Review on pollutant dispersion in urban areas-part B: Local mitigation strategies, optimization framework, and evaluation theory

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Review on the dispersion of traffic-related air pollutants in urban areas: Local mitigation strategies, optimization framework, and evaluation theory

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Abstract:

Outdoor air pollution is a significant global issue because it poses a major long-term health risk. A growing number of studies are conducted to develop local mitigation strategies for improving air quality. This review paper critically evaluates the available literature to provide a better understanding of potential local mitigation strategies and ascertain the methods for reducing local air pollution exposure. For these purposes, the first part of the review is categorized into three groups:

(i) improving urban ventilation and turbulence level for pollutant dispersion,

(ii) controlling source-receptor pathways by constructing barriers,

(iii) capturing and mitigating air pollution by introducing pollutant sinks.

Subsequently, a series of studies on optimization frameworks are summarized. It is found that surrogate model-based optimization frameworks efficiently handle multi-objective optimizations at a low computational cost. Finally, this review examines publications on the evaluation theory for pollutant dispersion to determine feasible methods for the removal of pollutants from urban areas. This study is useful for urban planners and architects responsible for decision-making.

Keywords: Pollutant dispersion; Local mitigation strategy; Optimization framework; Evaluation theory; Urban design.

1. Introduction

Outdoor air pollution is a significant global issue because it poses a major long-term health risk to children [1], the elderly [2], and people suffering from respiratory diseases [3]. Outdoor air pollution, a substantial hazard to human health, is responsible for approximately one in every nine deaths each year [4]. In Europe, 0.4 million premature deaths per year are caused by air pollution despite reduced concentrations over the last decades [5]. Thus, outdoor air pollution is of particular concern in the built-up urban environment, where elevated pollutant concentrations and potential sufferers converge [6]; the problem is intensified by rapid global population growth, especially in urban areas [7]. The reason is that air quality will continue to deteriorate as long as energy consumption and traffic emissions are increasing as a result of population growth [8]. In addition to advancements in policy and technology, which are required for curtailing emissions at the source, it is also essential to develop novel solutions and adopt appropriate strategies to manage and reduce outdoor air pollution to minimize the negative impact on public health [9], especially in developed cities. Developed cities have made it a priority to coordinate urban construction with air pollutant dispersion and have attempted to reduce air pollution for several decades with significant progress [10]. Nevertheless, the urban outdoor environment is facing significant challenges due to poor outdoor air quality [11]. It has been reported that the pollutant concentrations still markedly exceed public health standards in many cities [12]. Besides, there is convincing evidence that there is no safe threshold for exposure to air pollution [13,14].

Thus, it is crucial to reduce pollutant concentration continuously.

In some developed cities, the large-scale redevelopment of urban morphology is very costly due to extremely high land prices [15] and historical and cultural values [16]. Therefore, without sacrificing a substantial amount of usable floor area, alternative solutions, such as implementing local mitigation for reducing air pollution, must be considered by cities facing irreversible urbanization [17–19]. In effect, local mitigation strategies are broadly recognized as one of several promising methods for air pollution reduction. However, to date, no publication has reviewed and described these local mitigation strategies and their implementation for air pollution abatement. To the best of the authors' knowledge, several state-of-the-art reviews have been published in related areas (mitigation of air pollution) in the past decade, focusing on the influence of green infrastructure [20–22], solid and porous barriers [23], urban planning strategies [24–26], reactive pollutants [27], ventilation indices [28], isothermal and non-isothermal flow in street canyons [29], and summaries of computational fluid dynamics (CFD) studies [30–32]. Moreover, Li et al. [33] only reviewed pollutant dispersion in urban areas, with a specific focus on the effects of mechanical factors and urban morphology. Thus, it is difficult for urban designers or practitioners to determine how and where local mitigation strategies can improve air quality with maximum efficiency. Accordingly, this paper provides a review of studies that proposed and applied local mitigation strategies to improve outdoor air quality, filling the research gap. The review focuses on the advantages and limitations of the mitigation strategies, as well as on future perspectives.

Improving pollutant dispersion in urban areas is relatively complicated since the pollutant dispersion highly depends on different parameters, including mechanical factors (inflow condition, thermal effects, and vehicular motion) and urban morphology (effects of urban density, heterogeneity, and enclosure degree). These aspects were addressed in our previous review paper [33]. Thus, performing extensive parametric analyses to enhance pollutant dispersion is very difficult. However, most architects or urban designers tend to use passive design methods in urban design based on “trial-and-error” [34], which is very time-consuming and may neglect some important parameters. On the other hand, although many studies have shed light on the critical urban geometry or the governing design parameters for local mitigation strategies for air pollution, they have not guided designers to select the best design parameters, considering local and environmental conditions [35]. Due to the lack of systematized knowledge, it is essential to understand existing approaches that support the design of local mitigation strategies considering the dispersion of traffic-related air pollutants. Moreover, urban design always involves more than one objective, requiring multi-objective optimization for air pollution since all influences and constraints should be considered [34]. Accordingly, there is a strong need for a review of optimization frameworks that are suitable for a broad range of design parameters to determine the optimum parameter for different urban geometry or local mitigation strategies and that are widely applicable for multi-design objectives. Subsequently, it is necessary to review methods for evaluating the improvement in pollutant dispersion. In the past several decades, there has been a growing body of literature evaluating the processes governing pollutant dispersion using urban ventilation indices. This topic was reviewed by Peng et al. [28]. The evaluation indices allow for relating the efficiency of pollutant dispersion to urban morphology, incoming flow conditions, and various mitigation strategies. However, most of the evaluation indices are suitable only for the assessment of the existing situation of pollutant dispersion conditions and cannot be used for creating potential optimization pathways. For instance, the age of air can well reflect existing ventilation conditions [36]. A large age of air indicates a poorly ventilated region; thus, it is easy to detect regions with low air quality using this index. However, this index does not guide urban planners to reduce the pollutant concentration in this region. Thus, it is vital to consolidate our understanding of potential optimization pathways for pollutant dispersion before urban designers and planners alter the urban morphology or implement local mitigation strategies. An improved understanding greatly reduces the cost of “trial and error”. Some evaluation theories were developed to guide the optimization by evaluating urban geometry or local mitigation strategies. Consequently, there is a clear need for a review of these evaluation theories to enable appropriate decision-making.

Generally, beyond the scope of existing reviews, it is imperative to conduct an exhaustive summary of local mitigation strategies, optimization frameworks, and evaluation theories for pollutant dispersion. First, this article provides information on local mitigation strategies for reducing pollutant concentration in urban areas to answer the following questions. How do the mitigation strategies improve the air quality? What is the potential reduction in pollutant concentration of the mitigation strategies? How can we parameterize the mitigation strategies? Who are the final stakeholders (e.g., pedestrians walking on the pathways or residents of the surrounding high-rise buildings)? By enumerating these potential mitigation measures and related design parameters or application scenes, urban planners can obtain in-depth knowledge and strong support for future urban designs to implement local mitigation strategies. Second, several optimization frameworks are analyzed to determine the optimum approach to implement and optimize mitigation strategies to reduce outdoor pollutants. With the help of these optimization frameworks, urban planners can significantly improve the efficiency of urban design and reduce the costs of “trial and error”. In addition, the third objective is to review the evaluation theories of pollutant dispersion in an urban environment to ascertain the optimum pathway to improve pollutant dispersion for future urban design.

2. Scope, methods, and outline

This review investigates the local mitigation strategies, optimization framework, and evaluation theories for pollutant dispersion in urban areas. It should be mentioned that this review focuses specifically on the public health benefit of reducing exposure to air pollution produced by vehicles since traffic emissions are the dominant source of urban air pollution [37]. The review does not consider the background concentration due to other sources in the city, such as tall stacks from industrial plants.

Moreover, a literature search was conducted on articles published to date in the following internet databases: ScienceDirect, SpringerLink, Web of Science, and Google Scholar. The literature search was performed in early 2021, and articles published until late 2020 were included. The keywords included “urban”, “pollutant dispersion”, “ventilation”, “outdoor”, “mitigation strategies” and all factors mentioned in Sections 3- 5. As seen in Fig. 1, we combined all five keywords and each factor one by one for each search of the database (i.e., literature extraction) so that the search covered the following topics: “local mitigation strategies”, “optimization framework”, and “evaluation theory” (i.e., literature refinement). Subsequently, the articles suitable for the review were read thoroughly for data extraction. Only publications in English language journals were included.

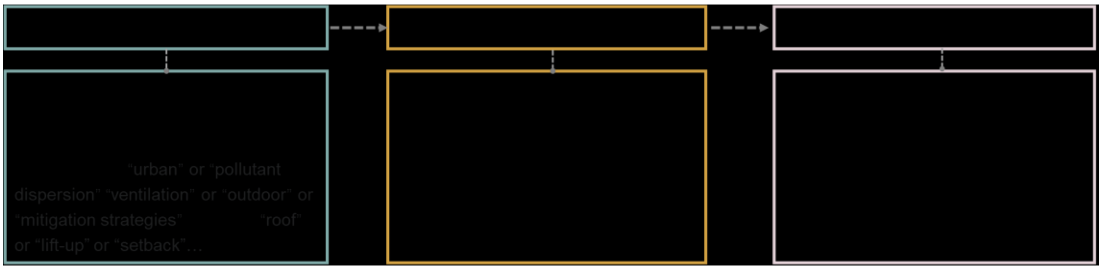

Fig. 1 The flow diagram of this systematic review

The review is divided into six sections, including the introduction (Section 1) and the present section. The remainder of this paper is organized as follows, according to the structure of this review in Fig. 2. Section 3 explores local mitigation strategies that have been used as potential solutions for managing and reducing outdoor air pollution in urban areas, including three aspects, i.e., improving ventilation, creating a barrier between traffic emission sources and receptors, and creating a pollutant sink. Section 4 presents the various optimization frameworks for improving pollutant dispersion in urban areas, including the general and advanced frameworks. Section 5 gives an overview of the evaluation theory of pollutant dispersion in urban areas, especially for the field synergy theory. Finally, Section 6 summarizes the findings from the review and draws the conclusions.

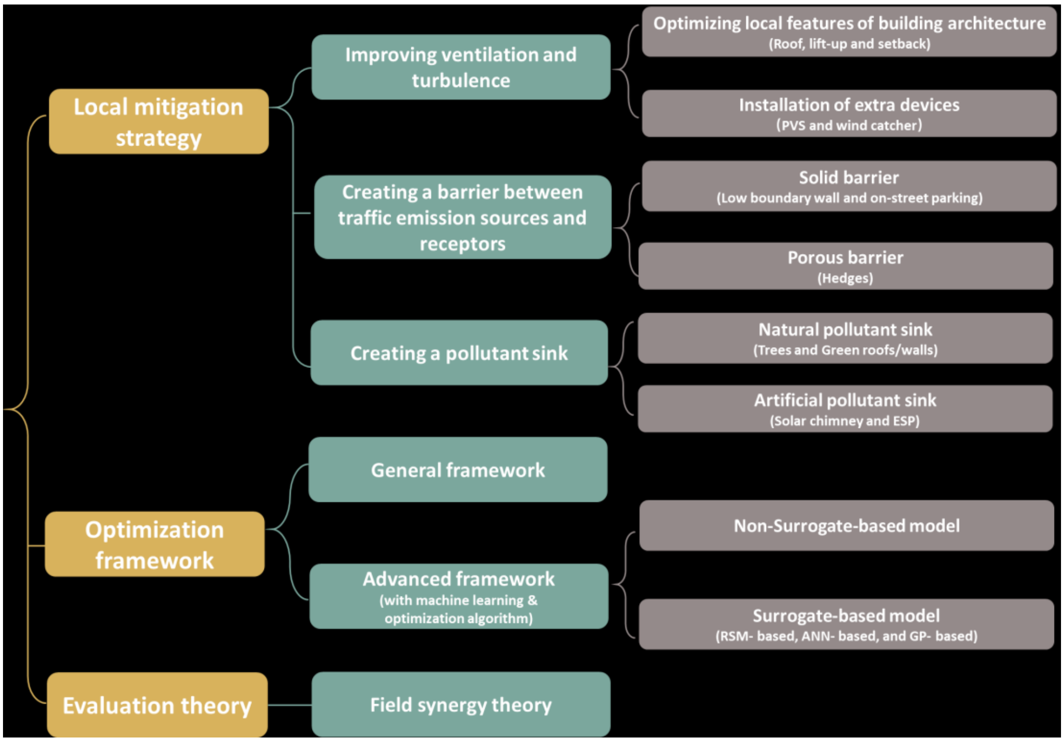

Fig. 2. The structure of this review.

3. Local mitigation strategies to improve air quality

In this section, three approaches of local mitigation strategies are introduced: (i) improving urban ventilation and turbulence level for pollutant dispersion, (ii) controlling source-receptor pathways by constructing barriers, and (iii) capturing and mitigating air pollution by introducing pollutant sink. It should be emphasized that in this section, only the mitigation strategies for reducing air pollution directly at local scales relevant to direct human exposure are summarized and reviewed. The focus is mainly on local-scale improvement of air quality, including the street scale (less than 100–200 m) and the neighborhood scale (up to 1 or 2 km) according to the classification proposed by Britter and Hanna [38].

3.1 Improving ventilation and turbulence

It is well known that poor ventilation and low turbulence levels result in high in-canyon pollutant concentrations [39]. Thus, it is believed that optimizing building geometry (roofs, lift-up design, and arcade design) plays an essential role in improving ventilation and enhancing turbulent flow, decreasing the accumulation of pollutants inside street canyons. Additionally, adding devices (such as pedestrian ventilation systems (PVSs) or wind catchers) to existing buildings can also increase in-canyon air movement.

3.1.1 Optimizing local features of building architecture (Roof, lift-up, and setback)

Roof design

Roofs are designed to prevent excessive rain and snow accumulation [40]. Besides, an appropriate roof design is broadly recognized as one of several promising passive control strategies for air pollution. Numerous studies have described the positive effects of an optimized roof design on air quality. For instance, Rafailidis [41] reported that sloped roofs improved the in-canyon natural ventilation and produced more turbulence at the roof level than flat roofs. Subsequently, this phenomenon was confirmed by the wind tunnel experiments of Kellnerova et al. [42]. The possible explanations are related to sloped roofs. First, sloped roofs produce a significant perturbation of the mean flow field behind the roof, enhancing the air exchange [43]. Second, Llaguno-Munitxa et al. [44] found that the larger gradient of wind velocity behind sloped roofs led to a higher potential for turbulence generation compared with flat roofs. Kastner-Klein et al. [45] reported that, in addition to improving streamwise ventilation, pitched roofs also increased the along-canyon velocity components in the entire span of the canyon. Accordingly, Rafailidis [41] concluded that altering the roof geometry might have a larger influence on urban air quality than modifying the canyon aspect ratios.

It is worth noting that the influence of roofs is directly related to the roof shape, roof slope (or roof height), and roof configuration (morphological arrangement). Kastner-Klein and Plate [46] compared the influence of a wedge-shaped, pitched, and flat roof in a wind tunnel experiment and observed that the roof shape played a significant role in determining the in-canyon vorticity dynamics and corresponding pollutant transport. Subsequently, Yassin [47] reported that a pitched or trapezoid-shaped roof resulted in significantly higher wind velocity and turbulence levels in the street canyon than a flat roof. Thus, as seen in Fig. 3(a), all four kinds of roofs reduce the pollutant concentration in street canyons compared to a flat roof, especially at the pedestrian level. Furthermore, Llaguno-Munitxa et al. [44] found that round roofs further improved the in-canyon ventilation more than pitched roofs. Interestingly, Huang et al. [48] argued that a change in the roof shape was not directly related to a reduction in pollutant concentration. The concentration reduction was also affected by the roof height of different roof shapes. For instance, at $H_{roof}/H = 1/6$, the pollution levels were similar for all roofs; at $H_{roof}/H = 1/2$, the round roof had the lowest pollution level, whereas the upwind-wedged roof had the highest pollution level. H_{roof} and H denote the roof height and building height, respectively. Similarly, Takano and Moonen [49] examined the influence of the slope of wedge roofs on pollutant dispersion in a canyon with $H/W = 1$. H is the building height, and W is the street width. The results showed that an increase in the slope of the downwind wedge-shaped roof (up to 30°) improved the ventilation and increased the turbulence level, lowering the pedestrian-level pollutant concentration by up to 34% (Fig. 3(b)). However, an increase in the slope of the upwind wedge roofs improved the in-canyon air quality only when the slope was lower than 18°. At slopes exceeding 18°, the single-vortex flow regime was transformed into a double-vortex regime, resulting in a higher near-ground pollutant concentration. Badas et al. [43] investigated the slope of pitched roofs (ranging from 0 to 40°). The results revealed that increasing the slope of pitched roofs played a key role in enhancing turbulence and ventilation. Thus, the steepest roofs (40°) increased the air change per hour (ACH) at the roof level by almost 200% compared with flat roofs. Huang et al. [50] analyzed the morphology of wedged-shape roofs and pointed out that a wedged-shape roof on the leeward building had much stronger aerodynamic impacts than the same roof geometry on the windward building (Fig. 3(c)). Similarly, Xie et al. [51] studied a combination of pitched and flat roofs. The results showed that most configurations reduced the pedestrian-level pollutant concentrations by approximately 38%, and the effect was more pronounced on the leeward side (up to 67%).

More information on these studies on roof design, including the study approach (e.g., CFD simulations, field measurement, wind tunnel experiment), urban configuration (e.g., ideal or realistic street canyon), focus (e.g., the sensitivity parameter for each local mitigation strategy), the coverage of influence (e.g., only within the street canyon), and some critical findings, are summarized in Table A.1. In general, the reviewed studies demonstrate the positive effect of roof design on ventilation and turbulence within street canyons. Thus, an appropriate roof design enhances the potential dilution of pollutants, which is beneficial for pedestrians and residents. However, the scope of influence of roof design is only limited to a small extent (within the street canyon), as shown in Table A.1. Besides, the roof shapes, roof slope, and roof configurations should be chosen carefully. The degree of reduction in pollutant concentration attributed to roof design is greater in a deeper street canyon [52].

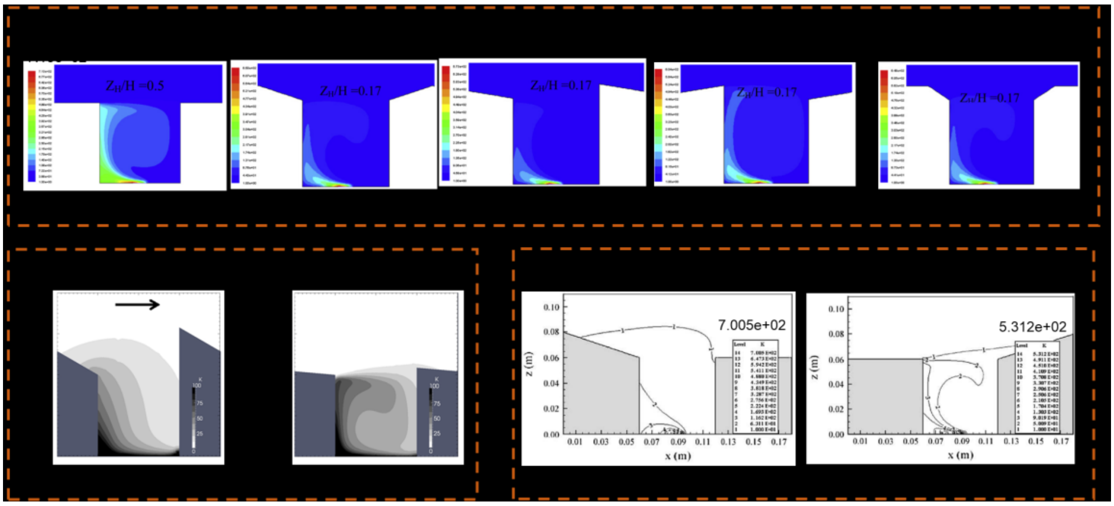

Fig. 3. (a) Relationship between roof shape and in-canyon pollutant concentration [47]; (b) relationship between roof slope and in-canyon pollutant concentration [49]; (c) relationship between the morphology of wedged-shape roofs and in-canyon pollutant concentration [50].

Lift-up design

The lift-up design of buildings (also known as elevated design or void decks) at the ground level is frequently used to enhance shading [53]. It creates a semi-open space underneath high-rise residential buildings as a public space for social activities (leisure and recreational activities or access routes) [54,55]. The space created by the lift-up design can act as a wind corridor to increase urban wind circulation and mitigate negative health impacts [56,57]. Therefore, the wind speed nearby elevated buildings (removing low-floor building layers) is enhanced [11,58].

The benefits of integrating the lift-up design into existing buildings for improving ventilation conditions have been demonstrated by several studies using a wind tunnel and CFD simulations. For instance, the wind tunnel experiments conducted by Xia et al. [59] demonstrated that the pedestrian-level wind (PLW) ventilation was better for a row of lift-up buildings and the PLW speed was almost 11% higher than that of the non-lift-up buildings. Druenen et al. [60] used CFD simulations and found that the average PLW speed increased (up to 21%), and the lower-speed wake region behind the building was reduced in size (Fig. 4(a)). Du and Mak [15], Due et al. [51], and Huang et al. [62] combined data from a wind tunnel and field measurements from a university campus in Hong Kong and reported that lift-up designs were effective in increasing the wind speed inside and near lift-up areas. These results were supported by prediction data based on lift-up building models with 22 unconventional configurations [63]. Furthermore, in different geometries of surrounding buildings and ambient wind speeds, the PLW speed increased by more than two-fold [64] and even five-fold [65].

To create a void space (lift-up design), the main building is elevated off the ground by columns, shear walls, center core(s), or a combination of these [35]. The optimization of the dimension or geometry of the lift-up design can significantly increase the PLW speed [55]. Generally, studies have shown a considerable influence of the height, width, locations, and configurations of these columns on ground-level ventilation. Tse et al. [66] concluded that the height and width of columns significantly affected the wind environment at the pedestrian level. Moreover, the column height had a more significant effect than the column width. Also, Du et al. [67] investigated the influence of the width and height of lift-up columns using multi-stage analysis. The results revealed that increasing the column width adversely affected the ventilation at the pedestrian level, whereas the effect of increasing the column height was positive.

Under an identical building configuration, the wind speed decreased by 38% as the column width increased from 1 to 4 m. In contrast, increasing the column height column from 4 to 8 m only resulted in a nearly 13% increase in wind speed. Similarly, Chew and Norford [54,68] examined the influence of elevated height in a building array with 6-15 streets. The results confirmed that the wind speed increased with an increase in the elevated height. A 2 m height was insufficient to sustain relatively high channeling wind in the approaching wind direction. Increasing the height to 3 m increased the PLW speed by about 25%. However, the improvement was negligible when the elevated height exceeded 4 m (Fig. 4(b)). The influence of the position of the lift-up design was studied by Sha et al. [69]. The results indicated that the first-floor lift-up design was more effective than the second- or third-floor lift-up design. The first-floor lift-up design resulted in a 34–50% reduction in the building intake fraction and daily pollutant exposure, whereas the third-floor lift-up design only yielded a 6%– 25% reduction (Fig. 4(c)).

More information on these studies on the lift-up design is provided in Table A.2. Although the lift-up design can enhance the wind speed in the upstream area of the target building [70], Liu et al. [58] pointed out that the effect of wind enhancement might be limited to a finite area around the target building with the lift-up design. Similarly, Chen and Mak [63] reported that the lift-up design significantly improved PLW ventilation in the near field of a building. However, the improvement weakened with the width of the research region. Besides, most previous studies mainly focused on improving pedestrian-level ventilation using the lift-up design. It might be deduced that the main stakeholders should be the pedestrians near the building with a lift-up design. However, if the lift-up design is used in a group of buildings, the pollutant concentration near the building walls can be reduced, which is beneficial to the residents of the surrounding buildings and not only the pedestrians near the road [69]. Furthermore, the lift-up design might be a more effective optimization design strategy for very deep canyons or very tall high-rise buildings. As reported by Zhang et al. [71], in an extremely deep canyon (H/W = 5), the pedestrian-level pollutant concentrations decreased by nearly two orders due to the lift-up design.

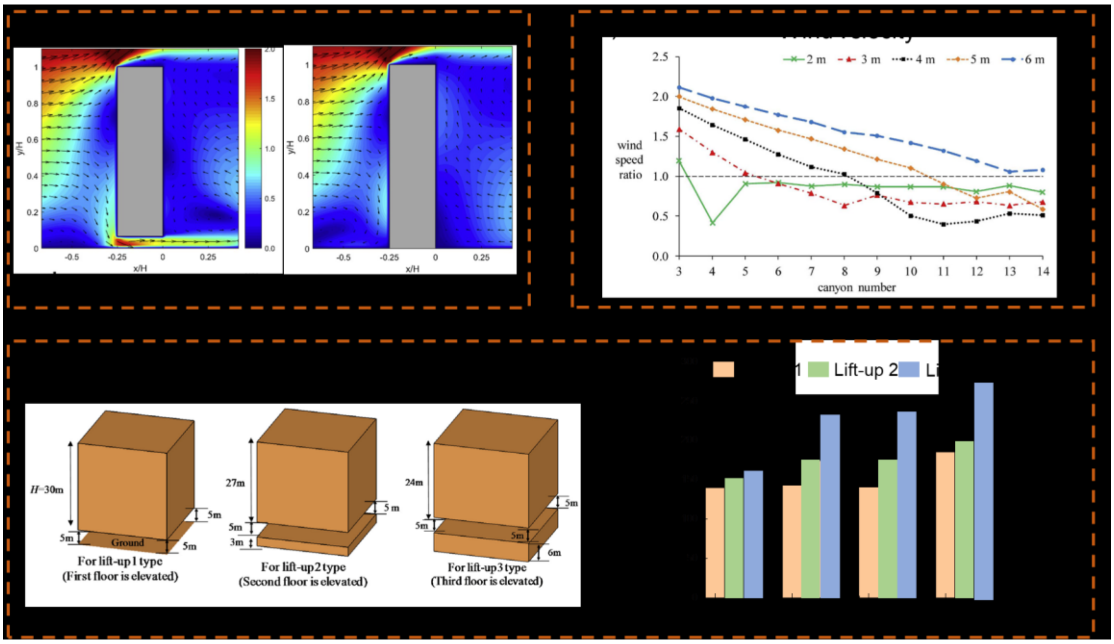

Fig. 4. (a) Contours of the dimensionless velocity magnitude in the vertical cross-section for the reference case and the lift-up case [60]. (b) The wind speed ratio in canyons 3–14. The legend indicates the void deck height (H_{vd}). For example, “2 m” represents the case with H_{vd} = 2 m [54,68]. (c) Daily CO exposure for different lift-up positions and different ambient wind directions [69].

Building setback

The arcade is a type of building setback that provides a comfortable passage space for pedestrians, as well as improved ventilation [72]. This design is primarily implemented as a half-open space by creating an outside corridor on the side of the main building [35]. Hang et al. [73] demonstrated a direct relationship between the arcade design and the in-canyon ventilation. Wen et al. [74] found that incorporating an arcade design into the ideal street canyon arrangements resulted in a 60% increase in the ACH in the pedestrian pathway layer (PPL) for perpendicular wind since the arcade design increases the total volumetric airflow rate into the PPL through the windward and arcade openings (Fig. 5(a)). Interestingly, the ACH in the urban canopy layer (UCL) was minimally affected by the presence of the arcade because the extent of the UCL was much larger than the arcade space. This finding is consistent with the results of Juan et al. [75], who investigated realistic building models. Accordingly, Huang et al. [76] reported a lower pedestrian-level pollutant concentration when compared with the reference case; the result was attributed to the presence of the arcade (Fig. 5(b)). Lau et al. [77] observed that the building setback ensured sufficient ventilation in the area by creating effective air paths and breezeways in a nearly parallel wind.

It is worth noting that the dimensions (height and width) and configurations of the arcade significantly affect the ventilation performance. Wen et al. [74] revealed that increasing the height of the arcade (from 3 to 6 m) led to a nearly 25% reduction in the ACH, whereas increasing the width of the arcade (from 1.5 to 9 m) caused an almost 76% increase in the ACH. Ng and Chau [78] reported that, in addition to the typical horizontal building setback (arcade design), the vertical setback also improved the in-canyon air quality by enhancing the vertical dispersion of pollutants in the vertical setback area under a perpendicular wind (Fig. 5(c)). Further, they found that the effectiveness of the vertical or horizontal setback substantially depended on the street canyon height aspect ratio (H/W). The vertical setback was more suitable for canyons with $H/W = 2$ (6% reduction), whereas the horizontal setback was recommended for canyons with $H/W = 4$ (6.5% reduction) and 6 (13% reduction). These values provided the lowest reductions in the personal exposures in the total developed floor area (the total floor area that can be developed at a particular site).

More information on these investigations on the building setback design is listed in Table A.3. Generally, building setbacks can be implemented by increasing the distance between the building and the street to increase the airflow at the pedestrian level. Both the horizontal and vertical setbacks improve the air quality of the entire street canyon, thus reducing the pedestrians’ and residents’ pollutant exposure. Also, the height and width of the arcade should be carefully selected to improve the air quality. Besides, it should be noted that the influence of the building setbacks is limited to a small extent (within the street canyon).

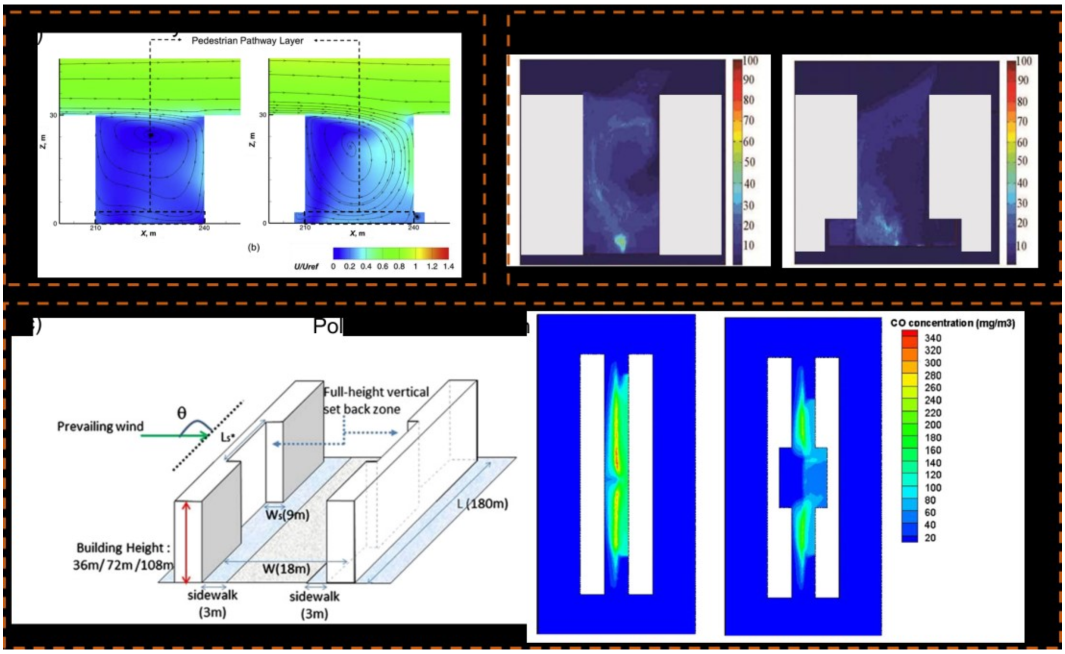

Fig. 5. (a) Contours of the dimensionless velocity magnitude in the vertical cross-section for the reference case and the arcade design [74]. (b) Contours of the pollutant concentration in the vertical cross-section for the reference case and arcade design [76]. (c) Contours of the pollutant concentration at the pedestrian level for the reference case and the vertical setback [78].

3.1.2 Installation of additional devices (PVS and wind catcher)

Pedestrian Ventilation System (PVS)

A PVS was proposed to control the ventilation at the pedestrian level and improve the air quality in the pedestrian ventilation zone [79]. A vertical duct system was used to move air from the building roof to the street level [80]. Heating the duct (by solar radiation) or using an electrical fan represents options to provide the required air movement.

Mirzaei and Haghighat [80,81] tested the effectiveness of several PVSs powered by an electrical fan, including exhaust strategies, a supply strategy, and washing flow strategies. The results showed that the pedestrian-level ventilation was improved using these proposed PVS strategies. Particularly, the supply strategy and exhaust strategy decreased the pedestrian-level pollutant concentration by up to 75% and 90%, respectively (Fig. 6(a)). Moreover, the performance of the proposed PVS depended on the fan pressure and ventilation strategy [79]. An increase in fan pressure produced high air velocity, significantly decreasing the air quality index (AQI) on the sidewalks (Fig. 6(b)).

More information on these investigations of PVSs is provided in Table A.4. Generally, PVSs can be flexibly controlled for removing pollution from pedestrian sidewalks by controlling the PVS configuration and the fan pressure. In addition to improving the pedestrian-level air quality, the air quality of the entire street canyon is also significantly enhanced; thus, pedestrians and residents benefit from PVSs. Besides, this local mitigation strategy is also limited to the area close to the PVS.

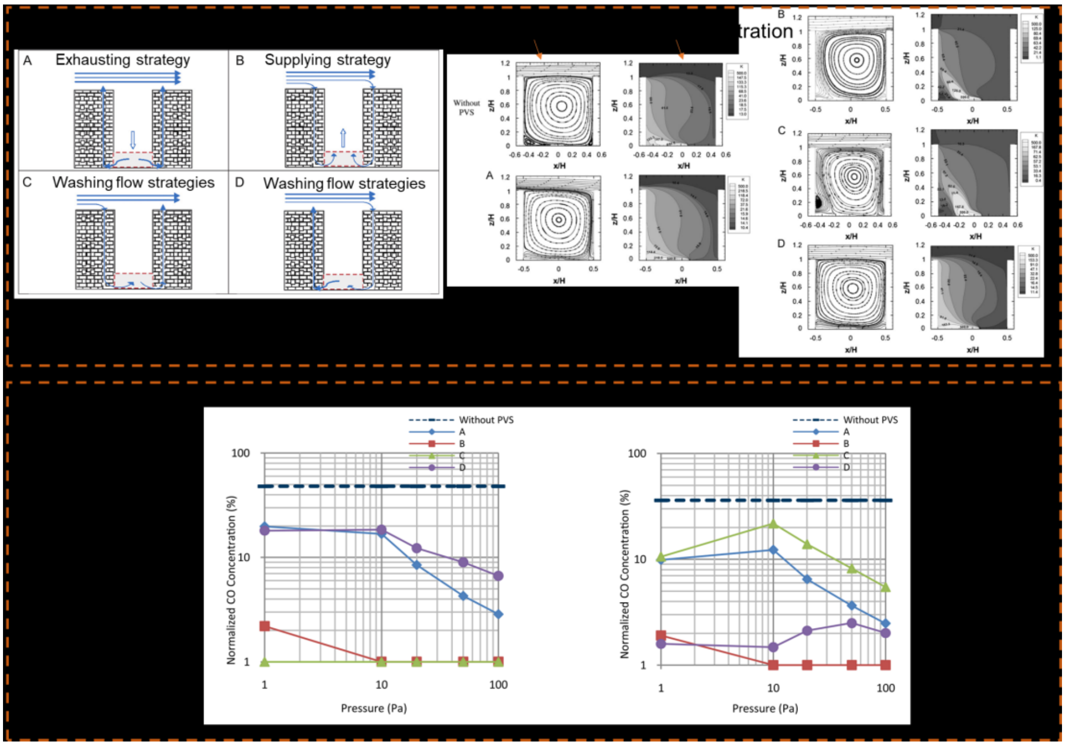

Fig. 6. (a) Streamline and normalized concentration contours for different configurations of pedestrian ventilation systems (PVSs) [80,81]. (b) Normalized CO concentration at the pedestrian level for various PVS combinations on the left sidewalk(left plot) and right sidewalk (right plot) for different fan pressures [79].

Wind catcher

Wind catchers are typically used at the indoor/outdoor interface for indoor passive cooling and natural ventilation; they are prevalent in the Middle East and North Africa. Chew et al. [82] extended the potential of wind catchers for outdoor ventilation by installing a wind catcher prototype in a water channel experiment. This wind catcher consisted of two rectangular plates. It was installed near the upstream building wall and above the roof over the street. The results showed that the wind catcher enhanced the PLW speed of the target canyon by 2.5 times (Fig. 7(a)). The ambient wind captured by the wind catcher moves through the narrow channel between the top plate and the building roof. The high-speed jet of airflow is directed in a 90-degree turn to the outlet of the wind catcher and flows downwards, boosting the pedestrian-level ventilation.

Furthermore, since the sidewalls of the wind catcher prevent span-wise leakage, the high-speed jet captured at the inlet of the wind catcher can travel downward with little momentum loss in the span-wise direction until it reaches the ground (Fig. 7(b)) [82]. Zhang et al. [71] evaluated the influence of wind catchers on reducing vehicle pollution in a deep canyon. The results showed that the PLW speed increased by one or two orders because of the wind catchers. Hence, wind catchers resulted in one or two orders of magnitude lower pollutant concentrations in the deep street canyon (Fig. 7(c)). A reduction of in-canyon pollutant concentration was also observed by Ming et al. [83]. The authors pointed out that the presence of a wind catcher at the roof level significantly enhanced the synergy of pollutant dispersion and airflow within the street canyon area, thus improving the dilution of pollutants (Fig. 7(d)).

More information on these studies on wind catchers is listed in Table A.5. Generally, a wind catcher improves the ventilation in the entire street canyon, thus improving the pedestrians' and residents' air quality. The effectiveness of wind catcher can be further improved by altering its position and structure. It is noteworthy that most of these studies used only 2D or quasi-3D simulations. Hence, an engineering analysis of wind catchers is necessary to design wind catchers that adapt to the wind direction and complex urban structures. Also, as summarized in Table A.5, the influence of wind catchers is limited to the street canyon. It was reported by Chew et al. [82] that a wind catcher caused a slight velocity decrease in the immediate downstream area of the canyon.

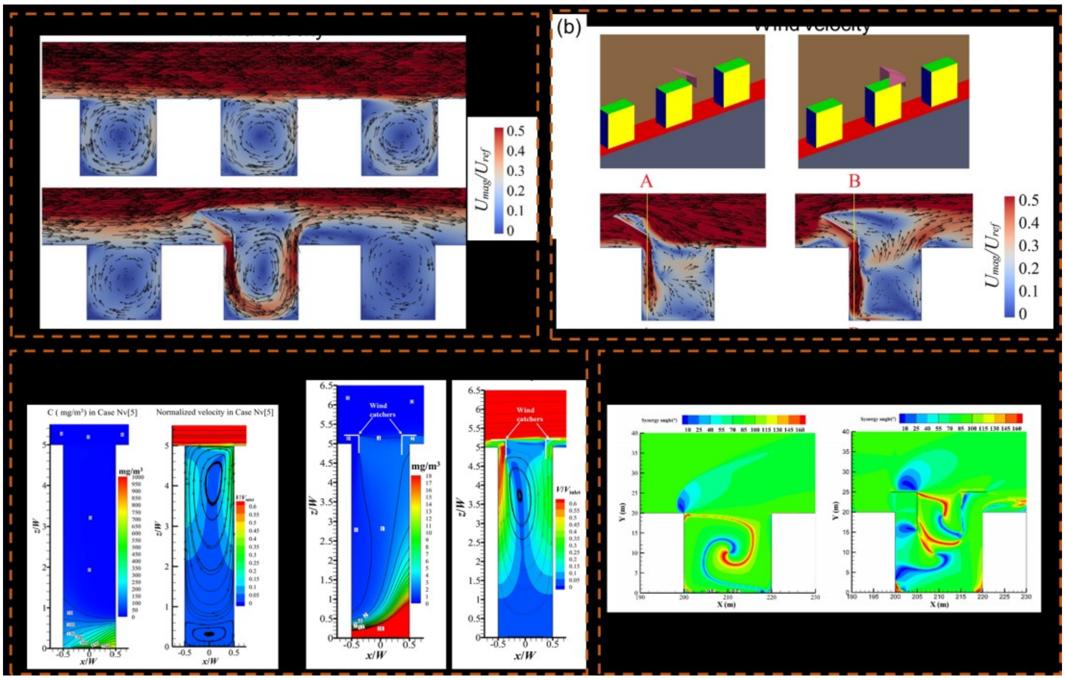

Fig. 7. (a) Comparison of normalized velocity magnitude contours and vectors for the reference case and the wind catcher case [82]. (b) Comparison of normalized velocity magnitude contours and vectors for the reference case with a wind catcher and a wind catcher with sidewalls [82]. (c) Comparison of normalized wind velocity and CO concentration for the reference case and the wind catcher case [71]. (d) Comparison of synergy angles for the reference case and the wind catcher case [83]

3.2 Creating a barrier between traffic emission sources and receptors

Pedestrians are typically most affected by traffic emissions due to the short distance between the source and receptor and minimal mixing. A passive control strategy that considers the source-receptor distance has been proposed as a viable option. In a long pathway, the air pollutants can be significantly diluted by mixing with clean air. Barriers can serve as potentially low-cost options to improve the roadside air quality, including solid barriers (low boundary walls (LBWs) and on-street parking) and porous barriers (hedges).

3.2.1 Solid barriers (low boundary walls and on-street parking)

Low boundary walls/noise barriers

The effectiveness of solid barriers on flow patterns and pollutant dilution has been widely researched, including the use of noise barriers (over 4–5 m tall) along highways

[84–86] and LBWs (1–2 m or less in height) [87–89] adjacent to low-speed roadways in urban areas. In general, these studies revealed that solid roadside barriers could act as baffle plates, redirecting the flow and affecting the pollutant dispersion at the street level [90]. Moreover, solid barriers induce significant vertical mixing and shift the plume upward due to an induced updraft motion [91]. Accordingly, traffic emissions must pass over the solid barriers, where the airflow is being directed toward the footpath, substantially increasing pollutant dispersion before the pollutant reaches the footpath [92].

McNabola [92] obtained field measurements in a typical street canyon in Ireland and demonstrated the ability of LBWs to influence pollutant dispersion. The presence of LBWs, which were located between the road and footpath, resulted in a 1.7–2.0 times reduction in the volatile organic compound (VOC) concentrations on the footpath behind the LBWs. On-site monitoring and numerical modeling indicated that the LBWs reduced the pollutant exposure of pedestrians walking on sidewalks by up to 40% and 75% under perpendicular and parallel wind conditions, respectively, by a combined study of the on-site monitoring and numerical modeling [93–95]. Gallagher et al. [96] provided an understanding of the impacts of LBWs in real-world settings. Their results showed a 1%–35% pollutant reduction resulting from LBWs under varying ambient wind directions and traffic conditions (Fig. 8(a)).

It is worth noting that the height and location of LBWs and the street canyon geometry significantly influenced the air quality. King et al. [93] observed that an increase in the height of the LBWs (1 to 2 m) caused a significant concentration reduction (by almost 50%). On the other hand, Mcnabola et al. [95] revealed that central LBWs were more suitable for wind perpendicular to the street, whereas footpath LBWs provided better air quality for a parallel wind. Also, Gallagher et al. [87] confirmed that central LBWs caused a more significant reduction in the in-canyon pollutant concentration than footpath LBWs (Fig. 8(b)). The authors reported that the street canyon geometry influenced the effectiveness of LBWs on pollutant concentrations.

The presence of LBWs resulted in a decrease (up to 30%) or increase (up to 19%) in the leeward pollutant exposure on the footpath for different building height ratios of street canyons.

Interestingly, Jeanjean et al. [97] observed that the usage of LBWs caused opposite trends of pollutant concentrations at the pedestrian level on the footpath and in the center zone of traffic lanes. They examined the effectiveness of a solid barrier in Oxford Street, London, considering local wind conditions, and found a 23.8% increase in NO_2 concentration in the road zone and a 2.3% reduction in NO_2 concentration on the footpath. Accordingly, it was concluded that the LBWs had a positive effect on the pedestrians but an adverse effect on cyclists or drivers on the roads. Therefore, it should be determined if pedestrians or drivers are the priority before installing LBWs. More information on these studies on LBWs is listed in Table A.6. Although optimizing the height or location of LBWs can improve the air quality at the pedestrian level, especially close to the LBWs, these structures appear not to improve the air quality of residents.

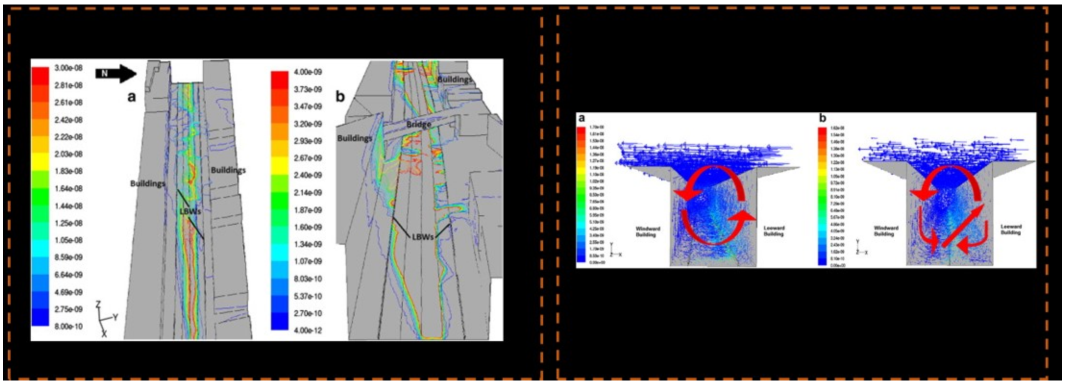

Fig. 8. (a) Plots of pollutant concentrations in a street canyon with an LBW [96] and (b) plots of pollutant concentrations in street canyons with footpath LBWs and a central LBW [87]

Car parking system

Parked cars have also been used as obstacles to protect pedestrians from traffic pollutants. Under varying wind conditions and urban geometries, the presence of parked cars led to a nearly 15% to 49% reduction in roadside pollutant concentrations

[96,98,99]. The reason is that parked cars extend the pathway of pollutants emitted at the road level. Thus, the pollutants have to travel a longer distance, around, over, or under the body of cars, minimizing dispersion [99].

The effectiveness of car parking systems depends on the parking configuration and parking space occupancy. For instance, Gallagher et al. [99] found that parallel parking (parked cars are parallel to the street) was the most effective method to reduce the pedestrian-level pollutant concentration. The likely reason is the relatively small space between the cars. Thus, fewer pollutants can penetrate the footpath through these small channels and reach the sidewalks. Abhijith and Gokhale [98] found that oblique parking (30°–60°) resulted in an increase in roadside pollutant exposure of up to 34.3% compared with parallel parking (Fig. 9(a)). On the other hand, Gallagher et al. [99] stated that high occupancy rates significantly reduced the pollutant concentration. A curvilinear pattern of concentration reduction was observed for a parking space occupancy range of 10% to 90% (Fig. 9(b)).

It should be mentioned that on-street car parking systems represent a temporary barrier to the dispersion of air pollutants, operating in much the same manner as an LBW. More information on car parking systems has been summarized in Table A.7. Car parking systems have almost the same scope of influence (pathways of the street canyon) and final stakeholders (pedestrians) as LBWs. An on-street car parking system at full capacity can lead to significant reductions in pollutant exposure on the footpath. Its effectiveness is similar to that of LBWs. However, the effectiveness decreases substantially with a decrease in the number of parked cars.

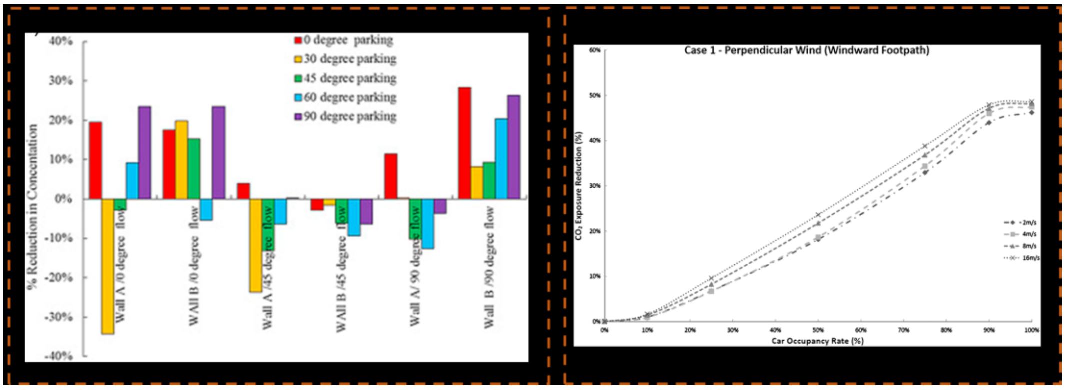

Fig. 9. (a) Percentage reduction in pollutant concentration for various car parking scenarios [98] and (b) plot of the average windward pollutant concentration on the footpath versus the occupancy rate under perpendicular wind conditions [99].

3.2.2 Porous barriers (Hedges)

Hedges

The leaf area density (LAD) of hedges (low-level vegetation with a continuous leaf covering from the ground to the top) is relatively high. The hedges can be utilized as a roadside barrier, limiting the exposure of pedestrians to air pollution [100]. The dispersion patterns of pollutants are altered by the hedges similarly to solid barriers. Vos et al. [101] reported that the positive influences of hedges on local air quality could be mainly attributed to the aerodynamic effect rather than the filtering capacity (Fig. 10(a)). Hence, hedges create a sheltered area of relatively fresh air just behind the barrier (i.e., within the first few meters, the pavement, sidewalks, and other pedestrian areas adjacent to traffic), where most of the polluted air is found [90]. Although a reduced wind speed was observed in street canyons due to the presence of hedges, the pollutant level was reduced by 24– 61% [13–15].

Porous barriers can substantially improve pedestrian-side air quality, but the critical parameters of hedges should be considered, i.e., the density (or, inversely, the porosity) and the dimension (height and thickness) [100]. First, Gromke et al. [90] observed higher reductions in pollutant concentrations for one central hedgerow than two parallel hedgerows (Fig. 10(b)). Second, vegetation barriers are not solid but allow some airflow. Accordingly, Kumar et al. [103] recommended that the thickness of hedges should exceed 1.5 m. Besides, according to field measurements obtained by Abhijith and Kumar [104] and CFD simulations reported by Tong et al. [105], pollutant concentrations in the sheltered areas of hedges generally decreased with an increase in LAD (Fig. 10(c)). Research has suggested an optimal LAD range of 1 to 5 m^2/m^3, depending on the urban geometry and the pollutant type [91,106,107]. Moreover, a larger reduction in the pollutant concentration behind the hedges was generally observed with higher and thicker hedges [90]. However, it should be mentioned that the effects of highly porous barriers in street canyons are variable and depend on local conditions, especially for the *H*/*W*. In a shallow street canyon ($H/W < 0.5$), it was found that 2 m was an appropriate height for hedges [103]. However, Li et al. [108] suggested an optimal height of 1.1 m for a relatively deep canyon ($H/W > 0.5$), as shown in Fig. 10(d). Vegetation barriers are more effective in open-road environments (including roads with buildings on only one side) than in street canyons due in part to the influence of complex street canyon geometry on airflows [20]. A relatively tall hedge occupying a sufficiently large area is required to offer adequate protection, e.g., for children in a school playground.

More information on hedges is listed in Table A.8. Similar to solid barriers, porous barriers (hedges) only improve pedestrian-level air quality immediately behind the barrier. Moreover, the parameters of the hedges, including the position and the geometry (thickness and height), should be carefully chosen.

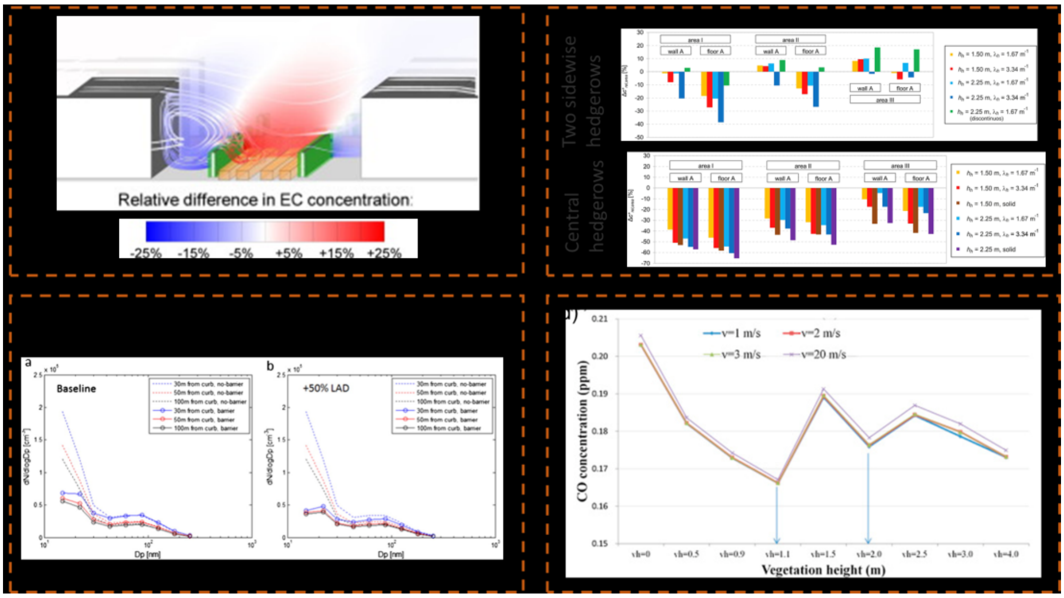

Fig. 10. (a) The relative difference in pollutant concentration for a 4 m high green barrier compared to the reference case without vegetation [101]; (b) area-averaged differences in pollutant concentrations for street canyons with two-sided and central hedgerows [90]; (c) particle size distribution with increasing LAD [105]; (d) the pollutant concentrations for vegetation barriers with different heights under different

wind conditions (v_h denotes the vegetation height) [108].

3.3 Creating a pollutant sink

The above methods can disperse air pollutants and reduce peak concentrations of harmful substances. However, the pollutants are not captured or treated to mitigate air pollution in urban areas. Mitigation can be achieved by creating pollutant sinks, including natural and artificial pollutant sinks.

3.3.1 Natural pollutant sinks (trees and green roofs/walls)

Trees

It should be noted that trees are generally regarded as the best mitigation method of pollutants regarding health outcomes. Accordingly, the public perception is that trees are effective natural pollutant sinks. However, the mitigation potential of trees is two-sided. Generally, trees interact with air pollutants by deposition (the deposition of gaseous and particulate matters (PMs) onto leaf surfaces) [109] and dispersion (the transport of pollutants by wind from the source and the dilution with cleaner surrounding air) [110]. The large and waxy leaf surface of trees facilitates the deposition, interception, and accumulation of pollutant particles [111], and various gaseous pollutants are absorbed through the stomata [21]. Therefore, trees typically improve air quality [21]. However, trees can also increase the flow resistance in street canyons, slowing down the air circulation and hindering the air exchange [112]. The combined effects of these two processes (deposition and dispersion) are manifold and context-dependent [113,114]. Thus, in-situ field measurements, wind tunnel tests, and CFD simulations have failed to demonstrate conclusively whether trees universally reduce air pollution in all scenarios [20]. Generally, there is no “one size fits all” strategy for planting trees since the effects of trees are highly localized [115]. It is essential to choose suitable tree species adapted to specific conditions.

Many cities have city-level plans for increasing the number of urban trees to reduce air pollution [116], a strategy that is supported by field measurements and model studies. Freiman et al. [117] found that ambient PM concentrations were lower in neighborhoods with dense urban trees. Similarly, Irga et al. [118] observed that areas with higher urban tree density had lower PM concentrations than other sites. In contrast, some studies demonstrated that urban trees had negligible pollution mitigation benefits. Nowak et al. [119] reported that urban trees generally provided a small contribution to the improvement in air quality of a city via deposition (0.2–1.0% for PM10, 0.1–0.6% for NO_2, and less than 0.005% for CO). Also, a previous review [120] indicated that urban trees only caused a 1% reduction in PM10 concentration in urban areas. Field measurements in Helsinki, Finland, suggested that the air quality in tree-covered areas improved only slightly when compared to treeless areas [121] (Fig. 11(a)). Yli-Pelkonen et al. [122] observed that the NO_2 concentration did not differ substantially between tree-covered and open areas in Baltimore, Maryland. Although urban trees are generally considered beneficial for reducing air pollution, they might not represent a viable solution to mitigating pollution at the city scale [22].

At the street canyon scale, improvements in air quality due to the presence of trees have rarely been reported in previous reviews [20,123] and research studies [113,124]. Vos et al. [101] and Vranckx et al. [112] investigated the dispersion and deposition effects on air quality and found that ventilation reduction exceeded the positive effect of deposition. The pollutant concentration was higher in street canyons with tree cover than no tree cover, as shown in Fig. 11(b). In-canyon trees resulted in a nearly 20% to 58% increase in the average concentration of in-canyon pollutants [97,98,110,125–130], depending on the canyon geometry, wind direction, and pollutant type. Yang et al. [130] reported that a taller tree canopy, a lower tree density, and a smaller LAD increased the personal intake fraction of pollutants.

In addition to roadside trees, planting trees in urban parks is an effective strategy for air pollution mitigation in parks [131,132]. Based on a seasonal field monitoring in several parks in Shanghai, China, Yin et al. [133] suggested that trees in parks removed traffic pollutants at the ground-level by 2–35% for total suspended particles (TSP), 2–27% for SO_2, and 1–21% for NO_2 in the park areas. This mitigation effect was more significant at higher NOx and PM10 levels [131]. In another study, a lower pollutant concentration was found in parks than in adjacent street canyons [134]. Nonetheless, it should be mentioned that while trees in urban parks create relatively unpolluted ‘oases’, their influence on surrounding areas as a pollutant sink is relatively limited.

More information on studies of trees as pollutant sinks has been summarized in Table A.9. Although trees act as pollutant sinks due to the deposition effect, they provide only a small contribution to the improvement in air quality since their influence is limited to parks or urban forests. Besides, in-canyon trees may even exacerbate outdoor air pollution. Thus, only the visitors to parks or urban forests will benefit from tree planting. Moreover, it should be noted that trees as natural pollutant sinks not always improve air quality. The release of biogenic VOCs from urban trees can contribute to the formation of photochemical smog [135–137].

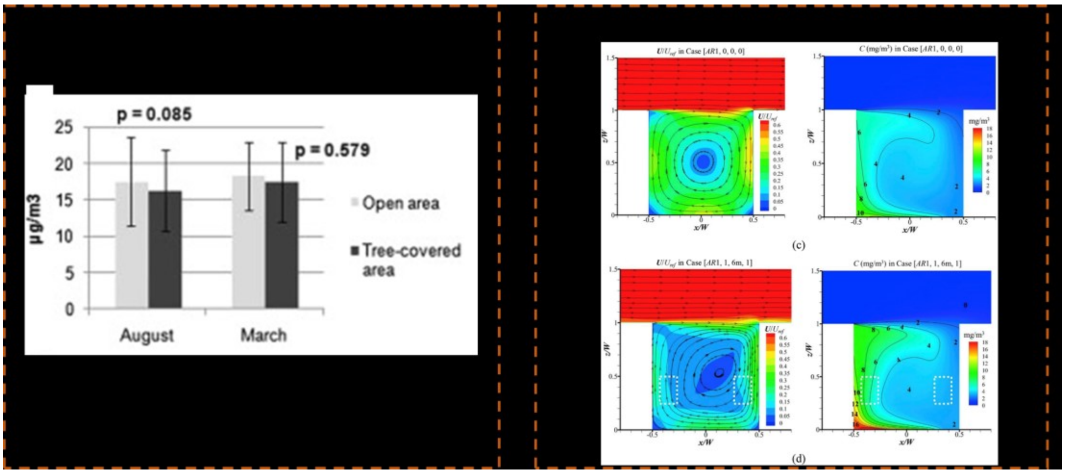

Fig. 11. (a) Concentrations of NO_2 in open and tree-covered areas [121]. (b) Plots of concentrations and wind velocity in canyons with and without trees [130]

Green infrastructure envelope (green roofs/walls)

Green infrastructures mounted on building facades or roofs have significant potential to reduce public exposure to outdoor air pollution. It has been well documented that the green infrastructure envelope (green walls or roofs) plays a significant role in diluting in-canyon airborne pollutants without taking up too much space [109]. In comparison with in-canyon hedges, the influence of green infrastructure is dominated by deposition since the green walls or roofs hardly alter the air circulation within street canyons [138]. Yang et al. [139] carried out a modeling study of green roofs in Chicago. The results indicated that the annual pollutant removal rate of green roofs was 85 kg $ha^{-1}yr^{-1}$. Similarly, Jayasooriya et al. [140] reported that the air quality at the city scale was enhanced significantly in Melbourne, Australia. It was found that green roofs were more effective for removing PM10 and O_3 than SO_2, NO_2, CO, and PM2.5 (Fig. 12(a)). On the other hand, Pugh et al. [10] found that a green wall reduced the street-level pollutant concentration due to deposition by as much as 60% (Fig. 12(b)). Qin et al. [141] reported that green walls were more effective than green roofs for improving in-canyon air quality given equal green coverage ratio and street canyon geometry. Moreover, increasing the LAD and green coverage ratio reduced in-canyon pollutant concentration.

More information on green infrastructure studies is listed in Table A.10. Green infrastructures reduce the pollutant concentration more efficiently than trees, especially in street canyons. Thus, the green infrastructure envelope plays a significant role in improving the air quality for both residents and pedestrians. Also, the LAD, green coverage ratio, and location of the green infrastructure can be controlled for better air quality.

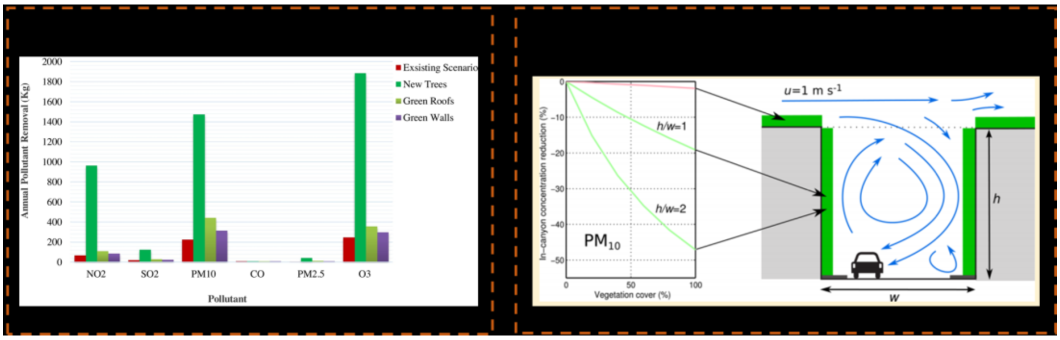

Fig. 12. (a) Comparison of the annual air pollutant removal amount of tree, green roof, green wall, and baseline scenarios [140]. (b) In-canyon concentration reduction versus vegetation cover [10].

3.3.2 Artificial pollutant sinks (solar chimney and electrostatic precipitator)

Solar chimney

The use of a solar chimney to reduce exposure to air pollutants is a relatively new area of research. Traditionally, solar chimneys were developed to generate electricity by capturing solar energy [142]. Since the air density decreases with the temperature, a solar chimney causes upward air movement due to buoyancy to drive turbines for generating electricity [143]. Zhou et al. [144] proposed a solar-assisted large-scale cleaning system to reduce air pollution during electricity generation. A filter bank was placed near the entrance of the chimney to separate the pollutant particles such as PM2.5 from the air. Similarly, Ming et al. [145,146] proposed a method for large-scale removal of non-CO_2 greenhouse gases (GHGS) using a solar chimney device with photocatalytic technology. This solar-driven system filtered out noxious particles and emitted clean air. Gong et al. [147] extended the study and proposed a new type of solar chimney system with an inverted U-shaped cooling tower and water spray system to remove large-scale air pollutants. This system provided 69,984,000 m^3 of clean air per day. Furthermore, a solar-assisted large-scale cleaning system (SALSCS) with a 500 m high chimney was proposed by Cao et al. [148]. By generating thermal airflow, the polluted air was moved through filters to separate PM (PM 10 and PM 2.5). Subsequently, a smaller experimental cleaning system with a solar-driven purifier called a smog-free tower (SFT) with a 60 m high chimney was put into operation in Xi’an, China [149–151] (Fig. 13(a)). Experiments showed that the SFT reduced the PM2.5 concentration by 11%-19% within a 10 km area around the solar chimney. Huang et al. [152] proposed a hybrid solar chimney and photovoltaic (PV) system with a small footprint (Fig. 13(b)). Suction fans powered by PV panels were used to improve the air quality, further reducing the required land area.

More information on studies on solar chimneys is listed in Table A.11. Solar chimneys represent a passive mitigation strategy and have excellent potential to remove pollutants from urban areas. These devices remove pollutants from a relatively large area, improving the pedestrians’ and residents’ air quality. Nonetheless, it should be mentioned that the land requirement for these devices should be carefully considered in future work.

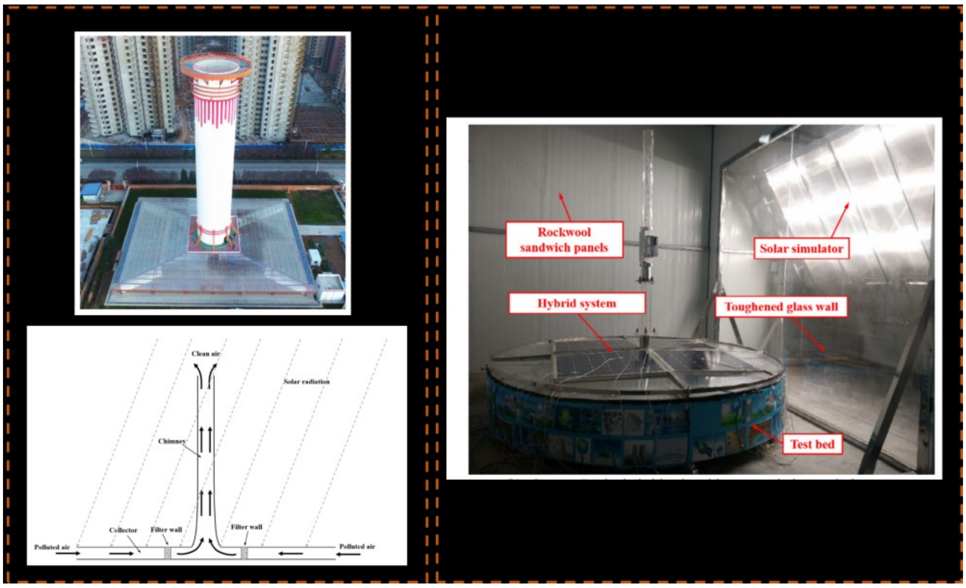

Fig. 13. (a) Photo and schematic diagram of SALSCS [149–151] and (b) photos of a hybrid solar chimney and photovoltaic system [152].

Electrostatic precipitator

In contrast to solar chimneys, an electrostatic precipitator (ESP) is powered by electricity and improves the local air quality. The potential of ESPs for air pollution exposure reduction has been demonstrated. For instance, ESPs were installed to ensure clean air in critical urban areas (such as hospitals or schools) to benefit particularly vulnerable people (such as patients or students) [153]. The ESPs were also installed near sources of high pollutant emissions, such as the major arterial roads or parking garages [154]. Blocken et al. [154] examined the effectiveness of ESPs for local pollutant removal in semi-enclosed parking garages. Significantly, the local outdoor PM10 concentration close to the garages was reduced by more than 50%, and the downstream concentration decreased by up to 10%. Boppana et al. [155] investigated the influence of an ESP installed in a typical street canyon in Singapore. The results confirmed that the radius of influence of an individual ESP was almost 5–6 times the unit’s length. A group of ESPs resulted in a 7.6% reduction in the average PM levels. Similarly, Lauriks et al. [156] analyzed the pollutant removal by an ESP in an urban street canyon in Antwerp, Belgium (Fig. 14(a)). In locations with poor ventilation, the ESP units significantly reduced the concentration level (up to 40%) (Fig. 14(b)).

Additionally, Dash and Elsinga [157] demonstrated that installing ESPs on solid barriers was beneficial for local air quality. ESPs can be effective in locations that are problematic in terms of air quality legislation [156].

More information on studies on ESPs has been provided in Table A.12. Generally, ESPs placed in strategic locations can significantly improve the local air quality, but the area of influence is limited. The use of ESPs represents an active mitigation strategy, but their cost and placing have to be considered. Besides, it should be stressed that ESPs require anthropogenic-generated energy in their operation, which may, in turn, create air pollution, although not necessarily in the urban areas. In this regard, although ESPs can be installed to reduce pollutant levels at concentration hotspots, they should not be used on a large scale.

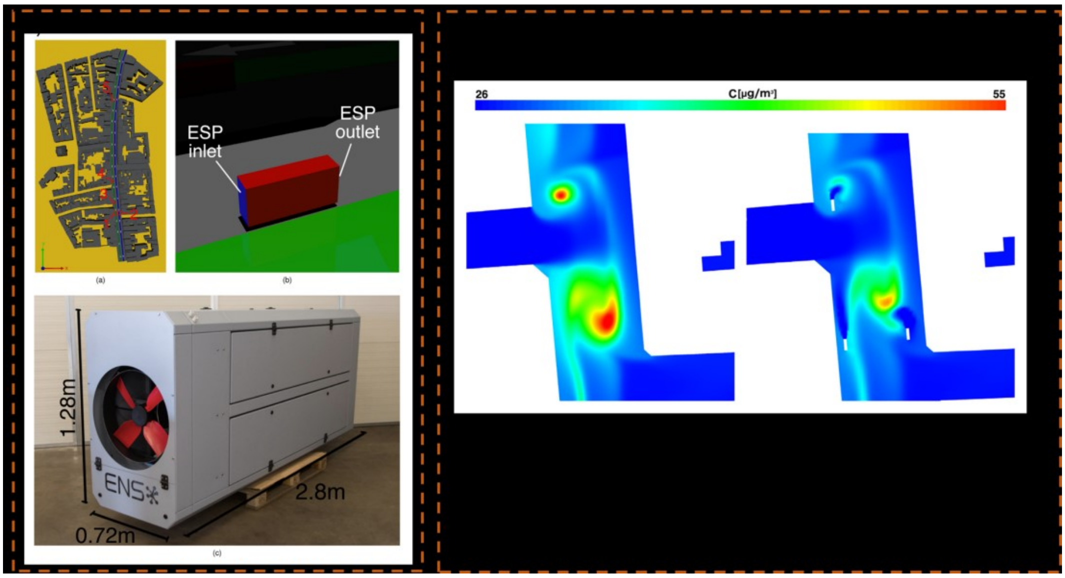

Fig. 14. (a) Schematic diagram of the locations of 5 electrostatic precipitators (ESPs) inside the domain, the magnification and orientation of the 5th unit, and a photo of the ESP unit [156]. (b) Comparison of PM10 concentrations for a case with and without an ESP [156].

Moreover, most studies on local mitigation strategies focused on the neutral condition (iso-thermal condition). Chen et al. [158,159] obtained outdoor measurements at different scales and demonstrated that the buoyancy force was the dominant force in urban ventilation, especially in deep street canyons. The synergy effect of mechanical ventilation and the buoyancy force should be considered in future work for optimization design.

4. Optimization framework for improving pollutant dispersion

The optimization frameworks can be classified into general optimization frameworks and advanced optimization frameworks that use machine learning and optimization algorithms, as shown in Fig. 15.

4.1 General optimization framework

Du and Mak [35] proposed a general optimization framework for increasing the wind velocity at the pedestrian level. The flowchart of this framework is presented in Fig. 15(a), showing the four steps. The first step obtains basic information on the target area, including the local wind conditions, the building, and geomorphological information. Different prediction methods are used (i.e., field measurement, wind tunnel experiment, and CFD simulation) to obtain the PLW environment. The next step is to detect the wind velocity by combining the prediction results and the evaluation criteria (e.g., the air ventilation assessment (AVA) scheme in Hong Kong). The following step applies the improvement measures to the target area. The final step is to re-evaluate the PLW environment after adopting the improvement measures. If the optimized results do not meet the evaluation criteria, new improvement measures are adopted. Subsequently, a case study of a university campus was conducted. The results indicated that the general framework substantially and systematically improved the local wind environment. Nonetheless, this general framework is based on a “trial- and-error” passive design method and has a single objective. Thus, an advanced optimization framework that uses machine learning and an optimization algorithm is urgently needed.

4.2 Advanced optimization frameworks

Advanced optimization frameworks can be divided into non-surrogate and surrogate model-based frameworks.

4.2.1 Non-surrogate model-based framework

Kaseb et al. [160] proposed a non-surrogate model-based framework that combined a CFD simulation with a genetic algorithm (GA), one of the most popular optimization algorithms to improve the local wind environment by optimizing the building heights and plan area density of a realistic urban area. As seen in Fig. 15(b), this optimization framework consists of four steps: urban area identification, optimization algorithms, CFD simulations, and evaluations. The first step is similar to that of the general framework; however, the GA is adopted in the second step. The attributes of the target urban areas (building height and plan area density) are assigned and updated using the GA combined with particle swarm optimization (PSO). The following step consists of the prediction and evaluation of the wind environment by CFD simulations. Steps 2 and 3 are repeated for each evolutionary period, and the evolution is controlled by a series of hyper-parameters, including the population size (the number of generated urban areas), the number of generations, the crossover rate, and the mutation rate. The population is then sorted based on the optimal value of the evaluation criteria up to the current evolutionary period. The process continues until the termination condition has been met. Finally, the optimal case is sent to Step 4 for evaluation. A case study of a real urban area in Tehran, Iran, was conducted using the proposed design framework. The results showed that the wind speed had increased by nearly 19%. Although the computational time and cost were lower than for the "trial-and- error" method, over 900 cases were predicted by the CFD simulation for an urban area with 20 buildings. This outcome was attributed to the limitation of combining the GA with a CFD simulation.

4.2.2 Surrogate model-based framework

In contrast, the surrogate model-based optimization framework does not integrate the CFD simulations with the optimization algorithms. Du et al. [161] proposed a response surface methodology (RSM)-based framework for improving the wind environment by optimizing the lift-up design, as illustrated in Fig. 15(c). The first step was to select the design parameters in the design of the experiment (DoE) and generate a design dataset. The second step was the establishment of reliable CFD simulations. A regression model (a type surrogate model) using the RSM approach was established using the dataset generated by the DoE. Subsequently, the surrogate models were coupled with the GA to determine the Pareto optimal design point (optimal result). This optimization framework with the optimum lift-up design parameters was successfully applied to improve the wind environment around an isolated building. Furthermore, Du et al. [67] proposed a more advanced framework to deal with a multi-objective problem. The optimization process was similar to the previous study, except for the final step, as shown in Fig. 15(c). In the final step, the Pareto optimal design points were processed using decision-making techniques, such as the Linear Programming Technique for Multidimensional Analysis of Preference (LINMAP) and Shannon's entropy, to determine the optimum values. Similarly, different approaches can be used to develop the surrogate model, such as an artificial neural network (ANN) [55] and the Gaussian process (GP) [162], as shown in Fig. 15(d) and (e), respectively.

Generally, fewer cases are needed to develop a surrogate model than a non-surrogate model-based framework. Thus, these frameworks significantly reduce the overall computational costs and speed up the optimization process. For example, the GP-based framework for optimizing the PLW environment around an isolated building is more than 400 times faster than its CFD counterpart [162].

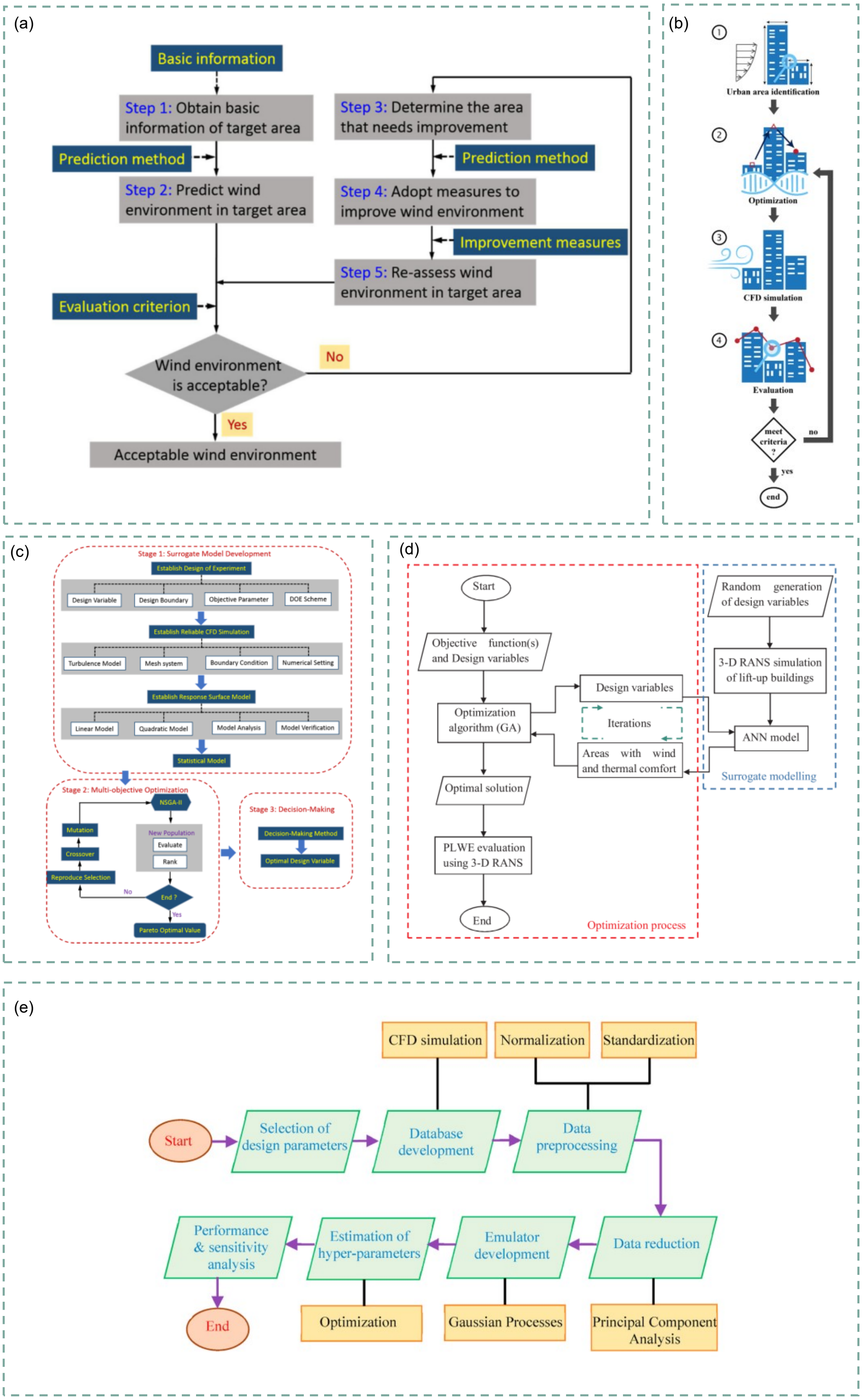

Fig. 15. (a) General optimization framework [35]. (b) Advanced optimization framework without a surrogate model [160]. (c) Advanced optimization framework

with RMS-based surrogate model [67]. (d) Advanced optimization framework with ANN-based surrogate model [55]. (e) Advanced optimization framework with GP-based surrogate model [162]

5. Evaluation theory for improving pollutant dispersion

Few studies focused on the evaluation theory for pollutant dispersion in urban areas, except for the mass transfer field synergy theory proposed by Ming et al. [83,163,164].

The mass transfer field synergy theory for outdoor urban areas originated from the well-established heat transfer field synergy theory. Guo et al. [165] regarded convective heat transfer as a heat conduction problem with an internal heat source. The authors proposed the field synergy principle of heat transfer enhancement by integrating the boundary layer energy equation. Subsequently, this field synergy principle of heat transfer was successfully applied to turbulent flow by Zeng and Tao [166]. Then, Liu et al. [167] established a synergy equation of energy and momentum for turbulent heat transfer, revealing the synergy between heat flow, mass flow, and fluid flow as a driving force during turbulent heat transfer. Subsequently, motivated by the analogy between heat transfer and mass transfer, Chen et al. [168] extended the field synergy theory to the analysis of convection mass transfer in an indoor space (confined space), revealing the impact of the synergy between the velocity vector and the pollutant concentration gradient on the decontamination rate of indoor ventilation. Based on the mass and heat transfer field synergy theory in confined spaces (e.g., the wavy channels, corrugate ducts, circular tube, and indoor space), Ming et al. [164] proved the applicability of the field synergy theory to the study of pollutant transmission in open spaces using model similarity, as seen in Fig. 16(a). The flow in a confined space (e.g., between two parallel plates) is symmetric about the centerline. There is an observable velocity gradient inside the boundary layer, whereas the velocity in the core flow region is constant. The half-domain of this confined space is analogous to a semi-confined structure, e.g., the fluid flow through a plate. Moreover, the mass transfer field synergy theory in open spaces has been successfully used to guide the optimization of urban geometry factors, such as in a viaduct, the roof shape [164], and the design of wind catchers [83].

Ming et al. [164] suggested, based on the field synergy theory, that it is possible to increase convective mass transfer, i.e., increasing the value of the dimensionless integral number of the field synergy, Fc_m. This proposed optimization pathway is related to the dimensionless number, i.e., the Sherwood number Sh, which can be derived from the concentration conservation equation of the steady-state mass diffusion. This Sh number characterizes the relative size of the convective mass transfer and diffusion mass transfer as follows:

$$Sh = \mathrm{Re}\, Sc \int_{\Omega} \overline{U} \cdot \overline{\nabla C} dV \Big/ V = \mathrm{Re}\, Sc Fc_m \quad (1)$$

where U is the flow speed, ∇C is the component concentration gradient, Re is the Reynolds number, Sc is the Schmidt number, and Fc_m is the mass transfer field synergy number. Accordingly, the Sherwood number is not only related to the Re and Sc but also depends on the coordinate angle between the velocity vector and the concentration gradient vector, i.e., the integration value of the dot product of the two vectors in the target area (Fc_m). Generally, the larger the dot product of the two vectors, the larger the Fc_m is, the larger the Sherwood number is, and the better the convective mass transfer effect is [164]. We use the field synergy analysis on the influence of the viaduct height on pollutant concentration as an example. As the height of the viaduct increased, the area with a large synergy angle in the street canyon increased, and the average synergy angle increased; thus, the more unfavorable the diffusion of pollutants in the street canyon was (Fig. 16(b)).

We provide a brief discussion on local mitigation strategies using this optimization pathway and the lift-up design as an example. This design significantly improves the pedestrian-level ventilation but has a negligible influence on vertical ventilation, which is in line with the pollutant concentration gradient. Thus, the lift-up design has a poor mass transfer synergy in the vertical direction and mainly improves the air quality at the pedestrian level. In contrast, the installation of wind catchers improves the air quality of the entire street canyon due to a better synergy of the velocity vector and the concentration gradient vector. Hence, these pollutants can be significantly diluted by incoming fresh air and can be removed from the street canyon. However, the control of the source-receptor pathways by constructing barriers does not seem to change the mass transfer synergy of the entire street canyon; thus, the in-canyon pollutant concentration hardly changes. Interestingly, creating an artificial pollutant sink can substantially improve the air quality since the flow direction toward the sink is consistent with the concentration gradient from the pollutant source (traffic lines) to the pollutant sink (solar chimney or ESP). However, a natural sink, such as street trees, does not provide a mass transfer synergy; thus, the influence of trees as a pollutant sink remains limited. Generally, the optimization pathway of enhancing the synergy of the velocity vector and the concentration gradient vector is quite effective. New local mitigation strategies can be developed using this pathway.

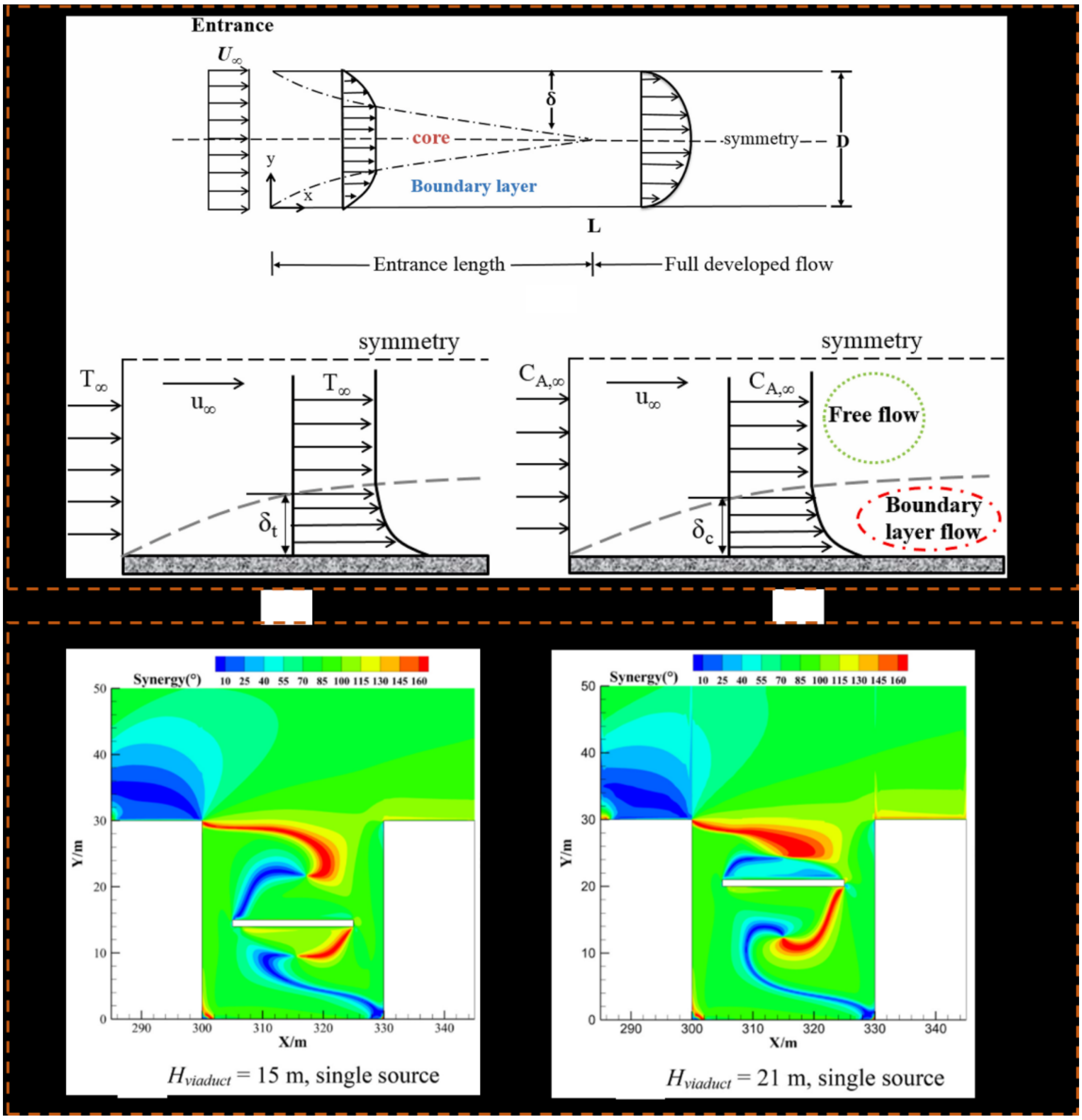

Fig. 16 (a) Illustration of the model similarity from a confined space to an open space and (b) Contours of synergy angle of viaducts with different heights [164]

6. Conclusion

Outdoor air pollution is a significant global issue due to the major long-term health risk. We reviewed studies on the optimization of pollutant dispersion, with a focus on traffic pollutants in urban environments. The main objective of the review was to investigate local mitigation strategies, with a particular concentration on the mechanism, the potential reduction in pollutant concentrations, and the parameterization of those strategies and the final stakeholders. Generally, local mitigation strategies can be divided into three categories: (i) improving urban ventilation and turbulence level for pollutant dispersion, (ii) controlling source-receptor pathways by constructing barriers, and (iii) capturing and mitigating air pollution by introducing pollutant sinks. Subsequently, we reviewed the optimization frameworks that consider a broad range of design parameters, including the design of local mitigation strategies, parameter optimization for different urban geometries or local mitigation strategies, and applicability for multi-design objectives. Evaluation theories were reviewed to consolidate the understanding of the potential optimization pathway for developing new local mitigation strategies and urban morphology. The following conclusions can be drawn from the literature review:

(1) The optimization of the building architecture (e.g., roof design, lift-up design, and setback design) and the addition of devices (e.g., pedestrian-level ventilation systems and wind catchers) provide significant potential to improving ventilation and the turbulence level. Both pedestrians and surrounding residents will benefit from a reduction in pollutant concentrations in urban areas resulting from these strategies. Nonetheless, it should be noted that most strategies are only effective in a small area (within the street canyon).

(2) Both solid barriers, including LBWs, noise barriers, on-street parking systems, and porous barriers (hedges), can create sheltered areas of relatively fresh air immediately behind the barrier at the pedestrian level, where most of the polluted air is found. It is noteworthy that this mitigation type is only beneficial to pedestrians behind the barriers since the pollutants are not removed.

(3) As a natural pollutant sink, the green infrastructure envelope, including green walls and green roofs, plays a significant role in improving air quality for residents and pedestrians. In contrast, urban trees provide a negligible contribution to the improvement in air quality, except in parks or urban forests. In addition, in-canyon trees may aggravate outdoor air pollution. Thus, only visitors of parks or urban forests will benefit from tree plantings. On the other hand, solar chimneys have significant potential to remove pollutants from urban areas and are effective in a broad area. Nonetheless, it

should be mentioned that the land requirements should be carefully considered in future work. In contrast, the installation of ESPs in strategic locations can significantly improve the local air quality level without occupying a large amount of space.

(4) Surrogate model-based optimization frameworks, including RSM-based, ANN-based, and GP-based frameworks, have lower computational costs and perform optimization faster than other types of frameworks. These optimization frameworks are well suited for multi-objective problems.

(5) Few studies considered optimization theories for pollutant dispersion in urban areas, with the exception of the mass transfer field synergy theory. This theory was used successfully to increase the synergy of the concentration gradient and wind velocity vector to improve pollutant dispersion in urban areas.

In summary, this paper provided a comprehensive and systematic review of the local mitigation strategies, optimization frameworks, and evaluation theories for improving pollutant dispersion in urban areas. Accordingly, this study is beneficial for urban planners and architects responsible for decision-making.

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Appendix

Table A.1. Overview of studies on roof design

Ref.	Study approach	Urban configuration	Focus	Coverage of Influence	Critical Findings
[43]	CFD (V)	2D-S (*H/W* = 0.08–2.5)	Effects of roof slope (0– 40° for pitch roof)	The whole street canyon	Pitched roofs enhanced the TKE at the roof level and provided a significant perturbation of the mean velocity field, increasing the air exchange rate, regardless of the slope and the aspect ratio.
[45]	WT	3D-S (*H/W* = 1, *L/W* = 5–15)	Effects of roof shape (flat & pitch)	The whole street canyon	Pitched roofs enhanced along-canyon velocity components in the entire length of the canyon
[42]	WT	2D-S (*H/W* = 1)	Effects of roof shape (flat & pitch)	The whole street canyon	Pitched roofs induce violent flow with large vortices penetrating the street, intensifying ventilating in the upper part of the canyon
[46]	WT	2D-S (*H/W* = 1)	Effects of roof shape (flat, pitch, & wedge)	The whole street canyon	Roof shape played a significant role in determining the in-canyon vorticity dynamics and corresponding pollutant transport
[47]	CFD (V)	2D-S (*H/W* = 1)	Effects of roof shape (flat, pitch, downwind/ upwind wedge, & trapezoid) & Roof height (H_{roof}/H = 0.17, 0.33 and 0.5)	The whole street canyon	Compared with flat roofs, the wind velocity increased for pitched & trapezoid-shaped roof and decreased for wedge-shaped roofs; wind velocity decreased as the H_{roof} increased; TKE increased as the H_{roof} increased; pollutant concentration decreased as the H_{roof} increased
[48]	CFD (V)	2D-S (*H/W* = 1)	Effects of roof shape (flat, pitch, downwind/ upwind wedge, trapezoid, & round) & Roof height (H_{roof}/H = 1/6, 1/3 and 1/2)	The whole street canyon	At H_{roof}/H = 1/6, the pollution levels were similar for different roof types; at H_{roof}/H =1/3, the pollution levels were much higher for the upwind-wedged and slanted roof than for the round, trapezoidal, and downwind wedge-shaped roofs; at H_{roof}/H = 1/2, the round roof had the lowest pollution level and the upwind wedge-shaped roof had the highest pollution level
[49]	CFD (V)	2D-S (*H/W* = 1)	Effects of roof slope (0– 30° for a wedged-shape roof)	The whole street canyon	The effect depended on the roof slope. A slope of 18° was the threshold between double and single vortex structures.

[50]	CFD (V)	2D-S (*H/W* = 1)	Effects of roof morphological configuration	The whole street canyon	The leeward wedged-shaped roof had much stronger aerodynamic impacts than the same roof geometry on the windward building

Study approach: Exp.= Experiment, MS= modeling study, WT = Wind tunnel measurements, WC = Water channel measurements, FM = Field measurements, CFD (V) = CFD with validation, and CFD (NO) = CFD without validation; **Urban configuration**: C = City, S= Street canyon, B = Building, GB = a group of buildings, λ_F = Frontal area density, *H/W* = Height aspect ratio (building height/street width), *L/W* = Length aspect ratio (street length/street width).

Table A.2. Overview of studies on lift-up design

Ref.	Study approach	Urban configuration	Focus	Coverage of Influence	Critical Findings
[59]	WT	Ideal GB	None	Pedestrian level behind buildings	Lift-up designs increased the surrounding PLW speed by almost 11%
[61]	CFD (V)	Realistic GB	Effects of building geometry	Pedestrian level inside and near lift-up areas	Lift-up designs increased the wind speed inside and near lift-up areas
[66]	CFD (V)	Ideal B	Effects of lift-up column height &weight	Pedestrian level behind buildings	The height and width of columns significantly affected the ventilation at the pedestrian level; the column height had a more significant effect than the column width
[67]	WT	Realistic GB	Effects of lift-up column height &weight	Pedestrian level behind buildings	Increasing the column width adversely affected the ventilation at the pedestrian level, whereas the effect of increasing the column height was positive
[68]	CFD (V)	Ideal GB	Effects of lift-up height	Pedestrian level throughout all buildings	Improvements in the pedestrian level ventilation were relatively small when the elevated height exceeded 4 m
[69]	CFD (V)	Ideal GB	Effects of lift-up position	The entire space around buildings	The first-floor lift-up design was more effective than the second or third-floor lift-up design

Table A.3. Overview of studies on setback design

Ref.	Study approach	Urban configuration	Focus	Coverage of Influence	Critical Findings
[74]	CFD (V)	Ideal S (*H/W* = 0.33 to 3)	Effects of height and width of arcade	The pedestrian level of the street canyon	Increasing the arcade height (from 3 to 6 m) led to a nearly 25% reduction in ACH, whereas increasing the arcade width (from 1.5 to 9 m) caused an almost 76% increase in ACH.
[76]	WT	Ideal S (*H/W* = 2)	Influence of arcade on pollutant concentrations	The whole street canyon	Arcade design resulted in a reduction in pollutant concentration at the pedestrian level.
[78]	CFD (V)	Ideal S (*H/W* = 2, 4, & 6)	Effects of horizontal & vertical setback	The whole street canyon	The vertical setback was more suitable for a canyon with *H/W* = 2, whereas the horizontal setback was more suitable for a canyon with *H/W* = 4 and 6

Table A.4. Overview of studies on PVSs

Ref.	Study approach	Urban configuration	Focus	Coverage of Influence	Critical Findings
[81]	CFD (V)	Ideal S (*H/W* = 1& 2)	PVS strategies	The whole street canyon	The exhaust strategy reduced concentrations in the street canyon by about 40%. The supply strategy showed similar performance. The washing flow strategy was satisfactory for removing pollutants from the duct system.
[80]	CFD (V)	Ideal S (*H/W* = 2)	PVS strategies	The whole street canyon	PVS improved the ventilation inside the building canopy under stable and unstable weather conditions.
[79]	CFD (V)	Ideal S (*H/W* = 1)	PVS strategies and fan pressure	The whole street canyon	An increase in fan pressure produced higher wind velocities, which significantly decreased the AQI

Table A.5. Overview of studies on wind catchers

Ref.	Study approach	Urban configuration	Focus	Coverage of Influence	Critical Findings
[82]	WC	Ideal S ($H/W = 1$)	Effects of wind catcher position & structure	The whole street canyon	Wind catchers installed on the upwind building enhanced pedestrian-level wind speed of the target canyon by 2.5 times; sidewalls of wind catcher prevented spanwise leakage
[71]	CFD (V)	Ideal S ($H/W = 5$)	Effects of wind catchers in a deep canyon	The whole street canyon	Wind catchers reduced the pollutant concentrations by one or two orders of magnitude in a deep street canyon
[83]	CFD (V)	Ideal S ($H/W = 1$)	Synergy analysis of wind catchers	The whole street canyon	The wind catcher significantly enhanced the synergy of pollutant dispersion and airflow in the street canyon

Table A.6. Overview of studies on LBWs

Ref.	Study approach	Urban configuration	Focus	Coverage of Influence	Critical Findings
[93]	FM	Realistic C	Effects of the height of LBW	Behind the LBW at the pedestrian level	An increase in the height of LBWs (1 to 2 m) caused a significant reduction in pollutant concentration (by almost 50%)
[95]	CFD (V)	Ideal S ($H/W = 1$)	Effects of the position of LBW	Pedestrian level	Central LBWs were more suitable for wind perpendicular to the street, whereas footpath LBWs resulted in better air quality for parallel wind
[87]	CFD (V)	Ideal S ($H/W = 1$)	Effects of the position of LBW	Pedestrian level	Central LBWs caused a more significant reduction in the pollutant concentration than the footpath LBWs
[97]	CFD (V)	Realistic C	Potential final stakeholders benefitting from LBWs	Pedestrian level	A solid barrier caused an increase in NO_2 concentration near the road and a reduction in NO_2 concentration on the footpath.

Table A.7. Overview of studies on on-street parking

Ref.	Study approach	Urban configuration	Focus	Coverage of Influence	Critical Findings
[98]	CFD (V)	Ideal S ($H/W = 0.5$)	Effects of parking density	Behind the cars at the pedestrian level	Oblique parking (30°–60°) caused an increase in roadside pollutant exposure of up to 34.3%
[99]	CFD (V)	Ideal S ($H/W = 1$)	Effects of occupancy rates	Behind the cars at the pedestrian level	A curvilinear pattern of concentration reduction was observed for a parking occupancy range of 10% to 90%
[169]	CFD (V)	Ideal S ($H/W = 1$)	Effects of the shape of parked cars	Behind the cars at the pedestrian level	The shape of parked cars might influence the air quality

Table A.8. Overview of studies on the hedges

Ref.	Study approach	Urban configuration	Focus	Coverage of Influence	Critical Findings
[90]	CFD (V)	Ideal S ($H/W = 0.5$)	Effects of hedge position	At the pedestrian level of street canyons	One central hedgerow provided higher reductions in pollutant concentrations than two parallel hedgerows
[104]	CFD (V)	Realistic C	Effects of LAD of hedge	Behind the hedges at the pedestrian level	The pollutant concentration in the sheltered areas of hedges generally decreased with an increase in leaf area density (LAD)
[108]	FM & CFD (V)	Ideal S ($H/W = 0.18$ &0.78)	Effects of the hedge height	Behind the hedges at the pedestrian level	The optimal height of 1.1 m was recommended for a canyon of $H/W = 0.78$

Table A.9. Overview of studies on trees

Ref.	Study approach	Urban configuration	Focus	Coverage of Influence	Critical Findings
[117]	FM	Realistic C	Effects of trees at the city scale	Around the trees	Ambient PM concentrations were lower in neighborhoods with dense urban trees
[121]	FM	Realistic C	Effects of trees at the city scale	N/A	Air quality in tree-covered areas only slightly improved as compared to treeless areas
[112]	CFD (V)	Ideal S (*H/W* = 0.5 & 1)	Effects of trees at the street canyon scale	The whole canyon	The reduction in ventilation was much stronger than the positive effect of deposition
[130]	CFD (V)	Ideal S (*H/W* = 0.5–5)	Effects of trees at the street canyon scale	The whole canyon	In-canyon trees increased the average concentration of in-canyon pollutants
[133]	FM	Realistic C	Effects of trees in urban parks	The coverage areas of urban parks	Trees removed traffic pollutant at the ground level by 2–35% for TSP, 2–27% for SO_2, and 1–21% for NO_2 in the coverage areas of the park

Table A.10. Overview of studies on the green infrastructures

Ref.	Study approach	Urban configuration	Focus	Coverage of Influence	Critical Findings
[139]	MS	Realistic C	Effects of green roofs at the city scale	N/A	The annual pollutant removal rate of green roofs was 85 kg $ha^{-1}yr^{-1}$
[140]	MS	Realistic C	Different pollutants	N/A	Green roofs were most effective for removing PM10 and O_3
[10]	CFD (V)	Ideal S (*H/W* = 1 & 2)	Green roofs in different canyons	The whole street canyon	Green walls cause a reduction in the street-level pollutant concentration of 60%
[141]	CFD (V)	Ideal S (*H/W* = 0.5– 2)	Comparing green roofs and walls	The whole street canyon	Green walls were more effective than green roofs for improving in-canyon air quality

Table A.11. Overview of studies on solar chimneys

Ref.	Study approach	Urban configuration	Focus	Coverage of Influence	Critical Findings
[149]	CFD (V)	N/A	Influence of solar chimney on nearby air quality	A 10 km area around the solar chimney	A smog-free tower reduced the PM2.5 concentration by 11%-19% within a 10 km area around the solar chimney
[152]	CFD (V) & Exp.	N/A	A hybrid solar chimney and PV system	Around the solar chimney	Suction fans powered by PV panels improved the air quality with a small footprint.

Table A.12. Overview of studies on ESPs

Ref.	Study approach	Urban configuration	Focus	Coverage of Influence	Critical Findings
[154]	CFD (V)	Realistic C	ESP for parking garages	Around the ESP	Local outdoor PM10 close to the garages was reduced by more than 50%, and the downstream concentration decreased by up to 10%
[155]	CFD (V)	Realistic C	ESP in realistic street canyon	Almost 5-6 times of the unit length around the ESP	A group of ESPs reduced eh average PM levels by approximately 7.6%.
[156]	CFD (V)	Realistic C	ESP in realistic street canyon	Around the ESP	In some locations with poor ventilation, the ESPs significantly reduced (up to 40%) the concentration level