et al., 2017: 18). The buildings' roofs and walls, with different surface materials, were the main urban facets. The only indicator applied by two publications was the percentage of vegetation cover on roofs and walls of buildings, which showed a positive relationship with air quality in 67% of cases and various outcomes in the remaining 33% (Table 3a). Optimum pollutant capture did not occur at 100% vegetation cover on roofs and walls (Viecco et al., 2021). Instead, 50% to 75% of green roof coverage on low-rise buildings and 25% of green wall coverage was found to achieve the highest $PM_{2.5}$ capture. Overall, to optimise the pollutant capture capability of green walls and roofs, vegetation coverage ratio, building height, and proximity to the pollutant source should be considered.

3.2.1.2. Urban canyon. The urban canyon unit is formed by a street and its flanking buildings (Oke et al., 2017: 19). Street vegetation, flanking roadside walls, and parked cars were other elements in urban canyons that were proven to impact air quality. Relevant indicators at this unit include aspect ratio (the ratio of the building height to the street width), view factors, vegetation size (height, length, width, and dimension), canopy characteristics (leaf area index, leaf area density, and canopy porosity), vegetation configuration (tree spacing, tree stand density, vegetation relative position), vegetation canopy coverage percentage, flanking roadside wall height, and the angle of parked cars. The aspect ratio, applied by 11 out of 15 publications, was the most crucial and commonly used indicator. The height of flanking roadside walls, which

Table 4
The impact of indicators of built-up and green spaces on air quality at the meso-scale. N. denotes the amount of evidence that the percentage reported is based on (one paper can contain multiple pieces of evidence). The asterisk (*) refers to a group of indicators.

	Indicators of built-up and green spaces	Impact of indicators of built-up and green spaces on air quality: Negative	Insignificant	Various	Positive	N.
Block	Building configuration					
	Building height*	-50%	17%	0%	33%	6
	Building width	0%	0%	0%	100%	1
	Spacing between buildings	0%	0%	0%	100%	2
	Total building area	0%	100%	0%	0%	1
	Average building volume	-67%	0%	0%	33%	3
	The standard deviation of building height*	-75%	0%	0%	25%	4
	Block layout					
	Block enclosure*	0%	100%	0%	0%	2
	Roughness of buildings and vegetation*	-67%	33%	0%	0%	3
	Block density					
	Building density*	-73%	13%	0%	13%	15
	Green space density*	-33%	33%	0%	33%	3
Neighborhood	Neighborhood composition					
	Urban construction area	-67%	0%	0%	33%	3
	Urban construction area density	-67%	0%	17%	17%	6
	High-rise building area	-100%	0%	0%	0%	1
	Low-rise building area	-100%	0%	0%	0%	1
	High-rise high-density building area	-100%	0%	0%	0%	1
	High-rise low-density building area	0%	100%	0%	0%	1
	Compact mid-rise area	-75%	0%	0%	25%	4
	Compact low-rise area	-50%	25%	0%	25%	4
	Large low-rise area	-75%	25%	0%	0%	4
	Dense trees area	-25%	0%	0%	75%	4
	Scattered trees area	-25%	25%	0%	50%	4
	Bush, scrub area	-25%	25%	0%	50%	4
	Low plants area	-25%	25%	0%	50%	4
	Residential area*	-7%	50%	0%	43%	14
	Number of points of interest of residential building	0%	100%	0%	0%	1
	Residential area density	-14%	0%	0%	86%	7
	Industry area	-50%	40%	0%	10%	10
	Number of points of interest of industrial facilities	-100%	0%	0%	0%	3
	Industry area density*	-13%	38%	13%	38%	8
	Transportation network area	-100%	0%	0%	0%	1
	Number of points of interest of transportation facilities	-67%	0%	33%	0%	3
	Transportation network area density	-50%	39%	4%	7%	28
	Other built-up area	0%	91%	0%	9%	11
	Number of points of interest of other built-up area	-50%	7%	0%	43%	14
	Other built-up area density	-50%	33%	0%	17%	6
	Park area	-13%	63%	0%	25%	8
	Park area density	-25%	19%	13%	44%	16
	Green space accessibility	0%	100%	0%	0%	2
	Transportation networks					
	Road length*	-50%	17%	17%	17%	6
	Road connectivity*	-41%	53%	0%	6%	17
	Spatial mixing degree of different land uses					
	Land use mix degree*	-22%	11%	0%	67%	9
	Land use evenness	0%	0%	0%	100%	2

are constructed to protect nearby houses, sky view factor, building view factor, and vegetation size indicators (e.g., trunk height, canopy width, canopy dimension) were each applied by only one study in the reviewed publications.

As for the impact of the aforementioned indicators on air quality, Table 3a shows that better air quality can be generally associated with a higher green view factor, more tree spacing, a higher percentage of vegetation canopy coverage, and higher flanking roadside walls. Conversely, a higher sky view factor, representing a wider canyon, a longer hedge, and bigger tree canopy dimensions can worsen air quality. Building view factor, trunk height, and leaf area index showed a statistically insignificant relationship with air quality in the reviewed publications. Various effects were observed on air quality improvement or degradation when different aspect ratios were combined with various green space characteristics. For example, when the value of the aspect ratio was low (e.g., 0.2), increasing vegetation height, tree canopy width, and leaf area density resulted in better air quality, and vice versa when the value of the aspect ratio was high (e.g.,1.0 and 5.0) (Wang et al., 2018).

The impacts of some indicators on air quality at the unit of the urban canyon were controversial or unclear. Two pieces of evidence showed that canopy porosity and tree stand density had statistically insignificant impact on air quality. Conversely, other two pieces of evidence concluded that higher canopy porosity and lower tree stand density were associated with better air quality. Similarly, b shows that the correlation between vegetation relative position and air quality remains unclear. One publication indicated that planting trees in two rows in canyons is more beneficial for air quality. Another concluded that the

Table 5
The impact of indicators of built-up and green spaces on air quality at the macro-scale. N. denotes the amount of evidence that the percentage reported is based on (one paper can contain multiple pieces of evidence). The asterisk (*) refers to a group of indicators.

	Indicators of built-up and green spaces	Impact of indicators of built-up and green spaces on air quality				N.
		Negative	Insignificant	Various	Positive	
City and urban agglomeration	Dwelling size					
	Total population	-67%	33%	0%	0%	3
	Rural population	-100%	0%	0%	0%	1
	Population density*	-57%	33%	7%	3%	30
	City composition					
	Total city area	-25%	25%	25%	25%	4
	Built-up area	-50%	40%	3%	8%	40
	Built-up area density*	-52%	24%	24%	0%	25
	Built-up proportion difference	-100%	0%	0%	0%	2
	Vegetation area	-10%	30%	0%	60%	10
	Vegetation area density*	-17%	17%	8%	58%	24
	Forest area	-9%	45%	0%	55%	22
	Forest area density	-11%	16%	0%	74%	19
	Open shrubland area	-100%	0%	0%	0%	1
	Grassland area	0%	30%	10%	60%	10
	Grassland area density	-11%	11%	0%	78%	9
	Water area	-8%	42%	13%	38%	24
	Water area density*	-6%	72%	17%	6%	18
	Farmland area	-56%	22%	0%	22%	18
	Farmland area density	-31%	19%	25%	25%	16
	Bare soil area	-6%	69%	25%	0%	16
	Bare soil area density	-22%	44%	33%	0%	9
	Spatial mixing degree of different land covers					
	Land cover mix degree	-33%	33%	33%	0%	3
	Land cover evenness*	-20%	13%	7%	60%	15
	Degree of clustering					
	Total city area degree of clustering*	-9%	45%	18%	27%	11
	Built-up area degree of clustering*	-29%	24%	12%	34%	41
	Vegetation area degree of clustering*	-67%	0%	11%	22%	9
	Forest area degree of clustering*	-19%	52%	0%	30%	27
	Grassland area degree of clustering*	-27%	7%	33%	33%	15
	Water area degree of clustering*	-4%	71%	21%	4%	24
	Farmland area degree of clustering*	-29%	61%	0%	11%	28
	Bare soil area degree of clustering*	0%	75%	25%	0%	16
	Fragmentation and isolation					
	Total city area fragmentation and isolation*	-20%	20%	0%	60%	5
	Built-up area fragmentation and isolation*	-14%	43%	7%	36%	28
	Vegetation fragmentation and isolation	-40%	20%	20%	20%	5
	Forest area fragmentation and isolation*	-22%	57%	0%	22%	37
	Grassland area fragmentation and isolation*	-25%	58%	8%	8%	12
	Water area fragmentation and isolation*	-3%	69%	11%	17%	35
	Farmland area fragmentation and isolation*	-8%	76%	3%	13%	38
	Bare soil area fragmentation and isolation*	0%	71%	29%	0%	14
	Shape complexity					
	Total city area shape complexity	0%	50%	50%	0%	2
	Built-up area shape complexity*	-8%	25%	33%	33%	12
	Vegetation area shape complexity	0%	33%	0%	67%	3
	Forest area shape complexity*	0%	20%	60%	20%	5
	Grassland area shape complexity*	0%	100%	0%	0%	5
	Water area shape complexity*	0%	20%	40%	40%	5
	Farmland area shape complexity*	-20%	60%	20%	0%	5
	Bare soil area shape complexity	0%	100%	0%	0%	1
	Shape elongation					
	Built-up area shape elongation	0%	80%	0%	20%	5
	Forest area shape elongation	0%	100%	0%	0%	1
	Grassland area shape elongation	0%	100%	0%	0%	1
	Water area shape elongation	0%	100%	0%	0%	1
	Farmland area shape elongation	0%	0%	100%	0%	1

vegetation planted windward, i.e., the side facing the direction from which the wind is blowing, was beneficial for reducing air pollution exposure. One publication demonstrated that the vegetation in the centre of the street or leeward, i.e., the side facing the direction towards which the wind is going, was beneficial for the dispersion of $PM_{2.5}$ and CO. The presence of parallel (0°) and perpendicular (90°) roadside car parking was proven to be better for air quality than cars parked at 30°, 45°, or 60° (Abhijith and Gokhale, 2015).

Overall, the specific combination of different aspect ratios of urban canyons and street vegetation characteristics can create distinct micro-

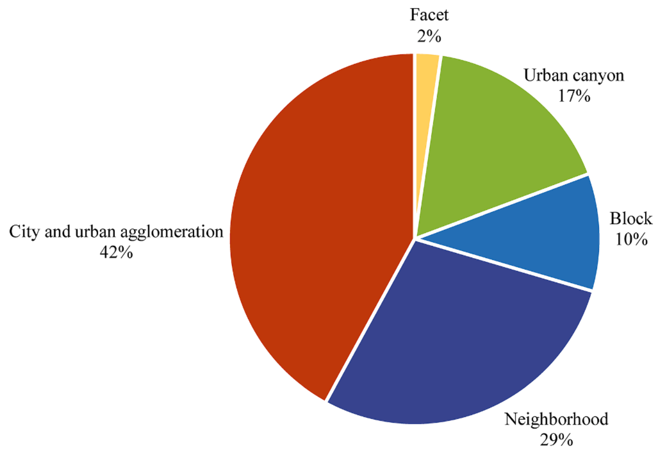

Fig. 6. Frequency of occurrence of spatial scales and units of built-up and green spaces. Percentages show the frequency of each unit's occurrence, considering multiple units may have been investigated within the same publication. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

environments, which have different potentials for improving air quality dispersion and deposition or mitigating personal exposure to pollutants (Zhu et al., 2022). In broad canyons, where the value of the aspect ratio is low (e.g., 0.2), taller trees, wider tree canopy, and higher leaf area density lead to better air quality, and vice versa in narrow canyons, where the value of the aspect ratio is high (e.g., 1.0 and 5.0) (Wang et al., 2018).

3.2.2. Meso-scale

3.2.2.1. Block. A block unit is a cluster of buildings that is surrounded by streets (Oke et al., 2017: 19). Built-up and green spaces were measured by building configuration, block layout, and block density. Building configuration includes building height, width, area, volume, spacing between buildings, and the standard deviation of building height. The block layout concernes the block enclosure and the roughness of buildings and vegetation. Indicators that measured building and green space densities were added to the block density category. Building density, applied by seven out of nine publications, was the most commonly used indicator. Building width and total building areas were applied only once across the reviewed publications.

Table 4 shows that, generally, an increase in building width and spacing between buildings led to better air quality. The building area and block enclosure had no statistically significant relationship with air quality. More than half of the evidence collected indicated that a higher building, a bigger average building volume, and a higher standard deviation of building height (i.e., higher variation in building heights) were associated with worse air quality. Also, poorer air quality was related to a larger roughness of buildings and vegetation and a higher building density. However, the impacts of green space density on air quality were controversial.

3.2.2.2. Neighborhood. The neighborhood unit includes various functional land use zones, e.g., industrial, residential, and park. It can also be defined by its capacity to modify local climates, such as the local climate zones (LCZs) (Stewart and Oke, 2012). Neighborhood characteristics such as composition, accessibility to green spaces, transportation networks, and spatial mixing degree of different land uses were discussed in the reviewed literature. The neighborhood composition was evaluated by the area and density of different land use zones. Road length and connectivity were the main indicators of the transportation network. The spatial mixing degree of different land uses was mainly related to land use mix degree and land use evenness. Transportation network area density, applied by nine out of 25 publications, was the most used indicator. The area of different LCZs (e.g., compact mid-rise, dense trees), and green space accessibility, were applied only once across the reviewed publications.

As shown in Table 4, more than half of the evidence showed that, at the neighborhood unit, larger dense trees, scattered trees, bush, scrub, and low plant areas contributed to better air quality. Also, the higher density of residential areas (Irin and Habib, 2016), land use mix degree, and land use evenness positively affected air quality. On the contrary, more than half of the evidence demonstrated that larger areas and higher densities of urban construction led to worse air quality. High- and low- rise building areas, high-rise high-density building areas, compact mid- and low-rise areas, and large low-rise areas all had a negative impact on air quality. Similarly, increasing the values of indicators measuring the composition of some artificial areas, like the area of industry and transportation networks and the density of transportation network areas and other built-up areas were associated with worse air quality. An increase in the number of points of interest of industrial facilities (factories, industrial parks, and industry facilities), transportation facilities (gas stations, bus stops, and parking lots), and other built-up facilities (restaurants, business buildings, and educational institutions) affected air quality negatively. The growth in road length was related to poor air quality.

More than half of the evidence showed that high-rise low-density building areas, residential areas, park areas, had a statistically insignificant relationship with air quality. The number of points of interest of residential buildings and other built-up areas (commercial and educational) had insignificant effects on air quality. Green space accessibility had a statistically insignificant relationship with air quality. Besides, road connectivity did not show a significant relationship with air quality. There is still inconsistency in findings regarding the impact of the density of industry area and park area on air quality.

Overall, poorer air quality was related to higher building density, higher buildings, higher variation in building heights, and lower land use mix degree. Increasing the values of indicators measuring the areas and density of built-up spaces like urban construction areas, transportation networks, and other built-up areas results in a negative effect on air quality. However, there is still a lack of consistent findings regarding how the density of green spaces and parks can impact air quality.

3.2.3. Macro-scale

3.2.3.1. City and urban agglomeration. Cities experience more severe pollution than suburban and rural areas (Huang et al., 2019). An urban agglomeration "comprises a city or town proper and the suburban fringe or thickly settled territory lying outside, but adjacent to, its boundaries" (European Environment Agency, 1998).

Cities and urban agglomerations can be generally classified by their land cover zones, like built-up, forest, and water. Dwelling size, city composition, spatial mixing degree of different land uses and land covers, degree of clustering, fragmentation and isolation, shape complexity, and shape elongation were the seven groups of indicators applied. Besides dwelling size, most of other indicators were measured by landscape metrics (Mcgarigal, 2015), quantifying the compositions and configurations of land cover patterns. We classified these indicators of landscape metrics into different groups according to their original definition and application in the reviewed publications. Total population, rural population, and population density were applied to measure dwelling size. The city composition included the area and density of land cover zones. The spatial mixing degree of different land covers was mainly related to land cover mix degree and land cover evenness. Indicators related to the degree of clustering were used to measure the degree of aggregation or clumping of land cover patches. Fragmentation and isolation were the physical disintegration of continuous areas into smaller land cover patches (Mcgarigal, 2015). Indicators belonging to shape complexity reflected the complexity of the shape of land covers. Shape elongation was representative of the degree of linear growth patterns of land cover patches, for example, along rivers and valleys (Lu et al., 2018). Population density, investigated by 18 out of 26 publications at this unit, was the most applied indicator. Shape elongation of forest, grassland, farmland, and water was applied only once across the reviewed publications.

As shown in Table 5, more than half of the evidence showed that a larger total population, a larger rural population, and a higher population density led to worse air quality. Among the city composition indicators that led to poorer air quality were an increase in built-up areas, higher built-up area density, a more significant difference between the proportions of built urban and suburban areas, and expansion of open shrubland and farmland areas. Conversely, the larger areas and densities of nature land covers, such as forest and grassland, correlated with better air quality. Water area density and bare soil area showed an insignificant impact on air quality. This review shows that there is still a general lack of consistent findings regarding how total city area, water area, farmland area density, and bare soil area density can impact air quality.

The majority of evidence showed the positive impacts of land cover evenness on air quality. In total, 67% of the evidence indicated that a higher degree of clustering of vegetation areas was related to worse air quality. The relationships between the degree of clustering of forest area, water area, farmland area, bare soil area, and air quality were statistically insignificant. The relationship between the land cover mix degree, degree of clustering of total city area, built-up area, grassland area, and air quality remains unclear. More fragmentation and isolation of the total city area positively affected air quality. The relationship between fragmentation and isolation of forest area, grassland area, water area, farmland area, bare soil area, and air quality was statistically insignificant. There is a lack of consensus inconsistent findings regarding the correlation between fragmentation and isolation of built-up areas, vegetation areas, and air quality.

A more complex shape of vegetation area was proven to impact air quality positively by three pieces of evidence. The shape complexity of the grassland area, farmland area, and bare soil area had a statistically insignificant correlation with air quality. The relationship between the shape complexity of the total city area, built-up area, forest area, water area, and air quality remains unclear. Shape elongation of farmland was related to worse air quality in second-level administrative cities, while it had an insignificant influence on air quality in bigger cities in China (Li and Huang, 2020). Besides farmland, the shape elongation of all kinds of land covers had a statistically insignificant relationship with air quality.

Overall, increasing built-up land and farmland generally worsened air quality because of the dense anthropogenic emissions and use of pesticides and fertilisers (Li and Huang, 2020). However, forests and grasslands had opposite effects (Lu et al., 2018). More than half of the evidence showed positive impacts of land cover evenness on air quality. A more complex shape and less clustered distribution for vegetation areas can improve air quality.

4. Discussion

This review demonstrates the complexity of the impact of built-up and green spaces on air quality. This complexity stems from the fact that there are different areas of air quality investigation, various pollutants, and various indicators of built-up and green spaces.

4.1. On the current state of the art, future research, and implications for urban planning, design, and policy

Proper management and mitigation of air pollution require a coherent understanding of all areas of air quality investigation. We found that more than 60% of the publications we reviewed focused on phenomena, which means observable events and occurrences related to air quality such as concentration and atmospheric visibility. This points out that research has given great attention to monitoring and observing pollutants while paying less attention to the potential contribution of action and intervention through planning, design, and policies to reduce emissions and human exposure. A recent study shows that urban design interventions can help to mitigate air pollution exposure (Voordeckers et al., 2024). It demonstrated that adjusting the positions of traffic lanes to the leeward direction and adding low boundary walls according to the local contexts can reduce pedestrian exposure to NO_2 by up to 8.0% on average. Future research can focus on proposing design and planning strategies to reduce emissions, enhance dispersion and deposition, and mitigate concentration and people's exposure to pollutants.

Based on eight areas of air quality investigation, we propose strategies for practitioners on how to address air pollution in urban environments. Firstly, to decrease traffic emissions, urban air quality management policies can focus on reducing private car usage, enhancing public transport, improving traffic flow, reducing speed limits, and implementing low-emission zones (Voordeckers et al., 2021a). Establishing mixed land use neighborhoods (e.g., residential, administrative, commercial, etc.) can increase the proximity between residents and their destinations, potentially reducing the length and frequency of automobiles, enhancing walking and cycling and, in turn, decreasing emissions of automobiles. Secondly, enhancing pollutant dispersion and ventilation through planning ventilation corridors and maintaining sufficient spacing between buildings can reduce the time that pollutants stagnate and avert the accumulation of air pollutants (Yang et al., 2020). Thirdly, vegetation enhances deposition by capturing particulate matter on leaf surfaces and facilitating gas absorption through stomatal uptake. However, vegetation should be selected and planned carefully since it can also block ventilation and pollutant dispersion, especially in dense urban areas, thereby causing more pollutant concentration (Lindén et al., 2023). Fourthly, monitoring air pollution phenomena, like pollutant concentration, atmospheric visibility, and urban particulate matter island effect, by satellite platform-based sensors, aerial platform-based sensors, official monitoring stations, or mobile measurements can help to identify the pollution sources (Singh et al., 2021). Also, sharing the monitoring results and including citizens in the measurements of air pollution through citizen science initiatives can help raise public awareness (Air-Break, 2022). This can result in stronger policies to address air pollution and changes in travel behaviour, for example, shifting from driving private vehicles to public transportation, waking, and cycling. Lastly, to reduce people's exposure and health impact to air pollutants, urban planners and policymakers can segregate pollutant sources and citizen activities. For example, at the macro-scale, strategic planning can position factories in the downwind direction of urban areas to create separation from residential areas, schools, and healthcare facilities (Giles et al., 2011). At the micro-scale, designers can align traffic lanes downwind and add barriers between traffic lanes and pedestrian routes to minimize pollutant exposure (Voordeckers et al., 2024).

Besides the six most studied air pollutants, including $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and O_3, future research is encouraged to focus more on other less-studied hazardous pollutants. For example, there are many medium- to long-lived pollutants that exist in cities, like nitrogen oxides (NO), carbon dioxide (CO_2), lead (Pb), non-methane volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons (PAHs), all of which impact human health and ecosystems (Oke et al., 2017: 296).

For each scale, specific methods are effective for investigating the impact of built-up and green spaces on air quality. At the micro-scale, validated numerical models, physical models, and empirical models are complementary. Computational Fluid Dynamics (CFD) models, as a type of numerical model, are essential tools in urban design and decision-making for studying the complex interactions between changes in built-up and green spaces and the emission, dispersion, deposition, concentration, and exposure of air quality. It is important to validate the simulation results of CFD models by either wind tunnel tests or field measurements (Allegrini et al., 2014). Besides, CFD models require input parameters and meteorological drivers from field measurements (Oke et al., 2017: 76). The application of physical models, e.g., wind tunnel tests, is still limited for urban design and planning becasue of the high cost of the equipment and models (Abohela and Sundararajan, 2024). Empirical models can help designers and planners understand the effects of spatial characteristics on pollution concentration and exposure. At the micro-scale, high spatial resolution air quality data can be collected by mobile air quality monitoring where the data is scarce (Hu et al., 2021). At meso- and macro- scales, designers and planners can apply empirical models to investigate the correlation between the air pollution phenomena from monitoring stations (Zeng et al., 2022) or remote sensing (Gheshlaghpoor et al., 2023) and indicators of built-up and green spaces. Empirical models can also contribute to predicting continuous air quality (Li et al., 2023a) using high resolution built-up, green spaces, meteorological, and demographic data. Numerical models at the meso-scale, e.g., WRF/CMAQ (Xu and Chen, 2021), which couple the Weather Research and Forecasting model with a chemistry-transport model, can be applied by planners and designers to capture spatial form and air quality at a larger scale.

4.2. *On the indicators of built-up and green spaces and their impact on air quality, future research, and implications for urban design and planning*

This work reviewed various built-up and green space indicators and their impact on air quality. Fig. 7 shows the connection between the different scales of indicators of built-up and green spaces and seven areas of air quality investigation from left to right. The majority of publications at the micro-scale focused on pollution dispersion, while most of the publications at the meso- and macro-scales analysed the pollution concentration. More details will be discussed in the following sections.

4.2.1. *Micro-scale*

At the micro-scale, the green space-related indicators in our review focused only on the characteristics of individual vegetation, such as tree height and canopy porosity, while overlooking the possibility of combining different types or forms of vegetation in street greenery design. Recent studies indicated that a combination of trees and hedge barriers were effective at minimizing pedestrians' exposure to pollutants (Jeong et al., 2022). We suggest future research consider the complex configuration of different vegetation types, species, and forms in the analysis of air quality at urban canyons and elevate vegetation as a quintessential feature in urban morphology studies.

Also, although recent studies indicated that view factors (e.g., sky view factor, building view factor, and green view factor) are promising for predicting air quality in urban canyons (Ganji et al., 2020), they were applied by only two of the publications we reviewed. These indicators can be derived through various urban data sources, such as street view images, 3D building databases, satellite visibility data, and fish-eye images (Miao et al., 2020), hence are becoming more and more accessible. Including view factors in future studies can help explore this topic with greater geographical coverage and temporal granularity.

Current research has mainly focused on assessing the impact of canyon geometry and street vegetation on pollutant dispersion, exposure, deposition, and concentration of pedestrians or cyclists at the micro-scale (see Fig. 7). Urban canyons have been pointed out as hot spots in terms of air pollution, and high levels of pollution concentration can cause pollution-related diseases in the exposed population (Ehrnsperger and Klemm, 2022). Built-up and green spaces impact air quality at urban canyons through the combined impacts of deposition and dispersion (Janhäll, 2015), and dispersion is generally considered as the dominant mechanism (Barwise & Kumar, 2020; Tomson et al., 2021). However, one publication we reviewed indicated that pollutant removal due to deposition can counterbalance the enhancement by insufficient dispersion under some vegetation planting scenarios and wind conditions (Morakinyo and Lam, 2016). Similarly, Barwise and Kumar (2020) demonstrated that deposition can serve as an essential additional mechanism for reducing pollutant concentration when vegetation is positioned and maintained effectively. This indicates the necessity of choosing the proper vegetation type and form by considering the surrounding canyon geometires and meteorological conditions to minimise the pedestrians' exposure to pollutants. However, using vegetation instrumentally to minimise human exposure places nature in a subordinate relationship to humans, challenging the anthropocentric definition of Nature-Based Solutions (NBS) (Lemes de Oliveira and Mahmoud, 2024). However, exploring the rights of nature—or those of non-human and biotic entities—is beyond the scope of this study.

Although controlling the traffic volume to reduce emissions is one of the most effective strategies to improve air quality, proper urban canyon geometry and street greenery design can mitigate air pollution to some extent. Our review suggests designing canyon geometry with low aspect ratios. Moreover, Huang et al. (2021) add other design guidelines for canyon geometry, including uneven building heights and high building porosity at the ground level. For future urban canyons, these strategies can improve ventilation and increase pollutant dispersion and, hence, reduce the exposure of pedestrians and cyclists.

For existing urban canyons, the design of vegetation types (green roofs, green walls, hedges, and trees), forms, and solid barriers (flanking roadside walls and parked cars) can prevent pollutant dispersion from traffic emissions to roadside routes of pedestrians and cyclists. Voordeckers et al., (2021b) concluded that for urban canyons with aspect ratio larger than 0.65, the maximum hourly traffic volume should be less than 300 vehicles per hour to provide an acceptable air quality. Voordeckers et al. (2021a) demonstrated that low boundary walls and noise barriers are also critical solid barriers to air quality. Green screens, composed of climbing vegetation growing on a steel or plastic mesh, can be considered for streets with limited space (Tomson et al., 2021). Implementing these interventions should consider the surrounding

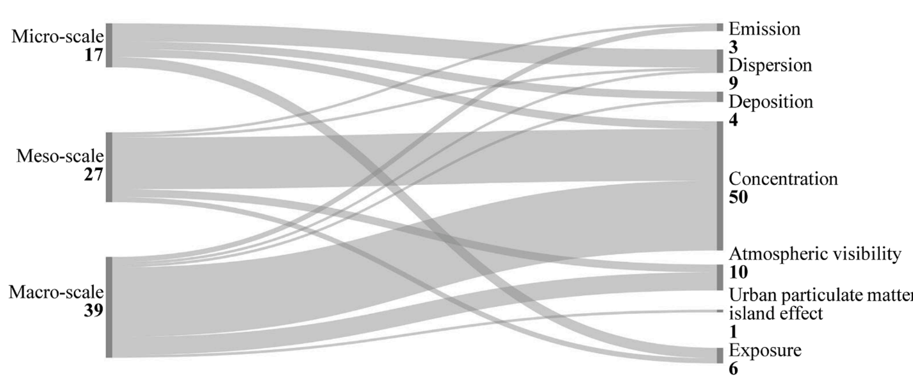

Fig. 7. Connections between scales and areas of air quality investigation.

urban canyon geometry, especially the aspect ratio, to avoid adverse ventilation effects. Our results demonstrated that in narrow canyons, tall, wide, and dense trees should be avoided. Green roofs, green walls, and green screens are recommended (Barwise and Kumar, 2020). Besides, one of the publications we reviewed indicated that green walls performed better than green roofs in improving air quality at the pedestrian level, and optimum air quality did not occur at 100% vegetation cover on roofs and walls. Building height, surrounding urban infrastructure, and proximity to the pollutant source impact the improvement of air quality through green walls and green roofs (Viecco et al., 2021). Huang et al. (2021) suggested that combining vegetation and solid barriers, such as constructing noise barriers (metal or concrete) combined with green walls, is more effective than individual use. Overall, the implementation of vegetation design and solid barriers design intervention requires careful consideration and evaluation of their suitability for urban canyon geometry contexts.

4.2.2. Meso-scale

At the meso-scale, in addition to traditional two-dimensional indicators (e.g., building area and building spacing), three-dimensional ones (e.g., the roughness of buildings and vegetation) were getting more and more interest (Kokkonen et al., 2021). Ke et al. (2022) demonstarted that, compared to two-dimensional indicators, three-dimensional indicators have a greater explanation of $PM_{2.5}$ concentration changes. We encourage future research to integrate three-dimensional and two-dimensional indicators to interpret their relationship with air quality.

We also found that most studies examine the effect of green spaces on air quality using generalised measures, such as area, density, and accessibility (Servadio et al., 2019). Future work could use additional indicators to evaluate the influence of green spaces on air quality, such as the differentiation between types, locations (distance to pollution resources) and qualities.

A few indicators of built-up and green spaces at the meso-scale varied in their definitions across different publications. For example, road connectivity was measured by both the road junction density (Yuan et al., 2019) and the distance to the nearest road (Shi et al., 2020). Furthermore, there were inconsistencies with the naming of the indicators, which creates ambiguity. For example, the roughness of buildings, represented by the ratio of the standard deviation of building height to the average building height, is referred to as construction otherness by Luan et al. (2020) and landscape height variation coefficient by Ren et al. (2022). Other researchers have also identified issues with terminological inconsistencies (Fleischmann et al., 2021). The inconsistent interpretation and naming of built-up and green spaces indicators have a striking impact on the understanding of knowledge between scholars from different subjects and between actors in the field of practice. We encourage future studies to facilitate the standard terminology in the indicators of built-up and green spaces across disciplines. We provide exhaustive taxonomy of built-up and green spaces that can impact air quality, which are listed in Table S4.

Most of the publications we reviewed investigated the impact of built-up and green spaces on concentration, atmospheric visibility, and exposure at the meso-scale (see Fig. 7). Few publications addressed emission and dispersion. However, as we discussed in Section 4.1, in addition to observing, urban planners and designers are responsible for intervening in cities (e.g., through density, land use, and transportation) to regulate emissions, enhance dispersion, increase deposition, and mitigate the exposure of citizens to pollutants.

The effect of building density on air quality remains ambiguous. Two publications we reviewed showed that high building density worsens air quality as it may reduce pollutant dispersion, causing the accumulation of pollutants (Yuan et al., 2019; Zhang et al., 2022). Another recent study estimated that a 1% rise in building density increases average residential $PM_{2.5}$ exposure by 0.14% (Carozzi and Roth, 2023). However, denser cities with compact and mixed-use lands tend to have fewer per capita emissions through lower levels of vehicle miles travelled and a lower level of emissions per capita from heating and electricity usage (Glaeser and Kahn, 2010). Overall, the impact of building density on air quality depends on whether the reduction in per capita emissions outweighs the decrease in pollution dispersion and increase in exposure resulting from the spatial concentration of citizens. Future research can explore the possible trade-off between density and these areas of air quality investigation, including emissions, dispersion, deposition, concentration, and exposure.

How the area and density of green spaces and parks affect air quality remains unclear at the meso-scale. Two publications we reviewed demonstrated that green spaces can mitigate air pollution concentration by providing leaf areas for pollutant deposition (Park and Ko, 2021; Shi et al., 2020). Besides, as we discussed in 4.2.1, green spaces can also affect air quality by dispersion. The relative effects of deposition and dispersion depend on an interaction of local factors, such as vegetation biophysical traits (e.g., leaf micromorphology, stomatal characteristics type, leaf size, and leaf complexity) (Barwise and Kumar, 2020), surrounding urban form (e.g., distances from streets and land-use) (Han et al., 2020), and meteorological factors (e.g., temperature, wind) (Diener and Mudu, 2021). Besides, the complex impact of green spaces and parks on air quality also depends on the physical and chemical characteristics of different pollutants. One of the publications we reviewed demonstrated that green spaces have a negative correlation with the concentration of nitrogen dioxide (NO_2), carbon monoxide (CO), and sulphur dioxide (SO_2) but a positive correlation with ozone (O_3) concentration (Gheshlaghpoor et al., 2023). This is due to the combination of biogenic volatile organic compounds (BVOCs) from vegetation and nitrogen oxides (NO_x) can cause the formation of ozone (O_3) (Wang et al., 2008). We recommend that future studies consider the complexities of green spaces' impact on different areas of air quality investigation and air pollutants to maximise the contribution of green spaces and parks on decreasing pollutant concentration and citizens' exposure.

Connecting parks, gardens, and urban green spaces to suburban forests can form ventilation corridors, allowing air pollutants to disperse (Badach et al., 2022). Green spaces, parks, and gardens should be designed and maintained carefully to enhance their reduction influence on pollutant concentrations through deposition.

4.2.3. Macro-scale

At the macro-scale, we found that built-up and green spaces were quantified by landscape metrics. Landscape metrics were initially developed to measure landscape patterns and to assess ecological functions (Norton et al., 2016). Furthermore, landscape metrics have been increasingly applied in studying the spatial characteristics of urban environments and interpreting the effects of these characteristics on ecological and environmental phenomena, like species diversity, heat island effect, and air pollution. However, uncertainties still exist around the application and interpretation of landscape metrics in urban environments. For example, one publication we reviewed indicated that directly using the urban patch will cause skewed metrics such as the mean patch area (McCarty and Kaza, 2015). This is because different urban fragments connected by transport networks are shown on the same urban patch. Complex urban environments increase the difficulty of understanding and modelling landscape structures in urban areas. Relying on broad and aggregate metrics for conceptualising urban characteristics risks oversimplifying the urban landscape structure (Grafius et al., 2018). There is a need to take a more rigorous perspective on landscape metric selection that considers the unique characteristics and scale requirements of urban environments.

Our review indicated that the vegetation areas, which have complex shapes and less clustered, showed positive correlations with air quality (Li et al., 2023a), because the distance between vegetation areas with built-up areas is closer, and vegetation can absorb more pollutants produced from built-up areas (Wu et al., 2015). However, other studies concluded that air quality is better if vegetation areas are more contiguous with each other (Bi et al., 2022; Li et al., 2021), since fragmented green spaces lead to a reduction of ventilation, potentially trapping pollutants (Cardinali et al., 2024). Future studies at the macro-scale can explore the correlation between the pattern of green spaces and the dispersion and deposition of air pollution.

Cities represent 3% of the planet's land area (Liu et al., 2014). Green spaces adjacent to built-up land covers represent a small fraction of overall land area but are critical to air quality in urban environments. One publication we reviewed applied urban forest mixing, which referred to the ratio of forest land within a one-kilometre buffer for each urban patch to the total urban area. Rather than forest density, this indicator showed a significant correlation with a reduction in air quality index exceedance days (McCarty and Kaza, 2015). We recommend that future macro-scale studies give particular consideration to green spaces adjacent to urban areas and air quality relationships.

Establishing urban boundaries to control urban sprawl and disorder of suburban development can decrease the demand of energy, resulting in less pollution emission. Integrating Green and Blue Infrastructures (GBI) planning (e.g., green–blue wedges and corridors) in different cities and urban agglomerations helps to enhance urban ventilation, and contributes to air pollution dispersion.

4.3. Limitations

This review has a few limitations that should be highlighted. Firstly, we restricted the search to publications written in English. This may have caused that most of the publications we reviewed were conducted in the United States, China, and Europe, possibly contributing to an unintentional "cultural bias".

Also, although in this review we have discussed eight areas of air quality investigation, some areas might have not been included, such as ventilation efficiency (Peng et al., 2019) and city breathability (Da Silva et al., 2022). This may be because existing studies have only explored the relationship between built-up spaces and ventilation efficiency or city breathability, without considering green spaces.

Furthermore, although the review has covered most units of built-up and green spaces, a few may have not been addressed, such as the single building scale (Oke et al., 2017: 18). Building envelope materials can influence the need for air conditioning, affecting greenhouse gas emissions. The reason we did not include the single-building scale is that studies at this scale typically focus only on the influence of building characteristics on air quality without considering vegetation.

It should also be noted that the results on the impacts of different indicators on air quality (Table 3, 4, and 5) should be interpreted with caution. This is because our results were gained by summarising different areas of air quality investigation and various pollutants to support decision-making in urban design, planning, and policy. For example, in this review, more than half of the evidence indicated that the standard deviation of building height is negatively correlated to air quality. This result is based on four pieces of evidence, among which three pieces show a negative correlation with pollutant concentration (Luan et al., 2020; Ren et al., 2022), and one piece shows a positive correlation with pollutant dispersion (Zhang et al., 2022).

5. Conclusion

Designing and planning built-up and green spaces at multiple scales is essential to improving air quality in cities. This article systematically reviewed 61 peer-reviewed publications to better understand how built-up and green spaces affect air quality at multiple spatial scales and hence support decision-making in urban design, planning, and policy. The main contributions of this systematic literature review are: (1) the development of a taxonomy identifying the indicators of built-up and green spaces that influence air quality across multiple spatial scales; and (2) the synthesis of scientific evidence on the impact of built-up and green space indicators on air quality.

The review showed that air quality phenomena (concentration, atmospheric visibility and urban particulate matter island effect) were the most investigated areas in air quality research. Six most studied air pollutants included $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and O_3. At the micro-scale, numerical models were mostly used and at the meso- and macro- scales, empirical models were mostly applied. Then, we developed a comprehensive taxonomy of indicators of built-up and green spaces distributed at various urban units, from micro- to macro-scales, that impact air quality (Table 2). Additionally, we collected and summarised quantitative evidence of the impact of built-up and green spaces indicators on air quality (Table 3, 4, and 5).

Several areas for future research were also identified. Besides monitoring and observing pollutants' pheonomena (e.g., concentration and atmospheric visibility), interventions through planning, design, and policies to produce a particular effect on air quality are highly recommended. For instance, paying attention to the built environment's role in air quality helps recognize the responsibility of urban planning and governance. In addition, the outcomes of this study encourage future research to focus on: (1) at the micro-scale, the impact of vegetation configuration on air quality; the influence of view factors on air quality; (2) at the meso-scale, the effect of three-dimensional built-up indicators on air quality; the influence of various green space indicators, like type, location, and quality, on air quality; a systems perspective on the trade-offs between building density and emissions, dispersion, concentration, and exposure; the impact of green space density on air quality; and (3) at the macro-scale, selecting landscape metric rigorously for analysing their effect on air quality; the impact of patterns of green spaces on air quality; the effect of green spaces adjacent to urban areas on air quality.

CRediT authorship contribution statement

Chenling Wu: Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Ahmed Hazem Eldesoky:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Eugenio Morello:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

Chenling Wu was supported by the Chinese Scholarship Council (CSC, China) for her Ph.D. study. We would like to acknowledge the CSC for this funding.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2025.105304.

Data availability

The data that support the findings of this study can be found in the supplementary materials.

References

Abhijith, K., & Gokhale, S. (2015). Passive control potentials of trees and on-street parked cars in reduction of air pollution exposure in urban street canyons. *Environmental Pollution, 204*, 99–108. https://doi.org/10.1016/j.envpol.2015.04.013

Abhijith, K. V., Kumar, P., Gallagher, J., McNabola, A., Baldauf, R., Pilla, F., Broderick, B., Di Sabatino, S., & Pulvirenti, B. (2017). Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments – A review. *Atmospheric Environment, 162*, 71–86. https://doi.org/10.1016/j.atmosenv.2017.05.014

Abohela, I., & Sundararajan, R. (2024). Analytical review of wind assessment tools for urban wind turbine applications. *Atmosphere, 15*(9), 1049. https://doi.org/10.3390/atmos15091049

Air-Break, 2022. AIR-BREAK: Co-producing healthy clean commuting air spots in town. https://airbreakferrara.net/. Accessed 08 November 2024.

Allegrini, J., Dorer, V., & Carmeliet, J. (2014). Buoyant flows in street canyons: Validation of CFD simulations with wind tunnel measurements. *Building and Environment, 72*, 63–74. https://doi.org/10.1016/j.buildenv.2013.10.021

Badach, J., Szczepański, J., Bonenberg, W., Gębicki, J., & Nyka, L. (2022). Developing the urban blue-green infrastructure as a tool for urban air quality management. *Sustainability, 14*(15), 9688. https://doi.org/10.3390/su14159688

Barwise, Y., & Kumar, P. (2020). Designing vegetation barriers for urban air pollution abatement: A practical review for appropriate plant species selection. *npj Climate and Atmospheric Science, 3*(1). https://doi.org/10.1038/s41612-020-0115-3

Berghauser Pont, M., Haupt, P., Berg, P., Alstäde, V., & Heyman, A. (2021). Systematic review and comparison of densification effects and planning motivations. *Buildings and Cities, 2*(1), 378. https://doi.org/10.5334/bc.125

Bi, S., Chen, M., & Dai, F. (2022). The impact of urban green space morphology on PM2.5 pollution in Wuhan, China: A novel multiscale spatiotemporal analytical framework. *Building and Environment, 221*, Article 109340. https://doi.org/10.1016/j.buildenv.2022.109340

Cardinali, M., Beenackers, M. A., van Timmeren, A., & Pottgiesser, U. (2024). Urban green spaces, self-rated air pollution and health: A sensitivity analysis of green space characteristics and proximity in four European cities. *Health & Place, 89*, Article 103300. https://doi.org/10.1016/j.healthplace.2024.103300

Carozzi, F., & Roth, S. (2023). Dirty density: Air quality and the density of American cities. *Journal of Environmental Economics and Management, 118*, Article 102767. https://doi.org/10.1016/j.jeem.2022.102767

Da Silva, F. T., Reis, N. C., Santos, J. M., Goulart, E. V., & de Alvarez, C. E. (2022). Influence of urban form on air quality: The combined effect of block typology and urban planning indices on city breathability. *The Science of the Total Environment, 814*, Article 152670. https://doi.org/10.1016/j.scitotenv.2021.152670

Diener, A., & Mudu, P. (2021). How can vegetation protect us from air pollution? A critical review on green spaces' mitigation abilities for air-borne particles from a public health perspective - with implications for urban planning. *The Science of the Total Environment, 796*, Article 148605. https://doi.org/10.1016/j.scitotenv.2021.148605

Ehrnsperger, L., & Klemm, O. (2022). Air pollution in an urban street canyon: Novel insights from highly resolved traffic information and meteorology. *Atmospheric Environment: X, 13*, Article 100151. https://doi.org/10.1016/j.aeaoa.2022.100151

European Environment Agency, 1998. urban agglomeration, 1998. https://www.eea.europa.eu/help/glossary/eea-glossary/urban-agglomeration. Accessed 23 March 2024.

Feng, S., Gao, D., Liao, F., Zhou, F., & Wang, X. (2016). The health effects of ambient PM2.5 and potential mechanisms. *Ecotoxicology and Environmental Safety, 128*, 67–74. https://doi.org/10.1016/j.ecoenv.2016.01.030

Fleischmann, M., Romice, O., & Porta, S. (2021). Measuring urban form: Overcoming terminological inconsistencies for a quantitative and comprehensive morphologic analysis of cities. *Environment and Planning B: Urban Analytics and City Science, 48*(8), 2133–2150. https://doi.org/10.1177/2399808320910444

Fu, W., Liu, Q., van den Konijnendijk Bosch, C., Chen, Z., Zhu, Z., Qi, J., Wang, M., Dang, E., & Dong, J. (2018). Long-term atmospheric visibility trends and their relations to socioeconomic factors in Xiamen City, China. *International Journal of Environmental Research and Public Health, 15*(10). https://doi.org/10.3390/ijerph15102239

Ganji, A., Minet, L., Weichenthal, S., & Hatzopoulou, M. (2020). Predicting traffic-related air pollution using feature extraction from built environment images. *Environmental science & technology, 54*(17), 10688–10699. https://doi.org/10.1021/acs.est.0c00412

Gheshlaghpoor, S., Abedi, S. S., & Moghbel, M. (2023). The relationship between spatial patterns of urban land uses and air pollutants in the Tehran metropolis, Iran. *Landscape Ecology, 38*(2), 553–565. https://doi.org/10.1007/s10980-022-01549-y

Giles, L. V., Barn, P., Künzli, N., Romieu, I., Mittleman, M. A., van Eeden, S., Allen, R., Carlsten, C., Stieb, D., Noonan, C., Smargiassi, A., Kaufman, J. D., Hajat, S., Kosatsky, T., & Brauer, M. (2011). From good intentions to proven interventions: Effectiveness of actions to reduce the health impacts of air pollution. *Environmental Health Perspectives, 119*(1), 29–36. https://doi.org/10.1289/ehp.1002246

Glaeser, E. L., & Kahn, M. E. (2010). The greenness of cities: Carbon dioxide emissions and urban development. *Journal of Urban Economics, 67*(3), 404–418. https://doi.org/10.1016/j.jue.2009.11.006

Grafius, D. R., Corstanje, R., & Harris, J. A. (2018). Linking ecosystem services, urban form and green space configuration using multivariate landscape metric analysis. *Landscape Ecology, 33*(4), 557–573. https://doi.org/10.1007/s10980-018-0618-z

Gromke, C., & Ruck, B. (2012). Pollutant concentrations in street canyons of different aspect ratio with avenues of trees for various wind directions. *Boundary-Layer Meteorol, 144*(1), 41–64. https://doi.org/10.1007/s10546-012-9703-z

Han, D., Shen, H., Duan, W., & Chen, L. (2020). A review on particulate matter removal capacity by urban forests at different scales. *Urban Forestry & Urban Greening, 48*, Article 126565. https://doi.org/10.1016/j.ufug.2019.126565

Hankey, S., & Marshall, J. D. (2017). Urban form, air pollution, and health. *Current Environmental Health Reports, 4*(4), 491–503. https://doi.org/10.1007/s40572-017-0167-7

Hofman, J., Stokkaer, I., Snauwaert, L., & Samson, R. (2013). Spatial distribution assessment of particulate matter in an urban street canyon using biomagnetic leaf monitoring of tree crown deposited particles. *Environmental Pollution, 183*, 123–132. https://doi.org/10.1016/j.envpol.2012.09.015

Hu, H., Chen, Q., Qian, Q., Lin, C., Chen, Y., & Tian, W. (2021). Impacts of traffic and street characteristics on the exposure of cycling commuters to PM2.5 and PM10 in urban street environments. *Building and Environment, 188*, Article 107476. https://doi.org/10.1016/j.buildenv.2020.107476

Huang, X., Cai, Y., & Li, J. (2019). Evidence of the mitigated urban particulate matter island (UPI) effect in China during 2000-2015. *The Science of the Total Environment, 660*, 1327–1337. https://doi.org/10.1016/j.scitotenv.2019.01.099

Huang, Y., Lei, C., Liu, C., Perez, P., Forehead, H., Kong, S., & Zhou, J. L. (2021). A review of strategies for mitigating roadside air pollution in urban street canyons. *Environmental Pollution, 280*, 116971. https://doi.org/10.1016/j.envpol.2021.116971

Irin, S., & Habib, M. A. (2016). Microsimulation-based emissions modeling for a major infrastructure renewal plan: Assessment of network attributes and land use effects on vehicular emissions. *Transportation Research Record, 2570*(1), 127–138. https://doi.org/10.3141/2570-14

Janhäll, S. (2015). Review on urban vegetation and particle air pollution – Deposition and dispersion. *Atmospheric Environment, 105*, 130–137. https://doi.org/10.1016/j.atmosenv.2015.01.052

Jennings, V., Reid, C. E., & Fuller, C. H. (2021). Green infrastructure can limit but not solve air pollution injustice. *Nature Communications, 12*(1), 4681. https://doi.org/10.1038/s41467-021-24892-1

Jeong, N.-R., Han, S.-W., & Kim, J.-H. (2022). Evaluation of vegetation configuration models for managing particulate matter along the urban street environment. *Forests, 13*(1), 46. https://doi.org/10.3390/f13010046

Ke, B., Hu, W., Huang, D., Zhang, J., Lin, X., Li, C., Jin, X., & Chen, J. (2022). Three-dimensional building morphology impacts on PM2.5 distribution in urban landscape settings in Zhejiang, China. *The Science of the Total Environment, 826*, Article 154094. https://doi.org/10.1016/j.scitotenv.2022.154094

Kokkonen, T. V., Xie, Y., Paasonen, P., Gani, S., Jiang, L., Wang, B., Zhou, D., Qin, W., Nie, W., Kerminen, V.-M., Petäjä, T., Sun, J., Kulmala, M., & Ding, A. (2021). The effect of urban morphological characteristics on the spatial variation of PM2.5 air quality in downtown Nanjing. *Environmental Science: Atmospheres, 1*(7), 481–497. https://doi.org/10.1039/d1ea00035g

Kumar, P., Druckman, A., Gallagher, J., Gatersleben, B., Allison, S., Eisenman, T. S., Hoang, U., Hama, S., Tiwari, A., Sharma, A., Abhijith, K. V., Adlakha, D., McNabola, A., Astell-Burt, T., Feng, X., Skeldon, A. C., de Lusignan, S., & Morawska, L. (2019). The nexus between air pollution, green infrastructure and human health. *Environment International, 133*(Pt A), Article 105181. https://doi.org/10.1016/j.envint.2019.105181

Lemes de Oliveira, F., & Mahmoud, I (2024). Desirable futures: Human-nature relationships in urban planning and design. *Futures, 163*, 103444. https://doi.org/10.1016/j.futures.2024.10344

Li, J., & Huang, X. (2020). Impact of land-cover layout on particulate matter 2.5 in urban areas of China. *International Journal of Digital Earth, 13*(4), 474–486. https://doi.org/10.1080/17538947.2018.1530310

Li, K., Li, C., Hu, Y., Xiong, Z., & Wang, Y. (2023a). Quantitative estimation of the PM2. 5 removal capacity and influencing factors of urban green infrastructure. *Science of The Total Environment, 867*, Article 161476. https://doi.org/10.1016/j.scitotenv.2023.161476

Li, K., Li, C., Liu, M., Hu, Y., Wang, H., & Wu, W. (2021). Multiscale analysis of the effects of urban green infrastructure landscape patterns on PM2.5 concentrations in an area of rapid urbanization. *Journal of Cleaner Production, 325*, Article 129324. https://doi.org/10.1016/j.jclepro.2021.129324

Li, S., Zou, B., Ma, X., Liu, N., Zhang, Z., Xie, M., & Zhi, L. (2023b). Improving air quality through urban form optimization: A review study. *Building and Environment, 243*, Article 110685. https://doi.org/10.1016/j.buildenv.2023.110685

Lin, J., Kroll, C. N., Nowak, D. J., & Greenfield, E. J. (2019). A review of urban forest modeling: Implications for management and future research. *Urban Forestry & Urban Greening, 43*, Article 126366. https://doi.org/10.1016/j.ufug.2019.126366

Lindén, J., Gustafsson, M., Uddling, J., Watne, Å., & Pleijel, H. (2023). Air pollution removal through deposition on urban vegetation: The importance of vegetation characteristics. *Urban Forestry & Urban Greening, 81*, Article 127843. https://doi.org/10.1016/j.ufug.2023.127843

Liu, Z., He, C., Zhou, Y., & Wu, J. (2014). How much of the world's land has been urbanized, really? A hierarchical framework for avoiding confusion. *Landscape Ecology, 29*(5), 763–771. https://doi.org/10.1007/s10980-014-0034-y

Lu, D., Mao, W., Yang, D., Zhao, J., & Xu, J. (2018). Effects of land use and landscape pattern on PM2.5 in Yangtze River Delta. *China. Atmospheric Pollution Research, 9*(4), 705–713. https://doi.org/10.1016/j.apr.2018.01.012

Luan, Q., Jiang, W., Liu, S., & Guo, H. (2020). Impact of Urban 3D Morphology on Particulate Matter 2.5 (PM2.5) Concentrations: Case Study of Beijing, China. *China Geography Science, 30*(2), 294–308. https://doi.org/10.1007/s11769-020-1112-5

McCarty, J., & Kaza, N. (2015). Urban form and air quality in the United States. *Landscape and Urban Planning, 139*, 168–179. https://doi.org/10.1016/j.landurbplan.2015.03.008

Mcgarigal, K., 2015. FRAGSTATS Help. http://www.umass.edu/landec o/research/fragstats/documents/fragstats.help.4.2.pdf.

Miao, C., Yu, S., Hu, Y., Zhang, H., He, X., & Chen, W. (2020). Review of methods used to estimate the sky view factor in urban street canyons. *Building and Environment, 168*, Article 106497. https://doi.org/10.1016/j.buildenv.2019.106497

Morakinyo, T. E., & Lam, Y. F. (2016). Study of traffic-related pollutant removal from street canyon with trees: Dispersion and deposition perspective. *Environmental Science and Pollution Research International, 23*(21), 21652–21668. https://doi.org/10.1007/s11356-016-7322-9

Norton, B. A., Evans, K. L., & Warren, P. H. (2016). Urban biodiversity and landscape ecology: patterns, processes and planning. *Current Landscape Ecology Reports, 1*(4), 178–192. https://doi.org/10.1007/s40823-016-0018-5

Oke, T. R., Mills, G., Christen, A., & Voogt, J. A. (2017). *Urban climates*. Cambridge University Press.

Park, S., & Ko, D. (2021). Spatial regression modeling approach for assessing the spatial variation of air pollutants. *Atmosphere, 12*(6), 785. https://doi.org/10.3390/atmos12060785

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. https://doi.org/10.3390/atmos10010033

Qiu, Y., Zuo, S., Yu, Z., Zhan, Y., & Ren, Y. (2021). Discovering the effects of integrated green space air regulation on human health: A bibliometric and meta-analysis. *Ecological Indicators, 132*, Article 108292. https://doi.org/10.1016/j.ecolind.2021.108292

Ren, W., Zhao, J., & Ma, X. (2022). Analysis of the spatial characteristics of inhalable particulate matter concentrations under the influence of a three-dimensional landscape pattern in Xi'an. *China. Sustainable Cities and Society, 81*, Article 103841. https://doi.org/10.1016/j.scs.2022.103841

Riondato, E., Pilla, F., Sarkar Basu, A., & Basu, B. (2020). Investigating the effect of trees on urban quality in Dublin by combining air monitoring with i-Tree Eco model. *Sustainable Cities and Society, 61*, Article 102356. https://doi.org/10.1016/j.scs.2020.102356

Roof, K., & Oleru, N. (2008). Public health: Seattle and King County's push for the built environment. *Journal of Environmental Health, 71*(1), 24–27. https://www.jstor.org/stable/26327656.

Schweitzer, L., & Zhou, J. (2010). Neighborhood air quality, respiratory health, and vulnerable populations in compact and sprawled regions. *Journal of the American Planning Association, 76*(3), 363–371. https://doi.org/10.1080/01944363.2010.486623

Servadio, J. L., Lawal, A. S., Davis, T., Bates, J., Russell, A. G., Ramaswami, A., Convertino, M., & Botchwey, N. (2019). Demographic inequities in health outcomes and air pollution exposure in the atlanta area and its relationship to urban infrastructure. *Journal of Urban Health Bulletin of the New York Academy of Medicine, 96*(2), 219–234. https://doi.org/10.1007/s11524-018-0318-7

Seyedrezaei, M., Becerik-Gerber, B., Awada, M., Contreras, S., & Boeing, G. (2023). Equity in the built environment: A systematic review. *Building and Environment, 245*, Article 110827. https://doi.org/10.1016/j.buildenv.2023.110827

She, Q., Peng, X., Xu, Q., Long, L., Wei, N., Liu, M., Jia, W., Zhou, T., Han, J., & Xiang, W. (2017). Air quality and its response to satellite-derived urban form in the Yangtze River Delta, China. *Ecological Indicators, 75*, 297–306. https://doi.org/10.1016/j.ecolind.2016.12.045

Shi, T., Dirienzo, N., Requia, W. J., Hatzopoulou, M., & Adams, M. D. (2020). Neighbourhood scale nitrogen dioxide land use regression modelling with regression kriging in an urban transportation corridor. *Atmospheric Environment, 223*, Article 117218. https://doi.org/10.1016/j.atmosenv.2019.117218

Singh, D., Dahiya, M., Kumar, R., & Nanda, C. (2021). Sensors and systems for air quality assessment monitoring and management: A review. *Journal of Environmental Management, 289*, Article 112510. https://doi.org/10.1016/j.jenvman.2021.112510

Stewart, I. D., & Oke, T. R. (2012). Local Climate Zones for Urban Temperature Studies. *Bulletin of the American Meteorological Society, 93*(12), 1879–1900. https://doi.org/10.1175/BAMS-D-11-00019.1

Tomson, M., Kumar, P., Barwise, Y., Perez, P., Forehead, H., French, K., Morawska, L., & Watts, J. F. (2021). Green infrastructure for air quality improvement in street canyons. *Environment international, 146*, Article 106288. https://doi.org/10.1016/j.envint.2020.106288

Venter, Z. S., Hassani, A., Stange, E., Schneider, P., & Castell, N. (2024). Reassessing the role of urban green space in air pollution control. *Proceedings of the National Academy of Sciences of the United States of America, 121*(6), Article e2306200121. https://doi.org/10.1073/pnas.2306200121

Viecco, M., Jorquera, H., Sharma, A., Bustamante, W., Fernando, H. J., & Vera, S. (2021). Green roofs and green walls layouts for improved urban air quality by mitigating particulate matter. *Building and Environment, 204*, Article 108120. https://doi.org/10.1016/j.buildenv.2021.108120

Voordeckers, D., Lauriks, T., Baetens, D., Ysebaert, T., Denys, S., Billen, P., Tytgat, T., & van Acker, M. (2024). Numerical study on the impact of traffic lane adjustments and low boundary walls on pedestrian exposure to NO2 in street canyons. *Landscape and Urban Planning, 243*, Article 104974. https://doi.org/10.1016/j.landurbplan.2023.104974

Voordeckers, D., Lauriks, T., Denys, S., Billen, P., Tytgat, T., & van Acker, M. (2021a). Guidelines for passive control of traffic-related air pollution in street canyons: An overview for urban planning. *Landscape and Urban Planning, 207*, Article 103980. https://doi.org/10.1016/j.landurbplan.2020.103980

Voordeckers, D., Meysman, F., Billen, P., Tytgat, T., & van Acker, M. (2021b). The impact of street canyon morphology and traffic volume on NO2 values in the street canyons of Antwerp. *Building and Environment, 197*, Article 107825. https://doi.org/10.1016/j.buildenv.2021.107825

Wang, C., Li, Q., & Wang, Z.-H. (2018). Quantifying the impact of urban trees on passive pollutant dispersion using a coupled large-eddy simulation–Lagrangian stochastic model. *Building and Environment, 145*, 33–49. https://doi.org/10.1016/j.buildenv.2018.09.014

Wang, Q., Han, Z., Wang, T., & Zhang, R. (2008). Impacts of biogenic emissions of VOC and NOx on tropospheric ozone during summertime in eastern China. *Science of The Total Environment, 395*(1), 41–49. https://doi.org/10.1016/j.scitotenv.2008.01.059

WHO, 2024. Ambient (outdoor) air pollution. https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health. Accessed 25 October 2024.

Wu, J., Xie, W., Li, W., & Li, J. (2015). Effects of urban landscape pattern on PM2.5 pollution–A Beijing case study. *PloS one, 10*(11). https://doi.org/10.1371/journal.pone.0142449. e0142449.

Xu, H., & Chen, H. (2021). Impact of urban morphology on the spatial and temporal distribution of PM2.5 concentration: A numerical simulation with WRF/CMAQ model in Wuhan, China. *Journal of Environmental Management, 290*, Article 112427. https://doi.org/10.1016/j.jenvman.2021.112427

Yang, J., Shi, B., Zheng, Y., Shi, Y., & Xia, G. (2020). Urban form and air pollution disperse: Key indexes and mitigation strategies. *Sustainable Cities and Society, 57*, Article 101955. https://doi.org/10.1016/j.scs.2019.101955

Yuan, M., Song, Y., Hong, S., & Huang, Y. (2017). Evaluating the effects of compact growth on air quality in already-high-density cities with an integrated land use-transport-emission model: A case study of Xiamen, China. *Habitat International, 69*, 37–47. https://doi.org/10.1016/j.habitatint.2017.08.007

Yuan, M., Song, Y., Huang, Y., Shen, H., & Li, T. (2019). Exploring the association between the built environment and remotely sensed PM2.5 concentrations in urban areas. *Journal of Cleaner Production, 220*, 1014–1023. https://doi.org/10.1016/j.jclepro.2019.02.236

Zeng, L., Hang, J., Wang, X., & Shao, M. (2022). Influence of urban spatial and socioeconomic parameters on PM2.5 at subdistrict level: A land use regression study in Shenzhen, China. *Journal of Environmental Sciences (China), 114*, 485–502. https://doi.org/10.1016/j.jes.2021.12.002

Zhang, P., Cheng, H., Jiang, Z., & Xiang, F. (2022). How sensitive morphological parameters influence on the PM2.5 diffusion: An Empirical Study of Two Neighborhoods in central Beijing. *Atmosphere, 13*(6), 921. https://doi.org/10.3390/atmos13060921

Zhang, P., Ghosh, D., & Park, S. (2023). Spatial measures and methods in sustainable urban morphology: A systematic review. *Landscape and Urban Planning, 237*, Article 104776. https://doi.org/10.1016/j.landurbplan.2023.104776

Zhao, X., Yan, H., Liu, M., Kang, L., Yu, J., & Yang, R. (2019). Relationship between PM 2.5 adsorption and leaf surface morphology in ten urban tree species in Shenyang. *China. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 41*(8), 1029–1039. https://doi.org/10.1080/15567036.2018.1539136

Zhu, X., Wang, X., Lei, L., & Zhao, Y. (2022). The influence of roadside green belts and street canyon aspect ratios on air pollution dispersion and personal exposure. *Urban Climate, 44*, Article 101236. https://doi.org/10.1016/j.uclim.2022.101236