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## **Air Pollution Abatement Performances of Green Infrastructure in Open Road and Built-up Street Canyon Environments – A Review**

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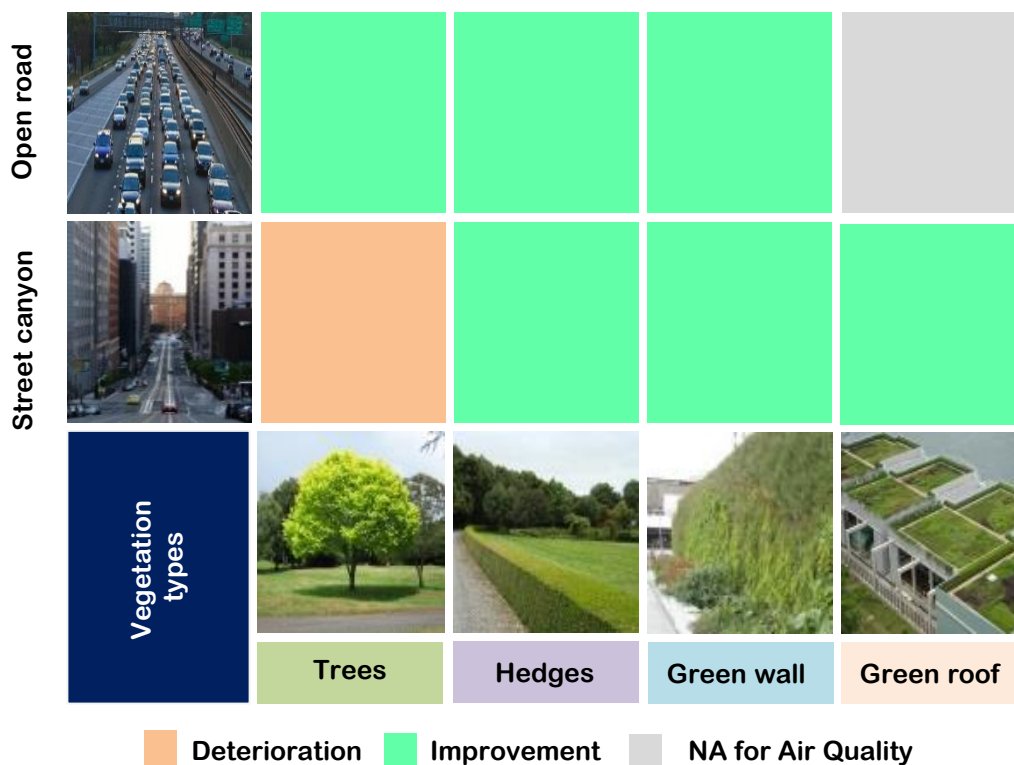
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**Graphical abstract**



**Abstract**

Intensifying the proportion of urban green infrastructure has been considered as one of the remedies for air pollution levels in cities, yet the impact of numerous vegetation types deployed in different built environments has to be fully synthesised and quantified. This review examined published literature on neighbourhood air quality modifications by green interventions. Studies were evaluated that discussed personal exposure to local sources of air pollution under the presence of vegetation in open road and built-up street canyon environments. Further, we critically evaluated the available literature to provide a better understanding of the interactions between vegetation and surrounding built-up environments and ascertain means of reducing local air pollution exposure using green infrastructure. The net effects of vegetation in each built-up environment are also summarised and possible

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recommendations for the future design of green infrastructure are proposed. In a street canyon environment, high-level vegetation canopies (trees) led to a deterioration in air quality, while low-level green infrastructure (hedges) improved air quality conditions. For open road conditions, wide, low porosity and tall vegetation leads to downwind pollutant reductions while gaps and high porosity vegetation could lead to no improvement or even deteriorated air quality. The review considers that generic recommendations can be provided for vegetation barriers in open road conditions. Green walls and roofs on building envelopes can also be used as effective air pollution abatement measures. The critical evaluation of the fundamental concepts and the amalgamation of key technical features of past studies by this review could assist urban planners to design and implement green infrastructures in the built environment.

**Keywords:** Local pollutant exposure; Street canyons; Open roads; Urban trees and hedges; Green wall; Green roof

**Research highlights**

- ▶ Green infrastructure can play a significant role in mitigating urban air pollution
- ▶ Air quality changes in local built environments due to vegetation are assessed
- ▶ Low-level hedges improves air quality in street canyons unlike high-level trees
- ▶ Green green walls and roofs are effective to reduce pollution in streets/open roads
- ▶ Prior design of green infrastructure should be performed for improving air quality

**1 Introduction**

Air quality in the built environment continues to be a primary health concern as the majority (i.e., 54% in 2014) of the world's population currently lives in urban areas, and this is projected to rise to 66% by 2050 (United Nations, 2014). Traffic emissions are the main source of air pollution in cities around the globe (Kumar et al., 2016, 2015, 2013). Green infrastructure in the built environment has been considered as one potential urban planning solution for improving air quality as well as enhancing the sustainability of cities for growing urban populations (Irga et al., 2015; Salmond et al., 2016). These green solutions

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include street trees, vegetation barriers (including hedges), green (or living) walls, and green (or living) roofs. These types of vegetation act as porous bodies which influence local dispersion patterns, and aid the deposition and removal of airborne pollutants (Escobedo and Nowak, 2009; Fantozzi et al., 2015; Janhall, 2015; Nowak, 2006; Yin et al., 2011). Apart from possible air pollution reduction, urban green infrastructure also provides benefits such as urban heat island mitigation (Chen et al., 2014; Gago et al., 2013), potential reduction in energy consumption (Berardi et al., 2014; Pérez et al., 2014) and noise pollution (Berardi et al., 2014; Cohen et al., 2014; Salmond et al., 2016), better stormwater management (Czemiel Berndtsson, 2010; Roy et al., 2012) and climate change mitigation (Matthews et al., 2015). In addition, eco-services provided by green interventions assist in improving the health and well-being of the urban population in several ways (Dean et al., 2011; Nowak et al., 2014; Tzoulas et al., 2007).

Road traffic emits a variety of harmful pollutants in the form of particulate matter – PM<sub>10</sub> (particulate matter  $\leq 10 \mu\text{m}$ ), PM<sub>2.5</sub> ( $\leq 2.5 \mu\text{m}$ ) and ultrafine particles (UFP;  $< 100 \text{ nm}$ ) – and gaseous pollutants such as the nitrogen oxides (NO<sub>x</sub>), carbon monoxide (CO) and in minor part sulphur dioxide (SO<sub>2</sub>). As for the air pollution abatement performance of various types of green infrastructure, either individually or in combination, in different urban environments (Gallagher et al., 2015), the majority of studies have focused on pollutants such as the PM<sub>10</sub> (Heal et al., 2012; Maleki et al., 2016), PM<sub>2.5</sub> (Ayubi and Safiri, 2017; Heal et al., 2012), UFP (Chen et al., 2016; Kumar et al., 2014), NO<sub>x</sub> (Beevers et al., 2012; Michiels et al., 2012), CO (Bigazzi and Figliozzi, 2015; Chen et al., 2011), and black carbon (Li et al., 2016; Rivas et al., 2017) that have implications for the adverse health effects. In future, urban green infrastructure can be implemented as a passive air pollution control measure in cities through limited alterations in the built environment (McNabola, 2010). The urban environments accounted for in the studies reviewed here were either near an open road or in an urban street canyon with high traffic volumes. For example, the impact of trees in street canyons were examined by numerous studies (Abhijith and Gokhale, 2015; Amorim et al., 2013; Buccolieri et al., 2011, 2009; Gromke et al., 2008; Gromke and Ruck, 2007; Hofman et al., 2016; Li et al., 2013; Moonen et al., 2013; Salim et al., 2011a; Salmond et al., 2013; Vos et al., 2013; Wania et al., 2012; Jeanjean et al., 2017). These studies generally indicated that the presence of trees increases the pollution concentration in a street canyon.

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Other studies investigated pollutant exposure in street canyons with hedges and reported that low-level hedgerows generally reduces pollutant levels along the footpath (Gromke et al., 2016; Li et al., 2016). Likewise, a few studies investigated the air pollution removal potential of vegetation along busy urban highways, reporting that vegetation barriers and trees along roads reduced roadside pollutant concentrations (Brantley et al., 2014; Hagler et al., 2012; Lin et al., 2016; Tong et al., 2016). A few studies also indicated that roadside vegetation can have adverse effects on air quality under certain conditions (Tong et al., 2015). Recently, Baldauf, (2017) summarised the vegetation characteristics that influence the beneficial and adverse effects of roadside vegetation on near-road air quality. A number of past studies also examined the air pollution removal potential of green roofs and green walls (Joshi and Ghosh, 2014; Ottel  et al., 2010; Pugh. et al., 2012) or the combinations of green infrastructure with other passive pollution control methods (Baldauf et al., 2008; Bowker et al., 2007; Tong et al., 2016; Baik et al., 2012; Tan and Sia, 2005). Overall, a general conclusion from these studies was that green infrastructure had both positive and negative impacts on air quality at street levels, depending on the urban and vegetation characteristics.

As summarised in Table 1, previous review articles on this topic have discussed particulate matter (PM) removal by vegetation (Janhall, 2015), the suitability of passive methods to reduce pollutant exposure (Gallagher et al., 2015), vegetation design characteristics for roadside applications (Baldauf, 2017, 2016; Baldauf et al., 2013) and pollutant deposition on plant canopies (Litschike and Kuttler, 2008; Petroff et al., 2008). Furthermore, previous reviews have focused on the benefits of urban infrastructure such as urban heat island mitigation from trees (Gago et al., 2013), thermal performance of green facades (Hunter et al., 2014) and energy aspects of green roofs (Saadatian et al., 2013). Recently, Berardi et al. (2014) published a state-of-the-art review on air pollution mitigation by green roofs. However, there is still a need to systematically review and summarise the individual findings of various published research studies on numerous types of green infrastructure that consider local air quality improvements in the diverse urban environment. Going beyond the scope of existing reviews on this topic, this article: (i) provides a detailed quantification of local scale aerodynamic effects and reduction potentials of urban vegetation such as trees, hedges, green wall and green roofs in both built-up (street canyon) and open road

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configurations, (ii) describes the individual and combined effects of the built environment, metrological and vegetation characteristics on neighbourhood air quality, (iii) identifies vegetation types and characteristics that result in the least pollutant exposure in various urban areas, and (iv) recommendations for deploying green interventions in diverse urban environments.

This synthesis of local scale air quality impacts for each vegetation type is essential for city level implementation that uses a bottom-up decision-making process. This ensures the success of these interventions irrespective of scales (Salmond et al., 2016). Therefore, it is necessary to consolidate and synthesise previous investigations on the air pollution abatement performance of urban green infrastructure (i) for urban planners to facilitate its practical application in future urban planning strategies and (ii) for researchers to identify gaps in knowledge and to undertake further evaluation and validation of the performance of green infrastructure to improve urban air quality and ameliorate urban microclimate.

Further, this review aims to develop generic recommendations on the selection and design characteristics of suitable green infrastructure in different urban environments. These recommendations can then be deployed in the future for existing city environments to reduce pollutant exposure from nearby emission sources at the local scale. We categorised the vegetation impacts on neighbourhood air quality based on different urban forms such as street canyons (Figure 1), open roads (Figure 2) and building envelopes (Figure 1d), and observed the distinct impacts of vegetation on air quality with respect to urban morphology. This revealed site-specific recommendations suitable for planting vegetation in street canyons as well as forming generic guidelines for open road configurations. In addition, the review provides insights into the least studied vegetation application (i.e. green walls and roofs) and highlights existing research gaps. A comprehensive summary of technical design inputs (e.g., leaf area density, LAD; deposition velocity; porosity) for four different types of vegetation are also compiled to assist any potential dispersion and deposition modelling activities. Altogether, the flow of the scientific knowledge consolidated in this review will aid in the practical usage of green interventions in the real-world cases for a healthier environment.

## **2 Common characteristics of urban vegetation (green infrastructure)**

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The terms ‘urban vegetation’ and ‘green infrastructure’ are used interchangeably in this review paper and refer to all types of vegetation such as trees (Section 3.1), hedges and bushes (Section 3.2), green walls (Section 5.1) and green roofs (Section 5.2) that are the focus of this article. Before examining individual urban built environment conditions (Sections 3 and 4), it is important to understand the common vegetation characteristics that affect near-road air quality. These characteristics include: (i) pollutant removal and dispersion characteristics, (ii) density/porosity of vegetation, (iii) physical dimensions (such as height, length, thickness and spacing), and (iv) species-specific characteristics (such as leaf thickness, presence of hairs or wax on leaf surface, seasonal variations, vegetation emissions and air pollution tolerance index).

Urban vegetation removes gaseous pollutants by absorption through leaf stomata or plant surfaces (Escobedo and Nowak, 2009; Fantozzi et al., 2015; Salmond et al., 2016; Vesa Yli-Pelkonen et al., 2017). Nowak et al. (2013, 2006) investigated pollution removal for several gases (O<sub>3</sub>, NO<sub>2</sub>, SO<sub>2</sub>, CO) and PM<sub>10</sub> by measuring the downward pollutant flux as the product of the deposition velocity and the pollutant concentration. They found that pollution removal values for each pollutant vary among cities based on the amount of tree cover, pollution concentration, the length of in leaf season, the amount of precipitation and other meteorological variables that affect tree transpiration and deposition velocities. Furthermore, PM deposited on vegetation can be retained for some time temporarily and then re-suspend to the atmosphere by high wind speed, washed off by precipitation, or transferred to soil with falling parts of vegetation including leaves (Nowak et al., 2014). Some vegetation species act as a pollutant source by emitting pollen (D’Amato et al., 2007) and some gaseous pollutants (Benjamin and Winer, 1998; Leung et al., 2011; Wagner and Kuttler, 2014). A porous body of vegetation can influence nearby pollutant concentrations by altering the wind flow around it (Ries and Eichhorn, 2001). The aerodynamic effects of trees affect pollutant concentration in two ways depending on the built-up environment and meteorological conditions. Under neutral thermal stratification (i.e. a typical condition reproduced in laboratory studies), tree crowns act as obstacles to the wind and depending on the shape and spatial configuration, they diminish the turbulent exchange of mass and momentum between the in-canopy volume and the air above the canopy. On the other hand, tree crowns may generate wind direction fluctuations below the tree crown (Di Sabatino et

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al., 2015), and depending on foliage shape and distribution, these act as a source of turbulence and hence increase turbulent diffusion and facilitate pollutant dilution. The aerodynamics effects of trees have been addressed extensively by several authors using wind tunnel investigations complemented by detailed CFD modelling. Also, the effect of the role of non-neutral thermal stratification has been addressed in both computational and observational studies. For example, De Maerschalck et al.(2010) showed that in specific meteorological conditions or geometries of built environment, vegetation can decrease turbulent kinetic energy and act as a diffuser breaking down the turbulent eddies. Based on real-atmospheric observations in street canyons, Di Sabatino et al. (2015) showed that the presence of trees alters the thermal vertical distribution inside street canyons, especially in nocturnal hours, with the bottom layer much warmer than the top of the canyon, but with a remarkable decoupling of the flow and diminished vertical exchange. In synthesis, there is a consensus that an increase in pollutant concentrations in street canyons occur with the presence of trees (Buccolieri et al., 2009; Gromke and Ruck, 2009, 2007). However, a reduction in pollution concentrations may occur depending on micrometeorological conditions and type of foliage; this is especially true due to the presence of hedges in street canyons and dense vegetation along highways (Al-Dabbous and Kumar, 2014; Brantley et al., 2014; Gromke et al., 2016). Critical in interpreting these findings is that vegetation can both introduce extra mechanical turbulence, but also reduce turbulent kinetic energy, while the strong wind speed reduction around the vegetation causes strong shear stresses and therefore extra turbulence. Nevertheless, the combination of local meteorological conditions and vegetation has received less attention and extra research efforts may be foreseen in future years.

The nature of vegetation effects are dominated by the geometry of the built-up environment. In street canyons, trees may deteriorate air quality if their configuration is not planned adequately (Abhijith and Gokhale, 2015; Buccolieri et al., 2011; Ries and Eichhorn, 2001; Salmond et al., 2013; Vos et al., 2013; Wania et al., 2012) whereas in open road environments a mixture of trees and bushes can act as barriers to improving air quality behind them (Brantley et al., 2014; Hagler et al., 2012; Islam et al., 2012; Lin et al., 2016; Shan et al., 2007). These dispersion and deposition characteristics are affected by the density and area of the vegetation with the deposition rate due to vegetation being estimated by two



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methods: the leaf area index (LAI) that is defined as the amount of vegetation surface area per  $\text{m}^2$  of ground area, or leaf area density (LAD) that is defined as the area per unit volume ( $\text{m}^2 \text{m}^{-3}$  or  $\text{m}^2 \text{m}^{-1}$ ). The porosity, pressure drop or drag force can be estimated by studying pollutant dispersion around vegetation. Janhall (2015) provided a detailed explanation on PM dispersion and deposition caused by vegetation. Previous studies have employed different methods to quantify the density of vegetation. Low porosity (high-density) vegetation had a similar effect to solid barriers such as low boundary walls (Gallagher et al., 2012; Gromke et al., 2016; Janhall, 2015; McNabola et al., 2009), which forces the air to flow above and over it, while high porosity (low-density) vegetation allows air to pass through it. The porosity and drag force changes with wind velocity (Gromke and Ruck, 2008; Tiwary et al., 2005). During the high wind speed conditions, a decrease in porosity of broad-leafed trees and drag force on trees were observed by Gromke and Ruck (2008) and Tiwary et al. (2005), respectively. On the other hand, an increase in porosity was noted in conifers and no change in porosity up to a particular threshold value of wind speed (i.e. 0.8 - 1.7  $\text{ms}^{-1}$ ) was shown by hedges (Tiwary et al., 2005).

Vegetation parameters have contrasting impacts on local air quality with respect to the surrounding urban geometry. In general, vegetation with gaps and spacing lead to lower concentrations in street canyons as opposed to an increased concentration in open road conditions. Dense (low porosity) vegetation can usually lead to concentration reductions in street canyons. Vegetation species with thick leaves show less deposition as opposed to those with hairs and or waxes (Sæbø et al., 2012). Likewise, urban vegetation with less seasonal variations (i.e. no change in foliage) and lower pollutant (biogenic compounds) emission are preferred. A study by Pandey et al. (2015) suggests an evaluation of air pollution tolerance index of vegetation before planting them in an urban area. In conclusion, the aforementioned vegetation characteristics were covered as a part of this review during the evaluation of vegetation impacts on air quality in different urban built environments.

### **3 Effect of green infrastructure on air quality in street canyons**

Street canyons are a commonly found urban feature and typically consists of buildings along both sides of the road (Kumar et al., 2011; Vardoulakis et al., 2003). Vegetation planted in street canyons are typically part of urban landscaping strategies and

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are periodically maintained by landscape professionals employed within or on behalf of the local authorities. Green infrastructure in the urban street canyon can be classified as trees and hedges and specific details for both types are discussed in Section 3.1 and Section 3.2, respectively.

### **3.1 Trees in street canyons**

Trees are widely employed as an environmental tool to improve urban outdoor climate and are planted and/or managed as part of the urban landscaping in streets, parks, and other common accessible spaces. This section focuses on the impact of tree design characteristics on air quality based on their proximity to traffic emissions sources in a street canyon. There are many examples of trees being placed along the two sides of the street, an avenue style of planting or a single tree stand in the middle (Hofman et al., 2016; Kikuchi et al., 2007; Li et al., 2013). The spacing between trees varies and the physical dimensions change with species (Amorim et al., 2013; Kikuchi et al., 2007). The tree canopy is elevated from ground surface creating a clear area about one or two meters and thus it is referred as high-level vegetation. On the other hand, hedges and bushes are mentioned as low-level vegetation as these have continuous leaf covering from the ground surface to top. It has been observed that trees can have an adverse effect on air quality within the street canyon (Gromke et al., 2008; Gromke and Ruck, 2007; Salmond et al., 2013; Vos et al., 2013). Trees can reduce the wind speed in a street canyon, resulting in reduced air exchange between the air above the roof and within the canyon and hence leading to accumulation of pollutants inside the street canyon (Buccolieri et al., 2015, 2009; Gromke et al., 2008; Gromke and Ruck, 2007; Kumar et al., 2009; Jeanjean et al., 2017). Thus, pollutant concentrations in a street canyon with trees show higher concentrations compared with those without trees. Apart from common vegetation characteristics listed in Section 2, the other unique factors of street canyon and trees that affect pollutant exposure are aspect ratio, wind direction and speed, spacing between trees, distance from pollutant source to trees and the sectional area occupied by trees of the street canyon (Abhijith and Gokhale, 2015; Amorim et al., 2013; Buccolieri et al., 2011; Gromke and Ruck, 2012; Jin et al., 2014; Salmond et al., 2013; Vos et al., 2013). In addition, previous research have introduced parameters such as street tree canopy density (CD) that is defined as the ratio of the projected ground area of

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tree crowns to the street canyon ground area (Jin et al., 2014), and crown volume fraction (CVF) that is defined as the volume occupied by tree crowns within a street canyon section (Gromke and Blocken, 2015). Key flow patterns and pollutant dispersion in street canyon with and without various vegetation are shown in Figure 1.

A limited number of field measurement based studies have assessed pollutant exposure in street canyons having trees inside them (Hofman et al., 2016, 2014, 2013; Hofman and Samson, 2014; Jin et al., 2014; Kikuchi et al., 2007; Salmond et al., 2013). Another strand of studies evaluated the impacts of trees on street level pollutant exposure through combined measurement and modelling studies (Amorim et al., 2013; Buccolieri et al., 2011; Hofman et al., 2016). These studies measured air pollutants at one or more locations in street canyons, which were then used for validating the model so that the validated model could yield concentration profiles inside the study area. These validated models also allow ‘scenario analysis’ by choosing desired locations and vegetation parameters for identifying the least pollution exposure scenario in the study area. As an effective tool, laboratory experiments in a wind tunnel (Gromke and Ruck, 2012, 2009, 2007) as well as dispersion and deposition modelling studies have extensively evaluated pedestrian pollutant exposure to local emissions sources in street canyons with trees (Balczó et al., 2009; Buccolieri et al., 2011, 2009; Gromke et al., 2008; Gromke and Blocken, 2015; Li et al., 2013; Moradpour et al., 2016; Ng and Chau, 2012; Ries and Eichhorn, 2001; Salim et al., 2011a; Salim et al., 2011b; Vos et al., 2013; Vranckx et al., 2015; Wania et al., 2012; Jeanjean et al., 2017). A comprehensive summary of these studies are provided in Supplementary Information, SI, Tables S1 and detailed technical detail with key finding are tabulated in SI Table S2.

### *3.1.1 Effect of wind flow conditions*

In general, all the studies summarised in Table 2 and depicted in Figure 3 reported reduction in wind velocities within the street canyons and an increase in pollutant concentration in street canyons with trees than without the trees (Amorim et al., 2013; Buccolieri et al., 2011; Gromke and Ruck, 2012; Hofman et al., 2016; Jin et al., 2014; Kikuchi et al., 2007; Ries and Eichhorn, 2001; Salmond et al., 2013; Vranckx et al., 2015; Jeanjean et al., 2017). The relevant studies reported an average increase of 26 to 96% in concentrations of different pollutants due to the presence of trees in street canyon compared

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with those without the trees (Figure 3). The presence of trees in street canyon led to reduced pollutant concentrations with an increase in wind velocity under different wind directions (Hofman and Samson, 2014; Wania et al., 2012). Typically, three main wind directions – perpendicular ( $90^0$ ), parallel (aligned,  $0^0$ ) or oblique ( $45^0$ ) – were investigated in street canyon studies with respect to those without the trees. The studies on an isolated street canyon with trees reported higher and lower concentrations along the leeward and windward side of the canyon, respectively, under the perpendicular flow. Under oblique wind and parallel flow conditions, an increase in pollutant levels on both sides was reported along with increasing pollutant concentrations towards the outer end of the canyon (Abhijith and Gokhale, 2015; Buccolieri et al., 2011; Gromke and Ruck, 2012; Wania et al., 2012). Of the three wind directions studied, perpendicular flow is the most commonly investigated (Figure 3). An oblique wind direction was identified as the worst scenario, resulting in an accumulation of pollutants on both sides of the canyon (Abhijith and Gokhale, 2015; Buccolieri et al., 2011; Gromke and Ruck, 2012).

Some studies also reported conflicting results for pollution distribution in the street canyons. For example, the parallel wind flow showed up to 16% improvement compared to the tree-free scenario, Table 2 (Amorim et al., 2013). Similarly, Jeanjean et al. (2017) observed reduction in pollutant concentration under parallel wind direction. The larger concentrations measured during parallel winds (with respect to the street canyon axis) were due to the channelling effect of pollutants emitted from an intense traffic corridor at the end of the canyon, while lower concentrations under perpendicular winds occurred due to the blockage of polluted air masses entering the street canyon (Hofman and Samson, 2014). Larger concentration changes were observed in street canyons that were aligned with the wind direction than street canyon with perpendicular wind direction (Gromke and Blocken, 2015). Furthermore, the detailed percentage change in pollutant concentration under various aspect ratio and wind direction of all studies considered in this review are given in Figure 3. These variations account for local conditions, which have a significant impact on pollutant distribution within the street canyon.

### 3.1.2 *Effect of aspect ratio and vegetation characteristics*

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There is a complex relationship between aspect ratios of street canyons and vegetation characteristics. The aspect ratio significantly affects pollutant dispersion because of alterations in air flow patterns (Zhong et al., 2016). As detailed in Table 2, the ‘street canyon’ investigated by past vegetation studies were mainly regular ( $0.5 < H/W < 2$ ), deep ( $H/W \geq 2$ ) or shallow ( $H/W \leq 0.5$ ) as classified by Vardoulakis et al. (2003). In a vegetation-free street canyon, higher pollutant concentrations were observed for large aspect ratios (Buccolieri et al., 2011; Ng and Chau, 2012); this is mainly due to the reduced wind velocity and pollutant accumulation in deep street canyons. In presence of trees with the same density, higher  $\text{NO}_x$  concentrations were measured in deep street canyons (Moradpour et al., 2016) than shallow street canyons. The simplest explanation, as reported in the several computational fluid dynamics studies, is that the main mechanism of pollutant removal in the regular street canyon is the primary vortex. In deep street canyons, the primary vortex is split into two and hence makes them less effective in removing in street pollutants with the clean air above.

When considering vegetation characteristics, Janhall (2015) remarked on the ambiguity in choosing LAD or porosity for dispersion and/or deposition among published studies that makes it challenging to directly compare results of various studies. Even though past studies by Balczó et al. (2009) and Gromke (2011) have analysed the relationship between density parameters, there is a need for standardisation in the selection of these parameters in future studies, dealing with the deposition and dispersion. Studies examining the impact of trees in street canyons have considered LAD ranging from 0.2 to  $5.12 \text{ m}^2 \text{ m}^{-3}$  and porosities between 96% and 99% as listed in Table 2. A number of studies noted an increase in pollutant concentrations with an increase in LAD and decrease in porosity due to pollutants accumulation inside the street canyons (Abhijith and Gokhale, 2015; Balczó et al., 2009; Buccolieri et al., 2009; Gromke et al., 2008; Gromke and Ruck, 2012, 2009; Kikuchi et al., 2007; Salim et al., 2011a; Salim et al., 2011b; Vos et al., 2013; Wania et al., 2012).

While assessing the impact of aspect ratio and vegetation characteristics together, the past studies reported increased pollutant concentrations at street level due to a combined effect of vegetation LAD, aspect ratio and wind direction (Buccolieri et al., 2009; Moradpour et al., 2016). For example, Buccolieri et al. (2011) observed that under perpendicular wind

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conditions, the concentration increased in a regular street canyon with trees compared with those in the tree-free shallow street canyon. However, for an inclined wind direction, higher concentrations were observed in the shallow street canyon with trees than those in the tree-free regular street canyon. This abnormality was partially clarified by Moradpour et al. (2016). They examined the combination of different vegetation densities and aspect ratios and determined the critical exposure conditions at the breathing height in a street canyon. The denser vegetation resulted in worsening the air quality. The larger regions of higher concentrations were observed in street canyons that have aspect ratios of 0.5, 1.0 and 2.0 with trees having LADs of 2.0, 1.5 and 1.0, respectively. Further studies assessing the combinations of wind directions, aspect ratios and LADs can provide a better understanding of the relationship between these variables.

Other important vegetation parameters are tree spacing, also known as stand density, and the cross-sectional area covered by them in street canyons. Increasing the spacing between tree crowns and/or lowering their cross-sectional areas can decrease pollutant concentrations in street canyons (Abhijith and Gokhale, 2015; Buccolieri et al., 2009; Gromke and Ruck, 2007; Ng and Chau, 2012). This variation in pollutant concentrations with tree spacing was found to be predominant in shallow street canyons than that in deeper canyons (Ng and Chau, 2012). Similarly, a numerical investigation showed a slight increase (1%) in pollutant concentration per unit percentage increase in CVF (Gromke and Blocken, 2015).

Different kinds of trees such as deciduous and evergreen produced seasonal changes in pollutant exposure in street canyon. During the summer seasons, pollutants were trapped in street canyon with deciduous trees, however, in winter, higher pollutant concentration was found in street canyon with evergreen trees (Jin et al., 2014; Salmond et al., 2013). Non-foliated deciduous trees had no effect on pollutant concentration during the winter season (Jin et al., 2014; Salmond et al., 2013). Similar to seasonal variations, Vranckx et al. (2015) simulated annual average changes in concentration in a shallow street canyon having trees under a variety of wind directions in a street canyon in Antwerp (Belgium). This study analysed deposition and dispersion of elemental carbon (EC) and PM<sub>10</sub> under different LADs, deposition speed ( $V_d$ ) and drag coefficients ( $C_d$ ). The reported annual average change ranged from 0.2–2.26% for PM<sub>10</sub> and 1–13% for EC. The presences of trees caused a lesser

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increase in PM<sub>10</sub> concentrations in comparison to EC and NO<sub>2</sub> (Vos et al., 2013), with the similar observation made for EC in a study by Vranckx et al. (2015).

### **3.2 Hedges in street canyons**

Hedges or hedgerows consist of shrubs and bushes which grow less in size compared to trees and they are typically located at ground level, therefore typically representing the closest type of green infrastructure that exists to local emissions sources in an urban street canyon. Therefore, their performance for improving air quality is dominated by its ability to remove local sources of emissions and this is reflected in the results. They are usually planted along boundaries to serve as fencing or a living boundary wall. The shape of the hedgerows is commonly well maintained to a cuboidal or the other definite shapes (such as cuboidal bottom and spherical top) in the heavily built-up areas. Whereas, these may be allowed to grow with less pruning and maintenance along the sides of major highways. These low-level vegetation are usually a mixture of shrubs and other small vegetation. Hedges have comparatively less height and thickness than trees but possess higher leaf density.

Similar to trees in street canyons, hedges are planted along the streets in various configurations. Only a few studies examined the air pollution reduction potential of hedges in street canyon (Chen et al., 2015; Gromke et al., 2016; Li et al., 2016; Vos et al., 2013; Wania et al., 2012). Key findings are provided in Table 3 and further detailed summaries are documented in SI Table S4. Three of these studies observed that hedges reduced pollutant exposure by 24 to 61% at the footpath areas in street canyons (Figure 3). However, Vos et al. (2013) reported an increase in pollutant concentration with the presence of hedges in street canyons. Although, the study stated that it mainly focused on the general trend in pollutant concentrations with multiple vegetation scenarios in a built-up environment. Hence, the above observation should be generalised cautiously by considering them as an outcome of an individual scenario.

Matching to the effect of trees on wind velocity in street canyons, hedges were found to reduce wind velocity with-in street canyon (Gromke et al., 2016; Li et al., 2016; Wania et al., 2012) but the effects on the wind velocity were lesser than trees (Wania et al., 2012). Hedges diverted air pollutant from reaching footpath area by generating local vortices

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(Gromke et al., 2016; Li et al., 2016). Low permeable and higher (2.5m) hedges showed more pollutant reduction at the footpath area. While a central single hedgerow (in the middle of the street canyon) showed maximum concentration reduction in street canyon compared to hedgerows along both sides of roads (Gromke et al., 2016). The optimum height of a hedge was obtained through simulation by assessing its sensitivity to wind velocity and aspect ratio of street canyons (Li et al., 2016). This resulted in an optimum height between 1 and 2m in both shallow as well as regular street canyons. Maximum pollutant reduction occurred at breathing height along the foot path of two shallow street canyons ( $H/W = 0.18$  and  $0.4$ ) with a hedge of 2m height. Likewise, maximum pollutant reduction observed in the regular street canyon ( $H/W = 0.78$ ) with a hedge of 1.1m height. Gromke et al. (2016) observed a maximum reduction in pollutant concentration in the shallow street canyon with a hedge of 2.5m height. The above studies suggest an optimum height of hedges in shallow street canyons to be about 2m but further studies under different street aspect ratios are warranted to generalise the hedge heights.

#### **4 Effect of green infrastructure on air quality in open roads**

An open road is an urban built environment feature in which both sides of the traffic corridor are open with generally detached, single or multi-story buildings and other manmade structures. In open road conditions, trees as well as other vegetation such as hedges, shrubs and bushes, are planted or occur naturally along one or both sides of these corridors, and are referred to as ‘vegetation barriers’ or ‘green belts’ (Brantley et al., 2014; Chen et al., 2015; Islam et al., 2012; Morakinyo and Lam, 2016). These green belts offer a number of additional benefits including heat island mitigation, water runoff control and for aesthetic purposes (Escobedo et al., 2011). The role of vegetation barriers along open roads is examined in more detail in subsequent sections.

##### **4.1 Vegetation barriers**

In open roads conditions, vegetation can act differently than in street canyons. Nevertheless, rows of planted trees and other vegetation types provide a barrier between the road and population groups in adjacent residential areas, similar to that observed in a street canyon environment. This barrier effect leads to an accumulation of pollutant concentrations on the windward or upwind side of the vegetation, for example as observed in front of a



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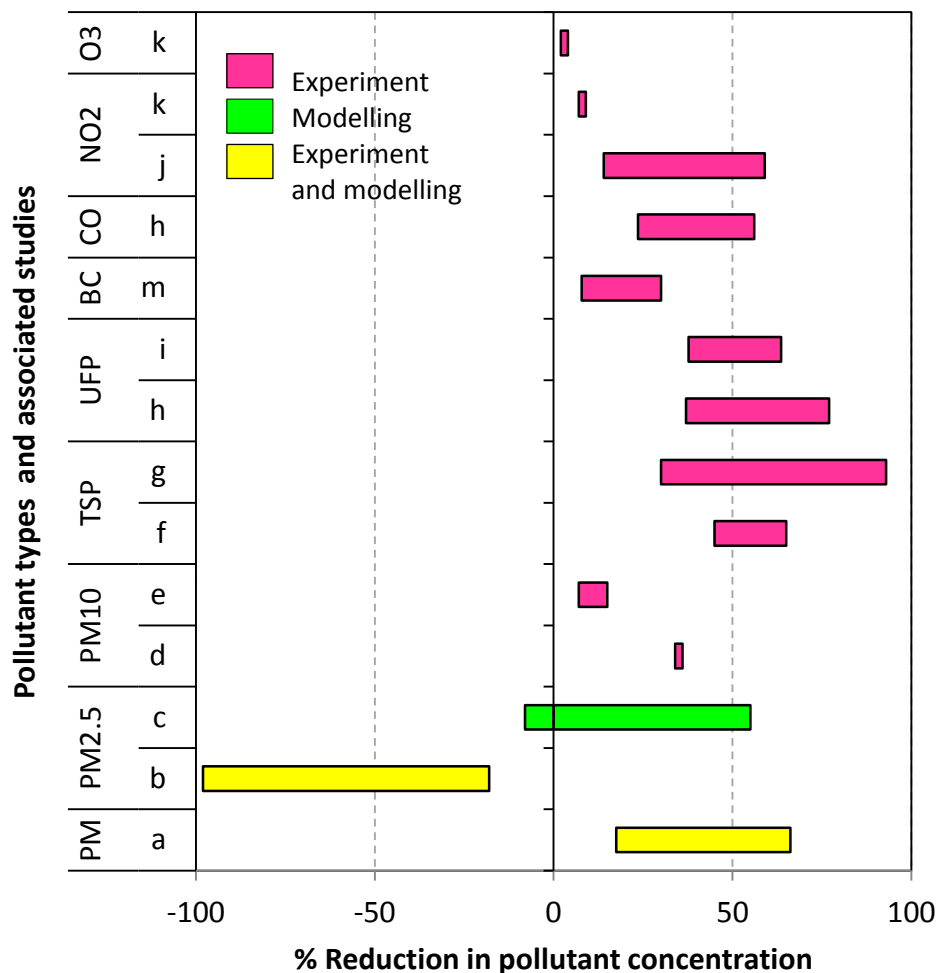
hedge by Al-Dabbous and Kumar (2014). Vegetation barriers force polluted air to flow either over or to pass through the vegetation, and this is dependent upon porosity and physical dimensions (Tong et al., 2016). Low density (high porosity) vegetation results in the majority of air flowing through the barrier, whereas high density (lower porosity) leads to little or no infiltration, similar to the behaviour evident around solid barriers like low boundary walls (Baldauf et al., 2008; Bowker et al., 2007; Brantley et al., 2014). Downwind of vegetation barriers i.e. behind the vegetation, a wake zone is created and pollutant concentrations decrease with increasing distance from the road. The formation and extension of a wake zone, pollutant concentration profile before and after vegetation, and pollutant deposition and dispersion within the barrier are controlled by wind direction and speed, position of vegetation, physical characteristic of the green belt (such as thickness, height and porosity), temperature, relative humidity, and the physical characteristics of leafs (Baldauf, 2017). A graphical representation of flow and pollutant dispersion patterns in open-road conditions are depicted in Figure 2. In addition to the vegetation parameters described in the previous section, some studies considered shelterbelt porosity, which is the ratio of perforated area to the total surface area exposed to the wind (Islam et al., 2012), and is defined as the fraction of light that vertically penetrates tree cover for a given section (Yin et al., 2011).

In contrast to street canyon investigations, most green infrastructure studies examining pollution exposure in open road environments followed an experimental approach (Al-Dabbous and Kumar, 2014; Brantley et al., 2014; Chen et al., 2016; Chen et al., 2015; Fantozzi et al., 2015; Grundström and Pleijel, 2014; Hagler et al., 2012; Islam et al., 2012; Lin et al., 2016; Shan et al., 2007; Tiwary et al., 2008; Tong et al., 2016, 2015). In these cases, the source of emissions is predominantly linked to the adjacent roadway. However, in comparison to an urban street canyon environment, the contribution of background concentrations represent a lesser fraction of localised air pollution in these scenarios. A small number of studies either combined measurement and modelling (Morakinyo et al., 2016; Tiwary et al., 2005) or solely employed a modelling methodology (Morakinyo and Lam, 2016, 2015; Neft et al., 2016; Tiwary et al., 2005). A comprehensive summary of vegetation effects in open-road conditions and detailed technical features with key findings are given in SI Tables S5 and S6, respectively. The literature provided a number of

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examples of the positive effect of trees and bushes on air quality i.e. reducing pollutant concentrations at the street scale (Al-Dabbous and Kumar, 2014; Brantley et al., 2014; Chen et al., 2015; Islam et al., 2012; Lin et al., 2016; Shan et al., 2007; Tiwary et al., 2008, 2005; Tong et al., 2016), with some cases having mixed and limited effects (Chen et al., 2016; Fantozzi et al., 2015; Grundström and Pleijel, 2014; Hagler et al., 2012), or negative effects (Morakinyo et al., 2016; Tong et al., 2015) with details shown in



**Figure 4.** As shown in Figure 4, the majority of the studies reported reductions in concentrations of between 15% and 60% for various pollutants with vegetation barriers along open roads. Most of the field measurement studies comparing downwind concentrations with and without the vegetation include background levels as part of their measurements. However, this is usually not the case with most of the modelling/wind tunnel studies that only account for the traffic emissions. Recently, Baldauf (2017) detailed

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the physical characteristics of vegetation barriers that influence air quality results, some of which are discussed in further details in the following sections.

#### *4.1.1 Effect of thickness and density of green belt on air quality*

The thickness and density of a green belt is a predominant physical characteristic that can alter near-road pollution exposure (Islam et al., 2012; Morakinyo and Lam, 2015; Neft et al., 2016; Shan et al., 2007). An increase in the thickness of a vegetation barrier can result in a direct reduction of pollutant concentrations (Neft et al., 2016; Tong et al., 2016), with a linear correlation to increasing filtration efficiency (Neft et al., 2016). Morakinyo and Lam (2016) reported pollutant removal/reduction from hedges can be positive or negative and it is not uniform across height and length from the barrier. Supporting this, Hagler et al. (2012) observed lower, higher and similar concentrations behind vegetation barriers when compared to open areas, as well as Lin et al. (2016) reporting differences in concentrations at different heights, with these variations in results due to irregular density characteristics along the length of the vegetation barriers examined. Morakinyo and Lam (2016, 2015) proposed the need for design in locating hedges and the selection of a suitable thickness for these barriers, recommending the distance between the source and plume's maximum concentration (DMC) and placing tree rows or vegetation barriers close to the source or behind the DMC, ensuring sufficient thickness to cover the DMC and a height close to plume height. Similarly, studies by Islam et al. (2012) and Neft et al. (2016) recommended a minimum vegetation thickness of 5 m and 10 m to remove approximately 50% of total suspended particles (TSP) and nanoparticles (20 nm), respectively. In addition, Shan et al. (2007) recommended a minimum thickness of 5 m and an optimum thickness of 10 m for a minimum removal rate of 50% for TSP. Islam et al. (2012) proposed a structure of green belts in which hedges or smaller shrubs were placed in front and trees behind to improve TSP removal. The limited number of studies on this topic suggest that further investigation of the relationship between vegetation characteristics and emissions intensity is necessary prior to proposing practical recommendations on the thickness of a selected vegetation barrier to achieving specified desirable pollutant concentration reductions.

Densities of vegetation belts are commonly expressed in terms of LAD, canopy density (CD), and shelterbelt porosity. Canopy density is defined as the ratio between the projected

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area of the canopy and the total ground area of the green belt/forest. Pollutant removal improved with an increase in CD and LAD and decreased with an increase in shelter belt porosity (Chen et al., 2016; Islam et al., 2012; Shan et al., 2007; Tong et al., 2016), yet reductions in pollutant concentration were non-linear with respect to LAD (Steffens et al., 2012; Tong et al., 2016). An optimum CD of 70-85% was recommended for 50% or more TSP reduction and for maintaining a healthy green belt (Shan et al., 2007). Optimum shelter belt porosity proposed by studies were 20-40% and 10-20% for TSP and PM<sub>10</sub> respectively (Chen et al., 2016; Islam et al., 2012). Shan et al. (2007) observed that shelter belt porosity of less than 25%, the percentage of TSP removal was stable, recommending an optimum shelter belt porosity of 25-33% for 50% or more TSP removal. Increasing the canopy density over 85% and the shelter belt porosity over 40% resulted in a decrease or no change in pollutant removal as the vegetation was no longer acting as a permeable structure, and more like a solid barrier (Islam et al., 2012; Shan et al., 2007).

#### 4.1.2 *Effect of meteorological and climatic factors on air quality*

Meteorological factors such as humidity, wind speed, wind direction and temperature are also known to affect neighbourhood air quality near open roads. The past studies revealed that the highest impact on PM<sub>10</sub> removal was exerted by relative humidity, followed by the wind speed and the least by temperature (Chen et al., 2015). Similarly, Fantozzi et al. (2015) observed high NO<sub>2</sub> concentrations with high relative humidity and low temperature. This indicates the important role of relative humidity in local air pollutant exposure analysis. Studies observed an increase in pollutant concentration with an increase in speed (Brantley et al., 2014; Morakinyo et al., 2016). Studies that examine wind direction have predominantly focused on assessing downwind pollutant concentrations in perpendicular wind conditions, with results suggesting that the greatest reductions occur behind the vegetation barriers for this wind direction (Brantley et al., 2014).

In addition to meteorological factors, seasonal variations and different climates impact the role of vegetation belts on pollutant exposure (Fantozzi et al., 2015; Grundström and Pleijel, 2014; Shan et al., 2007). Seasonal variations in pollutant concentration were captured through field assessments, with trees presenting the greatest improvement in air quality in summer (Fantozzi et al., 2015; Islam et al., 2012; Shan et al., 2007). Deciduous trees had no

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effect on PM removal in winter, with similar concentration measured in open areas with no trees (Hagler et al., 2012; Lin et al., 2016). Evergreen trees are commonly planted along open roads to promote pollutant reductions in all seasons (Baldauf et al., 2013; Islam et al., 2012; Shan et al., 2007). When it comes to climatic zone, warmer climatic regions such as China, Bangladesh and Italy (evidence in SI Tables S5 and S6) showed significant reduction in pollutant concentrations with vegetation barriers (Chen et al., 2016; Chen et al., 2015; Fantozzi et al., 2015; Islam et al., 2012), while cooler climatic regions such as Sweden and Finland showed limited or no change in pollutant concentration with vegetation (Grundström and Pleijel, 2014; Setälä et al., 2013). No particular explanation for these differences was provided in these studies and warrant further investigations, therefore further research is required in future investigations to support recommendations for the role of green infrastructures in air pollution abatement.

Chen et al. (2016) observed that grass was ineffective in capturing PM<sub>2.5</sub> in comparison to trees and shrubs. Significant deposition of PM on herbaceous plants was measured along open roads with different traffic intensities in Berlin (Weber et al., 2014). The study observed that the rate of deposition on plant leaves depended on the intensity of traffic emissions, leaf characteristics and plant height.

## **5 Vegetation on building envelopes as a passive air pollution control measure**

Green walls and green roofs are developed as sustainable building strategies which can increase vegetation cover in built up areas without consuming space at street level. These green infrastructure types were introduced for aesthetics purposes, but nowadays they are maintained and improved to create a sustainable urban environment. Green walls and roofs contribute to passive energy savings, reductions in ambient temperature and mitigating the urban heat island effect, storm water management, air pollution mitigation, noise reduction and urban biodiversity (Berardi et al., 2014; Hunter et al., 2014; Manso and Castro-Gomes, 2015; Pérez et al., 2014, 2011; Vijayaraghavan, 2016). Previous studies mainly focused on thermal performances and energy savings of green walls and green roofs. However, unlike other green infrastructures such as trees and hedges, these forms of vegetation are directly attached to building surfaces and have not been considered as a measure of air pollution abatement.

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## 5.1 Green walls

Green walls are vegetated vertical surfaces where plants are attached to the surface through various mechanisms. Green walls are broadly classified as ‘green facades’ or ‘living wall’. Green facades are created by directly attaching hanging pots or shrubs to the wall (direct green façade), or attached the plants to the wall using special supporting features such as cables, ropes, mesh and modular trellises (indirect green facades or double skinned green facades). Living walls are created by attaching growing media to the vertical wall, and this relatively new technique is classified as ‘continuous living walls’ or ‘modular living walls’ (Manso and Castro-Gomes, 2015; Pérez et al., 2014, 2011; Susorova, 2015). A schematic representation of how green walls impact air flow and pollutant dispersion in street canyon and open road environments are shown in Figure 1d and Figure 2d, respectively. Green walls can improve air quality and improve air quality from both local emission sources and background concentrations, depending on the contribution each source of pollution.

Limited studies have assessed the reduction of air pollution due to green walls at a local scale in the built environment, but these studies have recognised the potential capabilities of pollution removal (Joshi and Ghosh, 2014; Ottelé et al., 2010; Sternberg et al., 2010). Litschike and Kuttler (2008) recommended green walls as one of the planting concepts to reduce particulates through deposition without altering air exchange between the street canyon and air above it. Detailed summaries and important observations are listed in SI Table S7. Pollutant reduction along with a footpath in open roads (Morakinyo et al., 2016; Tong et al., 2016) and in a street canyon (Pugh. et al., 2012) have been presented in research findings. Moreover, other studies on green walls reported effective collection of pollutants by the vegetation on the green wall (Joshi and Ghosh, 2014; Ottelé et al., 2010; Sternberg et al., 2010). Figure 5a presents the results from published studies on green walls relating to pollutant concentrations. A city scale study showed significant improvement in air quality with the green wall (Jayasooriya et al., 2016), but reductions were not as substantial as the impact of trees (Jayasooriya et al., 2016; Tong et al., 2016). In open road conditions, a green wall resulted in dispersion patterns similar to the solid wall as a high concentration region in front of barrier (on road) and reduction behind the green wall (Morakinyo et al., 2016; Tong

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et al., 2016). In addition, vegetation cover on the wall removed pollutants through deposition (Joshi and Ghosh, 2014; Morakinyo et al., 2016; Tong et al., 2016). In a street canyon environment, green wall improved air quality in different street canyon aspect ratios ( $H/W = 1$  and 2), with reductions of up to 35% for  $\text{NO}_2$  concentration and 50% in  $\text{PM}_{10}$  concentration (Pugh. et al., 2012). Common climbing plants such as ivy (UK) and Lianas species (in China) were found suitable for the green wall (Chen et al., 2016; Ottel  et al., 2010; Sternberg et al., 2010). The removal potential of pollutants using a green wall was shown to be influenced by street canyon geometry, wind speed, humidity and LAI (Joshi and Ghosh, 2014; Pugh. et al., 2012). No variations in particle depositions were observed at different heights of the green wall near a traffic corridor (Ottel  et al., 2010). A study by Pandey et al. (2014) suggests that air pollution tolerance should be measured prior to selecting species for the green wall. These observations were made based on limited previous research, and further investigations are required to produce recommendations for determining the role of green walls on air quality.

## 5.2 Green roofs

A green roof is a vegetation planted on the roof of a building. Plants are cultivated on a growth media prior to being placed on the building rooftop and can consists of diverse vegetation, from mosses to small trees, growing substrate, filter and drainage material, root barrier, and insulation (Vijayaraghavan, 2016). These are classified as extensive, semi-intensive and intensive green roofs (Berardi et al., 2014; Vijayaraghavan, 2016). The location of this green infrastructure measure suggests that it may improve air quality by reducing pollutant concentrations from local emissions sources as well as background contributions. The most commonly adopted system is an extensive system which has a thin substrate layer with smaller plants such as grasses and mosses, due to its low capital cost, low weight and minimal maintenance. Whereas an intensive system requires high maintenance because of the thick substrate layer, which accommodates larger plants such as small trees, and this required more investment. A semi-intensive system is a hybrid option with a moderate substrate, maintenance, and capital cost. A typical green roof on a building in street canyon is showed in Figure 1d. Green roofs help reducing energy consumption, managing runoff water, mitigating the urban heat island effect, air pollution mitigation and

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noise pollution and enhance ecological preservation (Berardi et al., 2014; Castleton et al., 2010; Czemieli Berndtsson, 2010; Oberndorfer et al., 2007; Saadatian et al., 2013; Vijayaraghavan, 2016).

Despite a number of studies examining various aspects of green roof, limited research has been emphasised on air quality improvement capabilities of green roofs (Baik et al., 2012; Berardi et al., 2014; Currie and Bass, 2008; Li et al., 2010; Rowe, 2011; Speak et al., 2012; Tan and Sia, 2005; Yang et al., 2008). Most studies noted significant pollutant removal by green roofs, despite being inferior to trees at both local scale (Speak et al., 2012) and city scale (Currie and Bass, 2008; Jeanjean et al., 2015). Low surface roughness and distance away from pollutant source were found as reasons for its lower impact (Speak et al., 2012). Detailed information on previous studies and their observations are given in SI Table S8. The cooling effect of a green roof and its impact on air quality in street canyons demonstrated a potential 32% reduction in pollutant concentrations with 2<sup>o</sup>C cooling intensity at breathing level, due to enhanced canyon vortices and higher vertical dispersion arising from downward moving cool air (Baik et al., 2012). In comparison, Pugh. et al. (2012) recorded marginal pollutant removal by a green roof with no recognition of the associated cooling effect. Roofs near a traffic corridor exhibited a significant improvement of air quality (Speak et al., 2012) and the quantity of fine particles (less than 0.56 µm) emitted from vehicle sources decreased by 24% (Tan and Sia, 2005). The results for pollutant concentration reductions for studies with green roofs are summarised in Figure 5b. The removal rate of green roofs is influenced by wind conditions, seasonal variations, plant characteristics and species, and green roof location (Currie and Bass, 2008; Li et al., 2010; Speak et al., 2012; Yang et al., 2008). Intensive green roofs can further increase pollutant removal (Currie and Bass, 2008; Yang et al., 2008). Green roofs have potential to be used as a method of air pollution abatement in combination with green walls.

## **6 Combination of green infrastructure with solid/nonporous (passive) objects**

Solid passive methods such as noise barriers, low boundary walls, and parked cars can improve local air quality and detailed strengths and limitations of these physical interventions are reported in a comprehensive review by Gallagher et al. (2015). However, the combined effect of solid passive methods and vegetation on neighbourhood air quality is



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something that has only received limited attention (Abhijith and Gokhale, 2015; Baldauf et al., 2008; Bowker et al., 2007; Tong et al., 2016). Furthermore, the combination of these interventions is realistic of what is evident in the urban environment. In research findings to date, the combination of these air pollution control measures improves pollutant dispersion characteristics for better air quality at local scales when compared to that obtained with individual interventions.

Some arrangements of passive methods complemented one another in reducing pollutant exposure than individual reductions. A modelling study by Bowker et al. (2007) observed a combination of trees and solid noise barriers resulted in enhanced dispersion leading to reduced pollutant concentration in downwind locations. Similarly, trees with a noise barrier caused additional mixing and turbulence, as well as filtering of airborne particles by trees, leading to consistent concentration reductions. As reported by Baldauf et al. (2008), CO and PM concentrations were reduced immediately behind a solid noise barrier and vegetation along an open road, in comparison to the case of no inclusion of vegetation, both scenarios providing better downwind air quality than no noise and/or vegetation barriers. The lowest PM number concentrations were observed behind the noise barrier with trees along the entire distance measured from the road. These studies demonstrate the role of additional green infrastructure to promote deposition in conjunction with dispersion of localised emissions. Combining trees with on-street car parking demonstrated how the combination of interventions had a greater impact on air quality than the vegetation only case (Abhijith and Gokhale, 2015), and smaller trees with spacing and high porosity combined with parallel parking reduced pedestrian exposure in parallel and perpendicular winds (Gallagher et al., 2013, 2011). An arrangement of trees on the windward side of the street, in combination with perpendicular car parking, improved air quality in oblique wind conditions (which is considered to be most polluted wind direction, section 3.1). The combination of parked cars and trees presented the best air quality improvements for local source emissions. However, it is dependent on a combination of tree porosity, parking bay and local wind characteristics. For example, oblique car parking systems with trees showed an increase in pollutant concentration in street canyon (Abhijith and Gokhale, 2015). Vegetation-solid wall combinations were also examined for multiple near-road conditions using modelling by

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Tong et al. (2016). The study identified that the largest pollutant reductions occurred when a solid wall and vegetation barrier were combined.

The findings indicate that special arrangements for combining vegetation and solid passive methods could provide lower pollutant exposure in both street canyon and open road conditions. Further real-world studies are needed for validation and practical application of outcomes.

## **7 From measurements, modelling and experiments to delivering policy change**

The current status of research relating to the performance of green infrastructure on air quality presents a strong indication of its potential to mitigate pollution and has identified existing gaps in knowledge that still need to be addressed. However, transferring the findings of existing and future research into proposed generic recommendations is presented as the next milestone in this field.

Firstly, the findings from previous measurement studies have demonstrated the potential of green infrastructure for reducing personal exposure in street canyons and open roads under real world conditions. However, these studies have been restricted by their inability to directly compare precisely the same environment with and without green infrastructure, due to the timeframe required to implement mature trees, hedgerows or green roofs or walls in the same location. Therefore modelling and wind-tunnel experiments have been adopted and current findings originate from these studies as they allow for this comparison. However, their ability to replicate complex real-world meteorological conditions and traffic flow characteristics may provide uncertainty in these findings. In terms of developing recommendations, the use of modelling and experimental work can provide a strong indicator as to the expected performance of urban vegetation to affect local air quality, but validation of these findings are required from the data collected from previous measurement studies.

Secondly, the future for this research topic needs a focus on collating additional results from measurement studies in different meteoroidal and geometrical configurations. It also needs to encourage the openness of raw data from these studies to allow researchers using

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modelling and experiments to validate their findings. The development of generic recommendations requires a combined approach of each of these methods, as street canyon and open road environments are complex and subject to change. Therefore, the reach of measurement studies is constrained by budgets, while the ability of modelling tools can extrapolate findings for different climates and environments. The use of green infrastructure can play a part in responsive solutions to air pollution, and be more than aesthetic and cultural benefits.

There is a level of uncertainty in modelling and experimental results that does not exist in measurement studies, and only through further research can this be addressed. It also highlights the importance of this study and the synthesis of existing findings, to direct the next steps for green infrastructure research in terms of providing future guidance through generic recommendations to improve air quality in the urban environment.

## **8 Summary, conclusions and future outlook**

Available studies on the air quality impacts of vegetation placed in street canyons, open roads, and building envelopes were reviewed. The whole process of assessments was focused on understanding how air quality is affected by different types of vegetation under specific urban environments. This review analysed and listed factors affecting air quality such as urban morphology, meteorological conditions, vegetation characteristics, and observed both favourable and critical air pollution scenarios created by them. The common vegetation characteristics influencing neighbourhood air quality were discussed. Local scale pollutant exposure alterations made by street trees and hedges were recorded. Likewise, air quality changes due to green belts in open road conditions and vegetation on building envelopes such as green roofs and green walls were reviewed. The study focused on changes in pollutant concentration made by urban vegetation so that emerging findings can be used by urban planners for practical application. In addition, areas with a deficit in our knowledge or requiring further evidence are also identified for consideration by future studies to advance this research field.

The key conclusions arising are as follows:

- In a *street canyon* environment, high-level green infrastructure (i.e. trees) generally has a negative impact on air quality while low-level dense vegetation with complete

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coverage from the ground to the top of the canopy (i.e. hedges) hinder the air flow underneath and hence generally show a positive impact. Even though an oblique wind direction was identified as critical; improvements or deteriorations in air quality in a street canyon depended upon a combination of aspect ratio, vegetation density and wind direction. Increasing the spacing between trees and reducing the cross-sectional area occupied by tree canopies (through increased pruning and selecting smaller trees) can usually reduce street level personal exposure through increased ventilation. Available real world studies showed that surrounding built-up geometry can alter pollutant concentration profiles in street canyons. It was also noted that the predominant source of pollution in a street canyon environment was vehicular emissions, therefore the findings may reflect upon their impact on local emission sources more so than the background pollutant contributions. There are a limited number of studies examining hedges in street canyons, with results showing improvements in air quality and a proposed optimum height of hedge in shallow street canyons; detailed studies are required to provide favourable hedge dimensions and densities in different aspect ratios and meteorological conditions.

- In *open road* conditions, vegetation barriers have a positive impact on air quality with thick, dense and tall vegetation. Studies observed considerable pollutant removal through designing vegetation barriers closer to the pollutant source and plume's maximum concentration. In excess of a 50% reduction was observed with a 10m thick green belt for numerous pollutants. The optimum density for a vegetation barrier was suggested by various studies. Evergreen species and other vegetation not prone to seasonal effects were proposed for vegetation barriers in open-road conditions. In a similar manner to research findings from street canyon studies, the source of pollutants (i.e. local or background) was not differentiated in open road studies, but these mitigation measures were also considered to have a more significant impact upon local emission sources. Relative humidity showed significant impact on pollutant removal by green belts indicating that climate and regional conditions need to be considered. The impact of vegetation on air quality varied between warmer and cooler climatic regions, which needs further investigation.

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- Vegetation density has been represented by often dissimilar parameters in published investigations. This study observed the need for standardisation in expressing vegetation density, as it is important to facilitate a comparison of study outputs and to create generalised recommendations.
- The combination of vegetation and solid passive air pollution control measures has the potential to maximise the reduction in pollutant concentrations and improve personal exposure conditions, more than that achieved any individual intervention in both street canyon and open road conditions.
- Only a small number of studies investigated air quality improvements for green roofs and green walls. Reported reduction in air pollutants with green walls ranged up to 95% and in the case of the green roof, the same was 2% to 52%. However, their ability to remove pollutants were lesser compared to trees and vegetation barriers. Pollution reduction of green roofs was inferior to the green wall. These interventions require less spatial requirements than trees and green belts and can be part of building surfaces and structures such as bridges, fly-overs, retaining walls, and noise barriers. Further investigations are required to produce generic recommendations.

This review identified similarities in the designs and conditions of vegetation to achieve air quality benefits in open road and street canyon environment, although street canyon configurations are more complex and less easy to provide generic recommendations. Prior to implementing vegetation in street canyons, pilot modelling investigations can give possible locations and vegetation parameters to maximise its impact for least polluted conditions. Future investigations should focus on the impact of the relationship between vegetation and climatic zone, on air quality. Future studies should also focus on air pollution control potential of green roofs and green walls as both can be implemented in cities without consuming additional space.

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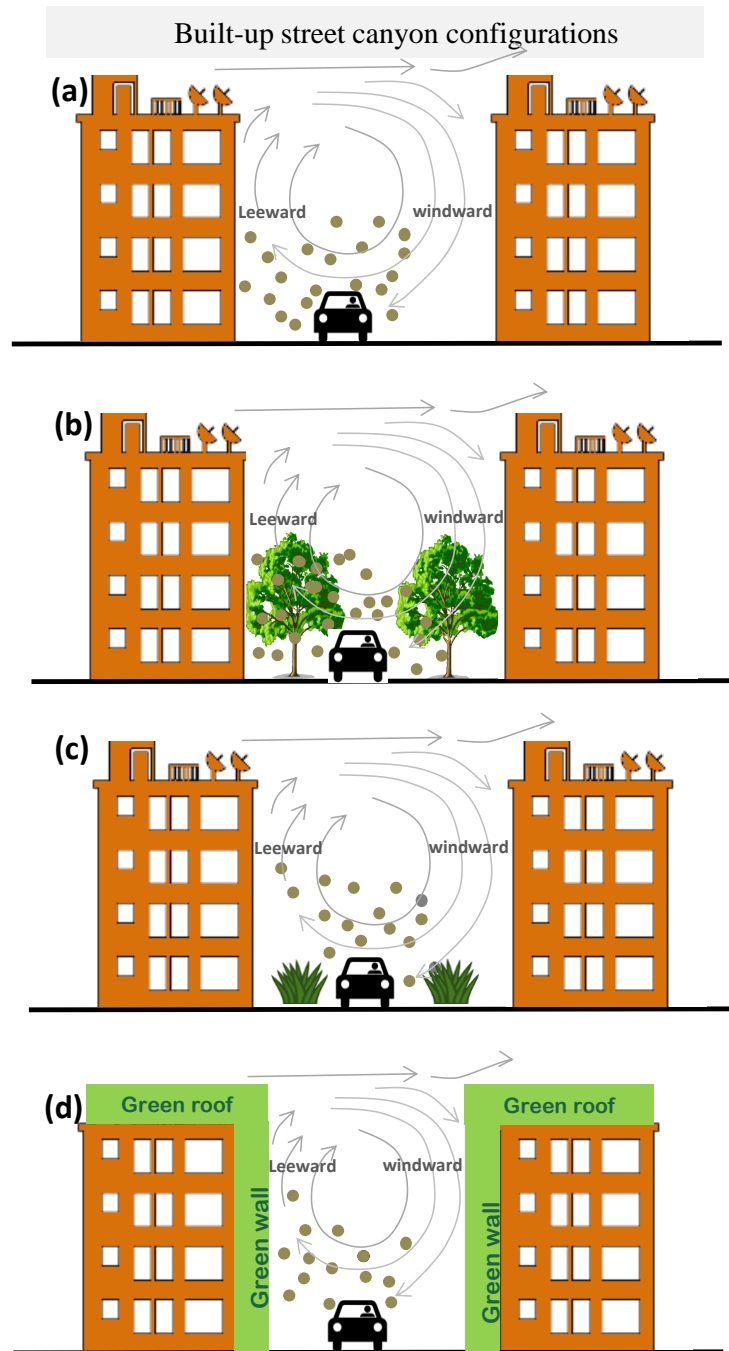
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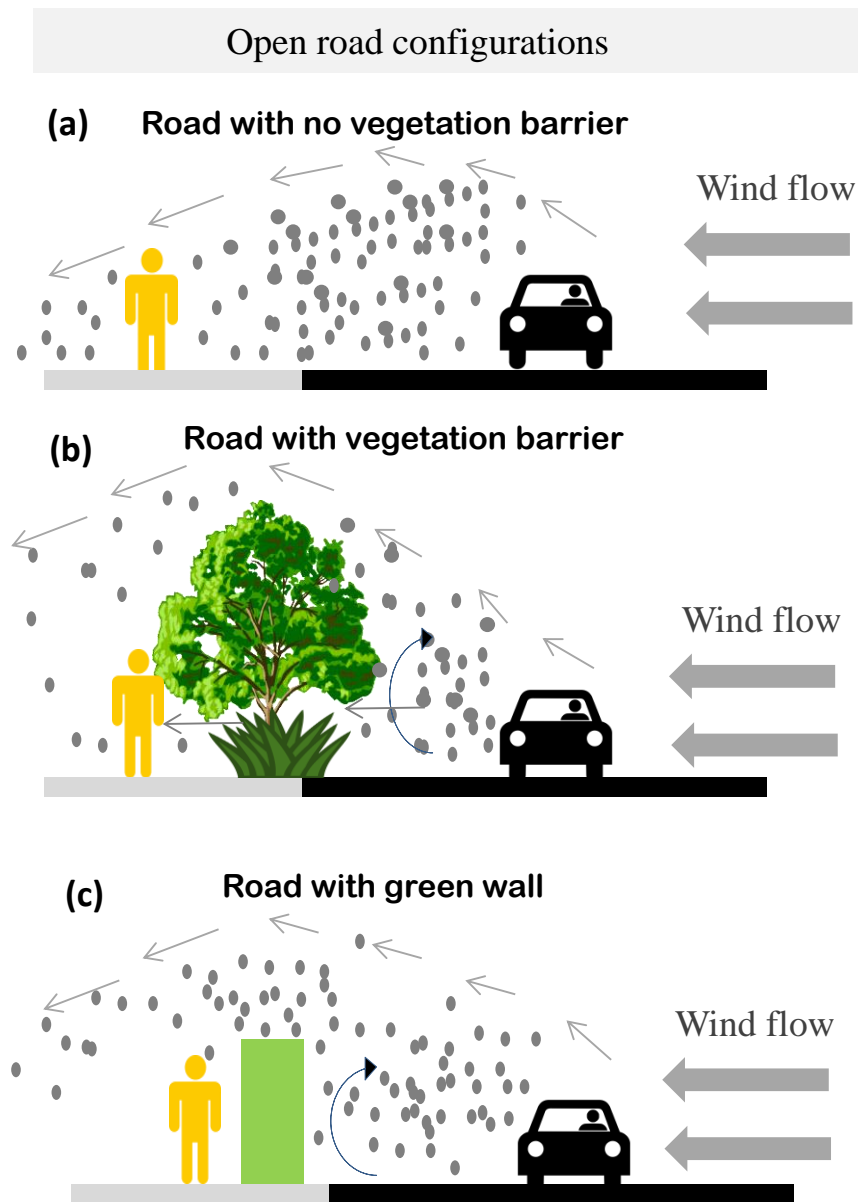


**Figure 1.** Description of flow and pollutant dispersion patterns in a street canyon with and without different types of vegetation: (a) vegetation free street canyon, (b) street canyon with trees, (c) street canyon with hedges, and (d) street canyon with green roof and green wall.

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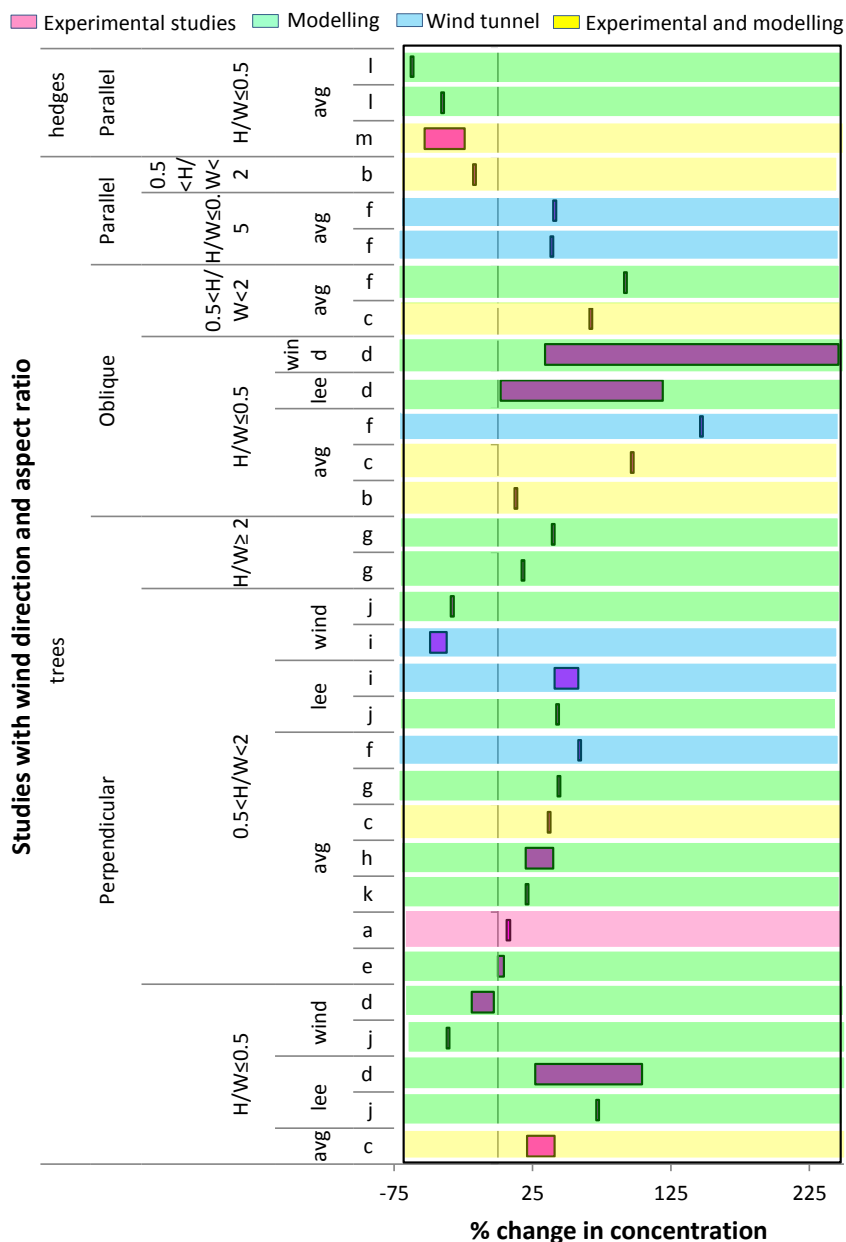


**Figure 2.** Dispersion patterns of road pollutants under open road configurations (a) without vegetation barrier (b) with vegetation, and (c) with green wall.

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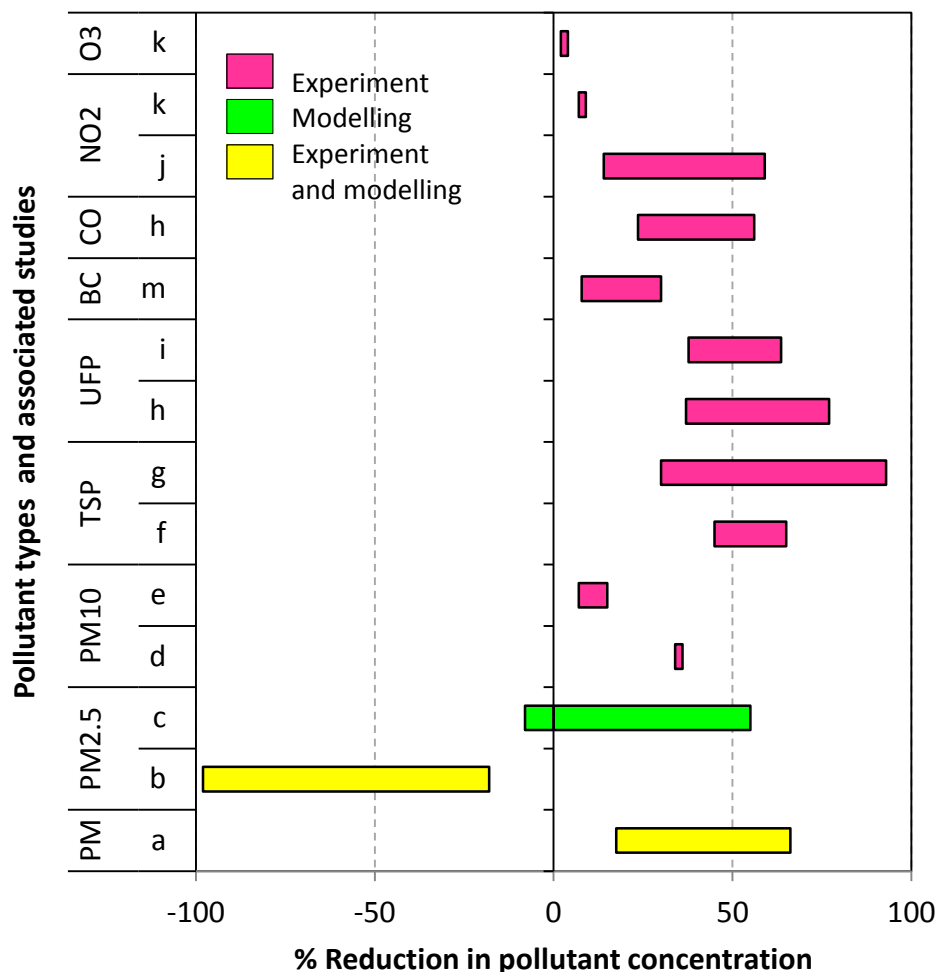


**Figure 3.** Figure depicts published percentage change in different pollutant concentration with trees and hedges in street canyon compared to vegetation free scenario. Positive changes denote increase in pollutant concentration and negative change show reduction in pollutant concentration. Please note that bar shown are reported range of pollutant change by studies. The following letters refer to the work from: (a) Jin et al. (2014), (b) Amorim et al. (2013), (c) Buccolieri et al. (2011), (d) Abhijith and Gokhale (2015), (e) Li et al. (2013), (f) Gromke and Ruck (2012), (g) Ng and Chau (2012), (h) Balczó et al. (2009), (i) Gromke and Ruck (2009), (j) Buccolieri et al. (2009), (k) Ries and Eichhorn (2001), (l) Gromke et al. (2016), and (m) Li et al. (2016).

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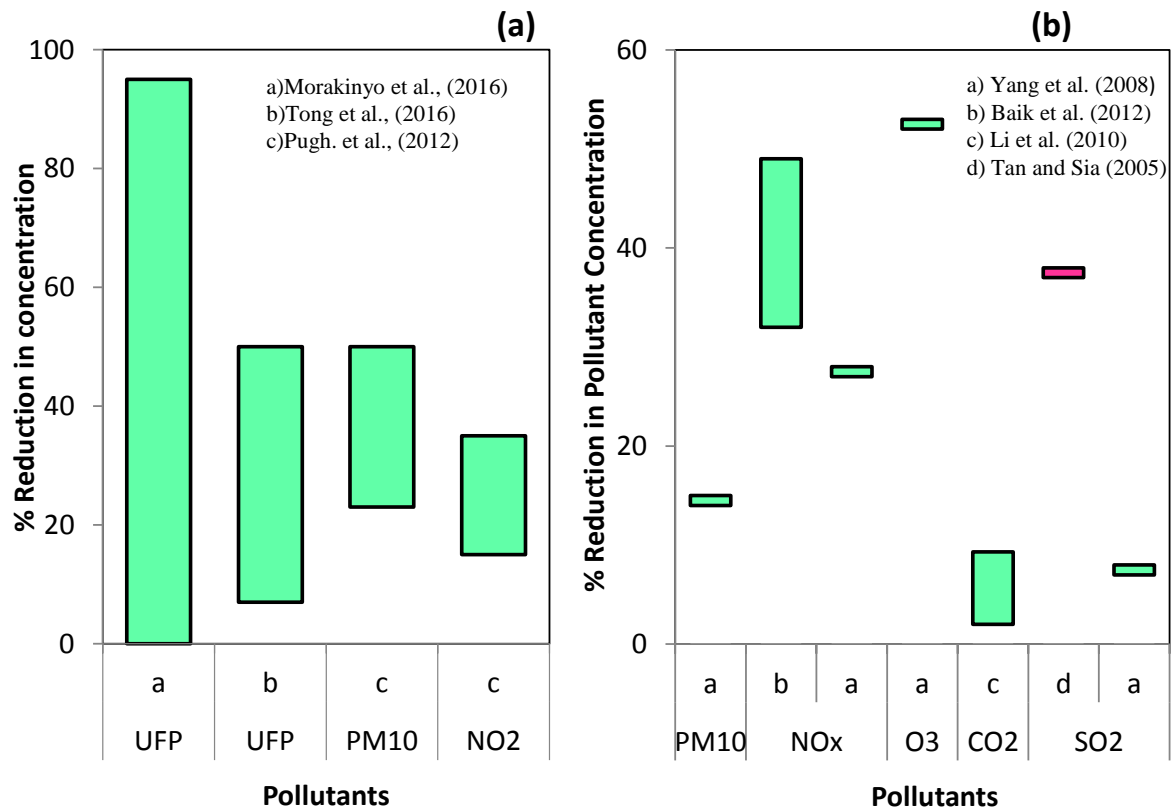


**Figure 4.** Figure shows published percentage reduction in different pollutant concentration with vegetation barrier in Open road situations to the vegetation barrier free condition. The bars depict reported range of pollutant reduction by respective studies. The following letters refer to the work from a) Tiwary et al. ( 2005), (b) Morakinyo et al. (2016), c) Morakinyo and Lam. (2016), d) Tiwary et al. (2008), e) Chen et al. (2015), f) Islam et al. (2012), g) Shan et al. (2007), h) Lin et al. (2016), i) Al-Dabbous and Kumar (2014), j) Fantozzi et al. (2015), k) Grundström and Pleijel (2014), m), Brantley et al. (2014).

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**Figure 5.** Published percentage reduction in pollutant concentration with (a) green walls to green wall free case and (b) green roof to green roof free case. Bars show the reported range of reduction by respective studies.

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**List of Tables****Table 1.** Summary of review articles discussing various aspect of green infrastructure.

Review	Description
Salmond et al. (2016)	Reviewed ecosystem services provided by street trees for the improvement of human well-being and health. Urban tree benefits were analysed through an urban ecosystem services approach. Street tree modification of air quality, climate and aesthetic and cultural services were listed. Review argued to develop a bottom-up decision-making process for implementing street trees as immediate impacts are seen in local scale. The study provides detailed ecosystem services of trees which can be used by urban planners in evaluating and implementing urban trees.
Gallagher et al. (2015)	Review summarised various passive methods of controlling air pollution exposure in the built environment and discussed strength and limitations of porous as well as solid barriers. The study listed potentials of these passive methods to reduce exposure and improve air quality in urban built environment.
Janhall (2015)	Reviewed effect of vegetation on dispersion and deposition of particulate matter in urban built environments. The study provided a comprehensive description of vegetation and particulate matter deposition and dispersion. The study was able to deliver design consideration on the closeness of vegetation to the pollution source and density of vegetation for improving air quality.
Berardi et al. (2014)	An extensive review of environmental benefits of green roofs covering energy conception reduction, air pollution mitigation, noise reduction, heat island effects etc. classification and technical aspects of the green roof were explained. The study showed capabilities of green roofs for a sustainable urban environmental.
Mullaney et al. (2015)	Listed social, environmental and economic benefits of street trees and challenges associated with growing along the street.
Gago et al. (2013)	Review various heat island mitigation strategies and pointed out vegetation can reduce heat island effect
Hunter et al. (2014)	Reviewed thermal performance of green façade. This study listed thermal modulation of different types of climbing plants.
Pérez et al. (2014)	Vertical greenery systems, which include green walls and facades, were reviewed considering their potential for saving energy.
Saadatian et al. (2013)	This study reviewed energy aspects of green roofs.
Petroff et al., (2008)	Reviewed particulate matter deposition on urban vegetation
Litschike and Kuttler (2008)	Reviewed dry deposition on vegetation canopies

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**Table 2.** Classification of street canyon studies based on wind direction and aspect ratio showing the percentage change in pollutant concentration with the presence of trees to tree free (detailed explanation of each study is provided in SI Tables 1, 2 and 3).



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Wind direction	Aspect ratio	Pollutant	LAD/Porosity	Changes in concentration with trees to tree free	Studies
Perpendicular 90°	H/W <0.5	SF <sub>6</sub>	97.5%, 96%	+21 to +41% average +27 to 105% leeward side -3 to -35% windward side	Buccolieri et al., (2011), Buccolieri et al., (2009), Abhijith and Gokhale, (2015) Gromke and Ruck, (2012)
		NO-NO <sub>2</sub> -O <sub>3</sub> . EC, PM <sub>10</sub> .	0.2 - 2 m <sup>2</sup> m <sup>-3</sup>	Increase in concentration	Moradpour et al., (2016), Vos et al., (2013) Wania et al., (2012), Salmond et al., (2013)
	0.5 < H/W <1.5	PM <sub>2.5</sub> PM <sub>10</sub>	0-5.12 m <sup>2</sup> m <sup>-3</sup>	+8.92% - 6.32%(other seasons) -0.58%(winter) Increase in concentration	Jin et al.,(2014) Wania et al., (2012)
		NO-NO <sub>2</sub> -O <sub>3</sub> CO <sub>2</sub> SF <sub>6</sub> CO	0.5-4.25 m <sup>2</sup> m <sup>-3</sup> 97.5%, 96% 0%	Increase in concentration +41% to + 58% at leeward -37% to -49% at windward +20% to +58% average change	Moradpour et al., (2016), Li et al., (2013) Gromke and Ruck, (2012), Salim et al., (2011,a), Salim et al., (2011b) Gromke et al., (2008), Gromke and Ruck, (2007), Gromke and Ruck, (2009), Balczó et al., (2009), Buccolieri et al., (2009), Buccolieri et al., (2011), Ries and Eichhorn, (2001), Ng and Chau, (2012), Jeanjean et al., (2017)
H/W >2	CO NO-NO <sub>2</sub> -O <sub>3</sub>	96% 0.5-2 m <sup>2</sup> m <sup>-3</sup>	+39% H/W=2 , +17% H/W=4 Increase in concentration	Ng and Chau, (2012) Moradpour et al., (2016)	
Oblique 45°	H/W <0.5	SF <sub>6</sub> , CO EC, NO-NO <sub>2</sub> -O <sub>3</sub> . PM <sub>10</sub> .	97.5%, 96% 0.2- 2 m <sup>2</sup> m <sup>-3</sup>	+2 to 119% in leeward side +34 to 246% in windward side +12% to +146% average	Buccolieri et al., (2011), Amorim et al., (2013), Abhijith and Gokhale, (2015), Vos et al., (2013), Wania et al., (2012), Gromke and Ruck, (2012)
	0.5 < H/W <1.5	SF <sub>6</sub> PM <sub>10</sub>	97.5%, 96% 0.2- 2 m <sup>2</sup> m <sup>-3</sup>	+66% to +91% .Maximum increase than other wind direction	Gromke and Ruck, (2012), Buccolieri et al., (2011), Wania et al., (2012)
Parallel 0°	H/W <0.5	NO-NO <sub>2</sub> -O <sub>3</sub> SF <sub>6</sub> , PM <sub>10</sub>	0.2-2 m <sup>2</sup> m <sup>-3</sup> 97.5%, 96%	+38% average Increase in concentration	Moradpour et al., (2016), Gromke and Ruck, (2012), Wania et al., (2012)
	0.5 < H/W <1.5	CO, NO-NO <sub>2</sub> - O <sub>3</sub> , SF <sub>6</sub> , PM <sub>10</sub>	97.5%, 96% 0.2- 2 m <sup>2</sup> m <sup>-3</sup>	Decrease in concentration -16% & +40% average Increase in concentration	Amorim et al., (2013), Moradpour et al., (2016), Gromke and Ruck, (2012), Wania et al., (2012), Jeanjean et al., (2017)
	H/W >2	NO-NO <sub>2</sub> -O <sub>3</sub>	0.5-2 m <sup>2</sup> m <sup>-3</sup>	Increase in concentration	Moradpour et al., (2016)

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**Table 3.** Summary of studies on air pollution impact of hedges in street canyon.

Study Location Methodology Climatic condition Pollutant	Street canyon H/W Wind direction and speed(m/s)	Dimensions(m)	Density- (LAD m <sup>2</sup> m <sup>-3</sup> , Porosity %)	Key findings
Gromke et al., (2016) Modelling Fluent SF <sub>6</sub>	0.5  90 <sup>0</sup> and 0 <sup>0</sup>  4.65	Height 1.5 & 2.5  Width 1.5	Pressure loss coefficients- (permeability) 1.67m <sup>-1</sup> & 3.34m <sup>-1</sup>	<ul style="list-style-type: none"> <li>• Hedgerows resulted in reduction of concentration</li> <li>• Higher and less permeable hedge had more reduction in concentration</li> <li>• Central single hedge was more effective in pollutant reduction than sidewise hedge</li> <li>• Discontinues hedgerow(9m spacing ) showed the least reduction</li> <li>• In parallel wind hedge on both sides showed improvement in air quality than a central hedge.</li> <li>• Maximum area averaged pollutant reduction by Single centre hedge= 61% &amp; Hedge on both side= 39%</li> </ul>
Li et al., (2016) Measurement and Modelling Fluent, Shanghai China-Mild monsoon Mean temperature 35°C, mean RH 60% CO	0.4, 0.18, 0.78  90 <sup>0</sup>  1, 2, 3, 20	Height 0.5, 0.9, 1.1, 1.5, 2.0 , 2.5, 3.0, and 4.0  Width 1.5	0%	<ul style="list-style-type: none"> <li>• Measurement showed improvement with air quality with hedges</li> <li>• Optimum heights for vegetation barriers are -1.1m and 2m for H/W=0.4 with maximum reduction at 2m -0.9 to 2.5m for H/W=0.18 with maximum reduction at 2m -1.1m and 2m for H/W=0.78 with maximum reduction at 1.1 m</li> <li>• Change in wind velocity has no effect on optimum vegetation height</li> <li>• Experimental study showed concentration reduction of 53%, to 27% at 1.4 m &amp; 36 to 24% at 1.6m</li> </ul>
Vos et al., (2013) Modelling ENVI-met PM <sub>10</sub> , elemental carbon (EC) NO-NO2-O3.	0.35  45 <sup>0</sup> and 90 <sup>0</sup>  3	Height 1, 3,4  Width 1	2 & 5 m <sup>2</sup> m <sup>-3</sup>	<ul style="list-style-type: none"> <li>• Hedge deteriorate air quality in street canyon</li> <li>• When LAD increased concentration was increased.</li> </ul>
Wania et al., (2012) Modelling ENVI-met PM <sub>10</sub> ,	0.5,0.9, 1.2  0 <sup>0</sup> , 45 <sup>0</sup> and 90 <sup>0</sup>  1, 3	Height 1.5	2.0 m <sup>2</sup> m <sup>-3</sup>	<ul style="list-style-type: none"> <li>• Showed better removal of pollutants than trees in street canyon</li> <li>• Hedges are recommended for deep canyons</li> <li>• Higher removal of pollutants with hedges close to source</li> <li>• Reduction in wind velocity was minimum with hedges</li> </ul>

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**Table 4.** Classification of studies investigated vegetation barrier in open road condition (detailed explanation of each study is provided in SI Tables 5 and 6).

Pollutant	Vegetation characteristics			changes in pollutant concentration compared to vegetation free condition	Studies
	Dimensions(m)	Type	Density((LAI, LAD, Porosity, CD, shutter belt porosity )		
UFP	---	--	LAD 1-5 m <sup>2</sup> m <sup>-3</sup>	Filtration efficiency increases with a thickness linearly	Neft et al., (2016)
	Height 6, 9. Width 6, 12, 18.	Coniferous and evergreen tree	LAD 0.33, 1, 1.15 m <sup>2</sup> /m <sup>3</sup>	Reduction behind vegetation barrier	Tong et al., (2016)
	Height 4-8., Width 2-6.	Mixed vegetation	LAI (fall) 3-3.3, LAI (winter) 1-2.8	37.7–63.6% reduction in pollutant concentration behind barriers	Lin et al., (2016)
	Height 3.4 Width 2.2	coniferous plants	--	reduction in PNC at footpath at 1.6 m height was 77% -180 <sup>0</sup> wind, 70%- 0 <sup>0</sup> wind, 37%- 90 <sup>0</sup> wind	Al-Dabbous and Kumar, (2014)
	Height 6-8	evergreen tree stand	LAD 3.3 m <sup>2</sup> /m <sup>3</sup>	Increase in LAD reduces concentration	Steffens et al., (2012)
	Height 6.1-7.2 Width 3.6-4.5	Evergreen and Deciduous tree stands	LAI 3-3.3 fall LAI 1-2.8 winter	Behind barrier, UFP concentrations were found to be lower, higher or nearly same as of open area	Hagler et al., (2012)
	Height 0.3,11,12, Width 1, Length 25,53	Mixed vegetation	Canopy Density CD=0.7,0.9	Increase as well as decrease in concentration observed	Chen et al., (2016)
PM <sub>2.5</sub>	--	--	Porosity 15.7%, 9.8%,21.9%(Derived photographic methods)	Concentration was higher downwind of trees than open fields	Tong et al., (2015)
	Height 1.5, 2, 3, 4, Width 1, 2, 3, 7.5 Length 20	--	LAD 2m <sup>2</sup> /m <sup>3</sup>	The higher volume of vegetation barrier can increase filtration or collection of particulates	Morakinyo and Lam, (2016)
	Height 2, 4 Width 1, 2 Length 25, 20	conifers vegetation barrier	LAD 2m <sup>2</sup> /m <sup>3</sup>	Higher concentration was observed behind hedges. The increase of 25% and ~18% for perpendicular and oblique wind, ~80% and 40% with strong and calm parallel wind.	Morakinyo et al., (2016)
	Height 2, 3 Thickness 1, 8 Length 20	--	LAD 2m <sup>2</sup> /m <sup>3</sup>	Behind barrier, UFP concentrations were found to be lower, higher or nearly same as of open area	Morakinyo and Lam, (2015)

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PM <sub>10</sub>	Width 2.5-3.5	--	CD 65-91%	Reduction of 7% to 15%	Chen et al., (2015)
	Height 2.2 Width 1.6	Hawthorn hedge		34% reduction in pollutant concentration was observed	Tiwary et al., (2008)
PM	Height 1.7, 2.2, 2.4	Hawthorn, Holly, yew	--	Hawthorn- 66.2% and 83.5%, Holly- 58.3% and 76.1% Yew -17.5% and 20.5%,	Tiwary et al.,( 2005)
	Width 1.6, 1.7, 3.2				
TSP	Height 0.3-12,	Mixed coniferous and evergreen vegetation	Shelter belt porosity 4-44% , CD 51- 90 %	Reduction in concentration behind vegetation barrier, maximum removal occurred in summer Reduction of 45-93%	Islam et al., (2012) Shan et al., (2007) Chen et al., (2016)
	Width 1,7-15, Length 20 -53				
black carbon	Height 10, Length 5-78	Mixed vegetation	LAI 2.6 to 4.7	Reductions :12.4% 90 <sup>0</sup> winds, 7.8% 0 <sup>0</sup> winds, 22% maximum	Brantley et al., (2014)
CO	Height 4-8,	Mixed vegetation	LAI (fall) 3-3.3, LAI (winter) 1-2.8	23.6–56.1% reduction in pollutant concentration behind barriers	Lin et al., (2016)
	Width 2-6				
NO <sub>2</sub> -O <sub>3</sub>	--	Evergreen	--	NO <sub>2</sub> removal rate 14–25% in January(highest concentration period), 35–59% in July(lowest concentration period) O <sub>3</sub> concentration was higher in all conditions	Fantozzi et al., (2015)
	Height 8-10 m	Mixed deciduous trees	--	7% reduction in concentration of NO <sub>2</sub> within canopy 2% reduction of concentration of O <sub>3</sub> (negligible)	Grundström and Pleijel, (2014)