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Green walls for mitigating urban particulate matter pollution - a review

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Abstract

Air pollution caused by particulate matter (PM) is a well-known health issue in urban environments. Urban green infrastructure offers opportunities as a nature-based solution to urban PM pollution. Green walls have advantages over other types of urban green infrastructure, since they can be applied to the enormous available wall area in cities and since they do not interfere with the prevailing ventilation resulting in elevated PM levels. However, this has raised questions about the effectiveness of GW in removing PM and this could explain the limited applicability of green walls to tackle PM pollution. Nevertheless, it is suggested that green walls have a significant unexploited potential and this review article aims to address current knowledge gaps and to propose future research requirements for the implementation of green walls to mitigate urban PM pollution. An in-depth analysis is given of the mechanisms behind PM deposition and the influence of vegetation properties on this process, as well as the practices followed to model PM dispersion and deposition. It was suggested that particle deposition on green walls depends on the green wall species, pollution level, and the residence time of PM in a street (canyon). Rainfall plays an important role in the PM pathway, although it is not a necessary requirement to sustain PM deposition on plant leaves. There are still some discrepancies in the literature about the ideal plant characteristics for PM deposition in terms of the macro- and microstructures that require further investigation, especially in comparison with tree and shrub species. In addition, extensively validated models are required to accurately calculate the impact of green walls on air flow and the PM concentration on site.

Keywords

Particulate matter, Green walls, Deposition, Local pollution exposure, Street canyons, Sustainable buildings

1 Background

Air pollution is a major health issue that affects people around the world today. Cities in particular account for a large proportion to both the burden and the causes of this issue. Since the percentage of the world's population living in urban areas is projected to increase from 54% in 2015 to 60% in 2030 and to 66% by 2050, the pressure will only increase and affect more and more people (WHO, 2016a). Particulate matter (PM) is one of the main air pollutants in urban environments globally. It is a complex mixture of various components of both small particles, liquid droplets including organic chemicals, acids, metals and soil or dust particles. The WHO classifies PM according to their size in coarse PM (PM_{10}), fine PM ($PM_{2.5}$) and ultrafine PM ($PM_{0.1}$) with an aerodynamic diameter smaller than 10 µm, 2.5 µm and 0.1 µm, respectively (WHO, 2016b). Both natural and anthropogenic sources of PM_{10} are present, but the sources of fine and ultrafine PM emissions are almost all man-made with major contributions coming from residential heating and traffic (HEI, 2010; WHO, 2016b). There is a strong correlation between increased PM levels and adverse health effects, predominantly on the respiratory and cardiovascular systems. Long term exposure can lead to lung cancer and premature death (WHO, 2016b). It is acknowledged that the risk of harmful effects on human health is greater for smaller particles, since they can penetrate deeper into the lungs and even end up in the blood stream (Kim et al., 2015). PM pollution also has an impact on ecosystems including agriculture and climate, and comes with a serious economic cost (Jimoda, 2012). Although improvement is seen in the last years, exposure reduction targets have not yet been achieved in large parts of Europe (EEA, 2017) and 84% of the global population is exposed to PM levels that exceed the WHO guidelines (WHO, 2016b). Furthermore, increasing urbanisation and increasing or remaining high air pollution levels will further result in serious health implications (Lelieveld et al., 2015; WHO, 2016a).

Vegetation has an influence on pollutant dispersion through its influence on air flow and is able to capture PM by deposition on its leaves and stems (Grote et al., 2016; Ottelé et al., 2010). Urban green infrastructure can potentially be implemented as a nature-based solution to mitigate urban PM pollution (Janhäll, 2015; Samson et al., 2019). These nature-based solutions include street trees, vegetation barriers (where vegetation forms a barrier between traffic emissions and citizens), hedges, green roofs (GR) and green walls (GW). GW can be an effective greening strategy in the built-up area, since they can be applied to the enormous available wall area in cities. Furthermore, GW can be placed close to the pollutant source (e.g. traffic) (Janhäll, 2015; Tallis et al., 2011) and it was measured that a green wall located next to a busy road captures roughly 10^{10} to 10^{11} particles per m^2 leaf area (Ottelé et al., 2010; Sternberg et al., 2010; Weerakkody et al., 2018a). Here GW can play a major mitigating role, since elevated PM levels, among which the most harmful part of PM i.e. ultrafine PM, are found approximately within 100 to 300 m from a road (Baldauf et al., 2013, 2016). In addition, GW do not interfere with the prevailing ventilation in street canyon situations. Therefore, GW do not obstruct natural ventilation, which was observed to be the case for trees and hedges, leading to higher concentrations than would be the case without green (Abhijith et al., 2017; Litschke and Kuttler, 2008; Vos et al., 2013). However, this has raised questions about the effectiveness of GW in removing PM and this could explain the limited applicability of GW to tackle PM pollution. Anyway, limited research has shown that GW can reduce PM_{10} levels by around 5-30% in deep street canyon situations (H/W = 2) (Pugh et al., 2012; Qin et al., 2018). In addition, the authors of this review believe that GW have a much greater, untapped potential, considering their great flexibility, and this review aims at describing the state of the art to explore the unknown potential of GW to mitigate urban PM pollution.

Green walls are categorised according to their growth method in green façades and living wall systems. Green façades (GF) are soil-bounded plants, typically woody or herbaceous climbers, that grow directly against the building wall (direct green façade) or on a support system (indirect green façade). Figure 1, on the left, shows a direct GF with a close-up of the rooting system. Living wall systems (LWS) involve plant support structures attached to the building wall such as a screen, tray, vessel, planter tiles and flexible bags (Manso and Castro-Gomes, 2015). The plants do not root in the soil, which considerably increases the application possibilities and allows to get a rapid, uniform coverage over a large surface. Figure 1, on the right, shows an LWS with panels made of rockwool. However, LWS have a high installation and maintenance costs related to irrigation and replacement of the plants (Riley, 2017).

2 Review strategy

Research into PM capture of trees and shrubs is widely performed and previous review articles on this topic have focused on deposition of PM on vegetation (Buccolieri et al., 2018; Litschke and Kuttler, 2008; Petroff et al., 2008a) and dispersion and deposition of particles in relation to vegetation (Gallagher et al., 2015; Janhäll, 2015). Although an increase was observed in the years 2017 to 2018 (Figure 2), studies concerning green walls are still limited and the greater part of studies was found in Europe. Research papers were searched at Web of Science (WoS) with an advanced search to combine the following terms: “green wall”, “vertical green”, “living wall”, “evergreen” or “green infrastructure” with “air quality”, “pollution”, “PM“, “ultrafine”, “particulate matter”, “dust”, “soot” or “particle” up to and including 2020. In addition, the same key words were used to search at Google Scholar with the same key words. It should be noted that articles concerning this topic which do not include these terms could not be found. Papers concerning indoor application of green walls or concerning other types of urban green infrastructure than green walls were excluded from this review.

Figure 1: On the left a direct green façade (GF) and on the right a living wall system (LWS) placed in a city. Below these pictures, the rooting system of the GF and the support structure (here a panel made of rockwool) of the LWS.

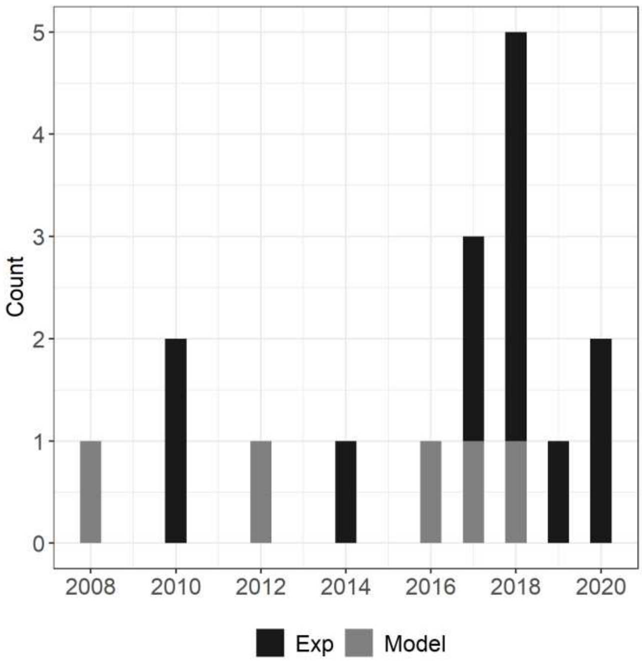


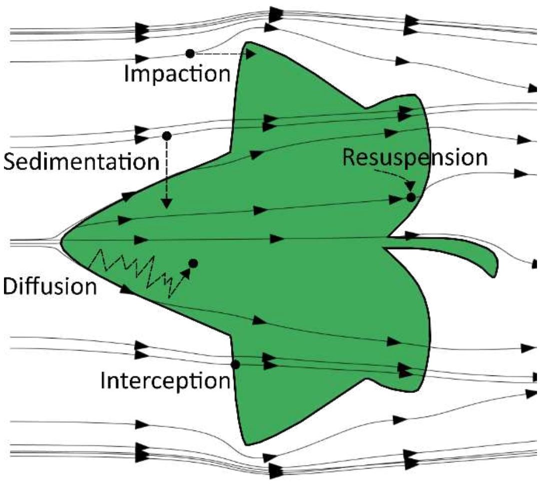
Figure 2: Number of published articles, found on WoS and Google Scholar, describing experiments (Exp) and modelling studies (Model) about PM deposition on green walls (review articles not included).

3 Impact of green walls on urban air quality

Both dispersion and deposition of PM determine local air quality. Dispersion refers to the transport by wind and dilution of pollutants by mixing with ambient air (Janhäll, 2015). Deposition results in the removal of particles from the atmosphere onto the leaf and can occur as a result of two processes: wet deposition - the transfer of particles from the air by precipitation, or dry deposition - the transfer of particles by gravity, diffusion, impaction and interception processes (Jacobsen, 2005; Lovett, 1994).

3.1 Mechanisms of PM deposition

Several mechanisms of dry deposition can be distinguished (Figure 3, left) and the relevant physical processes differ for the different PM size fractions, making the study more complicated. Brownian diffusion is the characteristic random wiggling motion of very small airborne particles ($PM_{0.1}$) in an air stream, resulting from constant collision with surrounding gas molecules. Direct interception occurs when a particle follows a streamline at a distance from the surface that is equal to or smaller than the particle diameter, resulting in the attachment (interception) of the particle onto the surface. Heavy particles can settle out of the air stream due to gravity and come to rest on a surface, a process called sedimentation. In the case of impaction, deposition is caused by the inertia of particles that possess so much momentum that they cannot follow the air streamlines curving around the object (Beckett et al., 1998; Petroff et al., 2008b). Particle removal from the air by leaves via dry deposition in terms of time is probably greater than via wet deposition, because precipitation events are episodic (Beckett et al., 2000; Sternberg et al., 2010). The intercepted particles are still interchangeable with the atmosphere through wind resuspension, especially during dry and windy periods (Hofman et al., 2014; Litschke and Kuttler, 2008; van Bohemen et al., 2008), and/or due to particle rebound immediately following impaction (Beckett et al., 1998). In addition, wash-off by rain can remove the deposited particles from the leaf surfaces. The washed-off PM is then immobilised in the soil or is resuspended from paved surfaces. Resuspension is of course not desirable, but some scarce studies have investigated wind or rain driven resuspension for urban green infrastructure at a local scale (Buccolieri et al., 2018; Petroff and Zhang, 2010) and a model-based approach was used to obtain estimations on an urban scale for trees (Nowak et al., 2013).



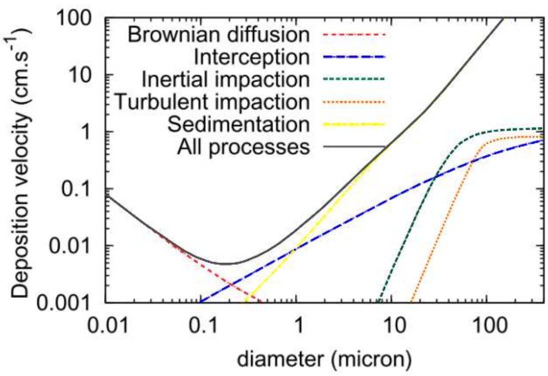


Figure 3: The different mechanisms of dry deposition of particulate matter on a leaf surface (by the authors) (left) and the deposition velocity (cm s^{-1}) as a function of the particle diameter (µm) for the different mechanisms (from the article of Petroff and Zhang (2010)) (right).

3.2 PM deposition velocity

The deposition rate of particles on surfaces is generally characterised by the deposition velocity v_d [m s^{-1}], which is the ratio of the pollutant flux F_p [g m^{-2} s^{-1}] towards the surface and the atmospheric particle concentration C_p [g m^{-3}]:

$$v_d = F_p C_p^{-1} \quad \text{Equation 1}$$

Petroff and Zhang (2010) developed an analytical and size-segregated aerosol dry deposition model for vegetative canopies and demonstrated the particle size dependency of the dry deposition rate (Figure 3, right). The deposition rate reaches a minimum for particles around 0.1-0.3 µm. Below 0.1 µm, the deposition velocity increases due to more effective particle transport through the leaf boundary layer due to Brownian diffusion. For particle diameters greater than around 0.1-0.3 µm, the deposition velocity also increases, but due to the increasing efficiency of impaction and interception processes which increase with particle size. Sedimentation becomes the key deposition process for particles greater than 10 µm (Fowler et al., 2003; Litschke and Kuttler, 2008). Dry deposition of PM also depends on turbulent diffusion and the collecting properties of the surface, which will be discussed in the next section. The deposition velocity has been empirically derived from measurements (Freer-Smith et al., 2005) or parametrisation (Jacobsen, 2005) (see 6 Modelling studies).

3.3 Effects of green walls on PM deposition

The presence of vegetation has an effect on the PM concentration in its surroundings. It alters the flow pattern and acts as a momentum sink by exerting pressure and drag forces encouraging deposition of particles on the leaf surface (Amorim et al., 2013; Janhäll, 2015). Studies demonstrate that vegetation captures pollutants from the atmosphere more effectively than other land surfaces due to the high air turbulence caused by their complex morphology and large surface area per unit volume (Roupsard et al., 2013; Tallis et al., 2011; Weerakkody et al., 2019a). Thus, PM can be effectively removed from the atmosphere, unless resuspension occurs. Next, the deposited particles can be washed off by precipitation or dropped to the ground by leaf or twig fall (Beckett et al., 2000; Nowak et al., 2006). However, some fine and ultrafine particles are not easily washed away from plant leaves (Ottelé et al., 2010; Perini et al., 2017). Some authors state that $PM_{0.1}$ can be assimilated via the stomata into the leaves, just like gaseous pollutants, but it is not yet clear whether and to what extent this may occur (Jimoda, 2012; Lovett, 1994).

It is clear that plant characteristics play a major role in the deposition process. Two categories can be distinguished, namely the macrostructure of vegetation and the microstructures of the leaf surface (Abhijith et al., 2017). The macrostructure is determined by the porosity and/or density of the vegetation and has an impact on the mean wind speed and turbulence in the bulk of the vegetation and hence, also on PM deposition. Vegetation macrostructure is usually quantified by the Leaf Area Index (LAI), which in case of a GW should represent the amount of vegetation surface area per vertical wall surface area [$m^2\ m^{-2}$], in contrast to e.g. trees where the reference surface is the projected ground surface (Janhäll, 2015). Hence, it is suggested to use the term Wall Leaf Area Index (WLAI) to have the correct definition of LAI when studying GW (Koch et al., 2020). Leaf Area Density (LAD) is another property used to describe the density of vegetation and represents the total one-sided leaf area per unit volume [$m^2\ m^{-3}$]. The microstructure of the leaves, on the other hand, refers to leaf shape and surface geometry, rigidity, and surface characteristics such as the presence of trichomes, leaf-wax content or chemical composition and structure of the epicuticular wax. These properties determine the deposition capacity of leaves in a more direct way (Leonard et al., 2016; Sæbø et al., 2012).

4 Overview of field studies

All field measurement data were statistically processed to identify significant relations between PM deposition and plant characteristics or between PM deposition and the environmental conditions to which the leaves were exposed. The variables studied will be discussed in detail in the next section, which is subdivided in studies about green façades and studies about living wall systems. It should be noted that the findings of these field measurements do not allow to calculate the PM removal efficiency of a green wall, because the dimensions of the green walls were not recorded and the pollution level was not quantified, apart from one article (Paull et al., 2020). Hence, it was not possible to make quantitative statements on the PM mitigating potential of a green wall. For this end, wind tunnel or modelling studies should be employed. Field measurements rather serve as an indication of which species can perform best and at which locations plants can have the highest impact. In addition, the analysis of deposited PM by any measurement technique is performed at a specific point in time so that it does not reflect the full capacity of a plant to capture PM during its lifetime. Therefore, it would be of interest to investigate the amount of deposited PM during a season and between seasons. Only a limited set of publications considered these (inter)seasonal dynamics for green walls (He et al., 2020; Przybysz et al., 2014) and trees (Hofman et al., 2014; Kardel et al., 2011; Perini et al., 2017).

4.1 Green façades

The most common species found in direct GF around the world is ivy (*Hedera helix*) and it is the only GF species studied in the field so far. In addition, no studies have been reported on indirect GFs. Ottelé et al. (2010) and Sternberg et al. (2010) studied the PM mitigation potential of ivy by means of counting particles on (Environmental) Scanning Electron Microscope ((E)SEM) micrographs in combination with Energy-dispersive X-ray spectroscopy (EDS or EDAX) techniques to obtain the size distribution and elemental composition of the deposited particles, respectively (Castanheiro et al., 2016). In both studies, the pollution level to which the leaves were exposed, appeared to be significant in terms of particle number, but only for particles smaller than 1.5 µm and not for the fraction 2.5-4 µm. The peak of ultrafine particles ($PM_{2.5}$) reflected the anthropogenic source associated with traffic, which was also described in other studies (Castanheiro et al., 2016; Hofman et al., 2017). In addition, there was a significant difference between the number of particles on the ad- and abaxial surface of the leaves with roughly twice as many particles on the adaxial surface. On the contrary, the leaf height in the GW over a range of 0.75 to 2.0 m and the season had no influence on PM accumulation, however with regard of the latter, only summer and autumn were compared (Ottelé et al., 2010). It was difficult to draw conclusions on the difference in PM capture by exposed and covered (interior of the canopy) leaves, since these results were not significant at every location with the different pollution levels (Sternberg et al., 2010).

Przybysz et al. (2014) determined the PM content on both the leaf surface and in the epicuticular waxes by washing the particulates off *Hedera helix* leaves followed by filtering and weighing of the residue (so-called gravimetric method). It was observed that the largest amount of PM was found on the surface of the leaves instead of in the wax. The study revealed that in addition to the pollution level, the size fraction, the amount of rainfall and the season had a significant influence on PM accumulation. Figure 4 clearly illustrates that a lower pollution level (Rural site) resulted in a lower amount of total deposited PM compared to a site with a lot of traffic (Roadside site). There was a significant difference between the sites for all PM fractions (not shown on Figure 4), hence not only for particles smaller than 1.5 µm as Ottelé et al. (2010) found. This difference in results could be attributed to the different measurement technique used. It was also observed that both natural (Roadside Wet vs. Roadside Dry) and simulated rainfall (spraying water on the leaves after outdoor exposure) removed a significant proportion of PM, and, in agreement with Weerakkody et al. (2018c), the wash-off was greatest for PM_{10}, followed by $PM_{2.5}$ and PM_1. Even though precipitation removed PM from the leaf surfaces, the accumulation of PM followed an increasing trend from period 1 (mid-February), when it was just planted, to period 2 (end of March) and 3 (early June). When particles were counted, there was no significant accumulation over a period of approximately 3 months (Ottelé et al., 2010; Perini et al., 2017). He et al. (2020) studied PM capture by *Hedera helix* along a wide road with traffic in Hannover (Germany) during winter (November-March). They used the gravimetric method to determine the PM content on the leaf surface, but they did not consider PM in the epicuticular waxes. The total amount of PM deposited on the leaves of *Hedera helix* varied between the different winter months, with peak values in December and February (161 ± 8 µg cm^{-2} and 158 ± 28 µg cm^{-2}, respectively). It contradicts the increasing PM content over time reported by Przybysz et al. (2014) (see Figure 5). He et al. (2020) attributed this varying trend to changes in some leaf traits and changes in meteorological conditions, of which precipitation and humidity were the most important. On the other hand, Przybysz et al. (2014) also reported differences in the amount of precipitation during the different periods and still measured PM accumulation with time. Continuous particle accumulation with short-term fluctuations was also noted for the in-leaf season of urban tree leaves (Hofman et al., 2014; Kardel et al., 2011; Muhammad et al., 2019). It is clear that more research is requested on the accumulation of PM and the role of PM removal by precipitation.

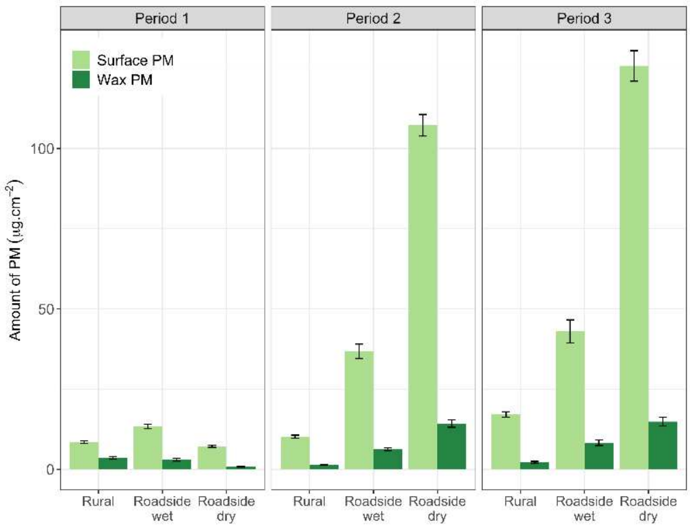


Figure 4: The total amount of PM deposited on the surface and in the waxes of *Hedera helix* leaves accumulated over three periods at three sites differing in pollution level (after Przybysz *et al.* (2014)).

4.2 Living wall systems

LWS allow to include a wide variety of plant species (Manso and Castro-Gomes, 2015) and plant leaves of different LWS species were assessed at different locations across Europe and Australia. Figure 5 shows the total mean PM density (i.e. the total number of particles per m^2 leaf area) on leaves of *Hedera helix* (section 4.1 Green façades) and LWS species studied by different authors (Ottelé et al., 2010; Sternberg et al., 2010; Weerakkody et al., 2018a, 2017). The location at which the GW was placed is categorised according to the pollution level in 'Background' (rural area or woodland), 'Railroad' and 'Traffic' (location with high traffic density with on average 20,000 cars per day). PM capture was found to be strongly determined by species (Paull et al., 2020; Perini et al., 2017; Weerakkody et al., 2018b, 2018a, 2017). The difference in PM capture between species can be attributed to the macro- and microstructure of the plant leaves, which will be further discussed in this section. In addition, the influence of the pollution level on the mean total PM density on GW leaves (based on Figure 5) and the influence of rainfall in the remobilisation of deposited PM will be discussed.

Macrostructure

A significant difference between LWS species was attributed to WLAI, and leaf size and shape. A higher WLAI resulted in enhanced PM accumulation, since the potential leaf area for deposition is increased (Weerakkody et al., 2018b, 2017). Smaller-leaved species were demonstrated to have a greater potential to accumulate PM, related to a relatively larger edge effect (Weerakkody et al., 2018b, 2018a). However, small linear-leaved or grass-like species tend to bend easily with wind flow so that less turbulence is created and less particles will deposit (Leonard et al., 2016; Paull et al., 2020; Weerakkody et al., 2017). These results reflect the findings on trees where coniferous species turn out ideal for PM deposition (Freer-Smith et al., 2005; Perini et al., 2017). As for trees and shrubs (Leonard et al., 2016), more complex leaf shapes were positive for PM accumulation, because of increased turbulence which enhances PM deposition (Weerakkody et al., 2018b, 2018a). To conclude, the most favourable species had smaller and more complex shaped leaves, and a high WLAI such as *Juniperus chinensis*, *Berberis buxifolia* and *Veronica vernicosa* (Figure 5). A study with Australian GW species showed that a rosette leaf arrangement (e.g. *Philodendron Xanadu*, *Spathiphyllum wallisii* and *Chlorophytum comosum variegatum*) created more turbulence and thereby more PM capture (Paull et al., 2020). LWS that had a heterogeneous topography, meaning that species are planted in an alternating order of shorter and taller specimens, also had more PM capture (Weerakkody et al., 2019b).

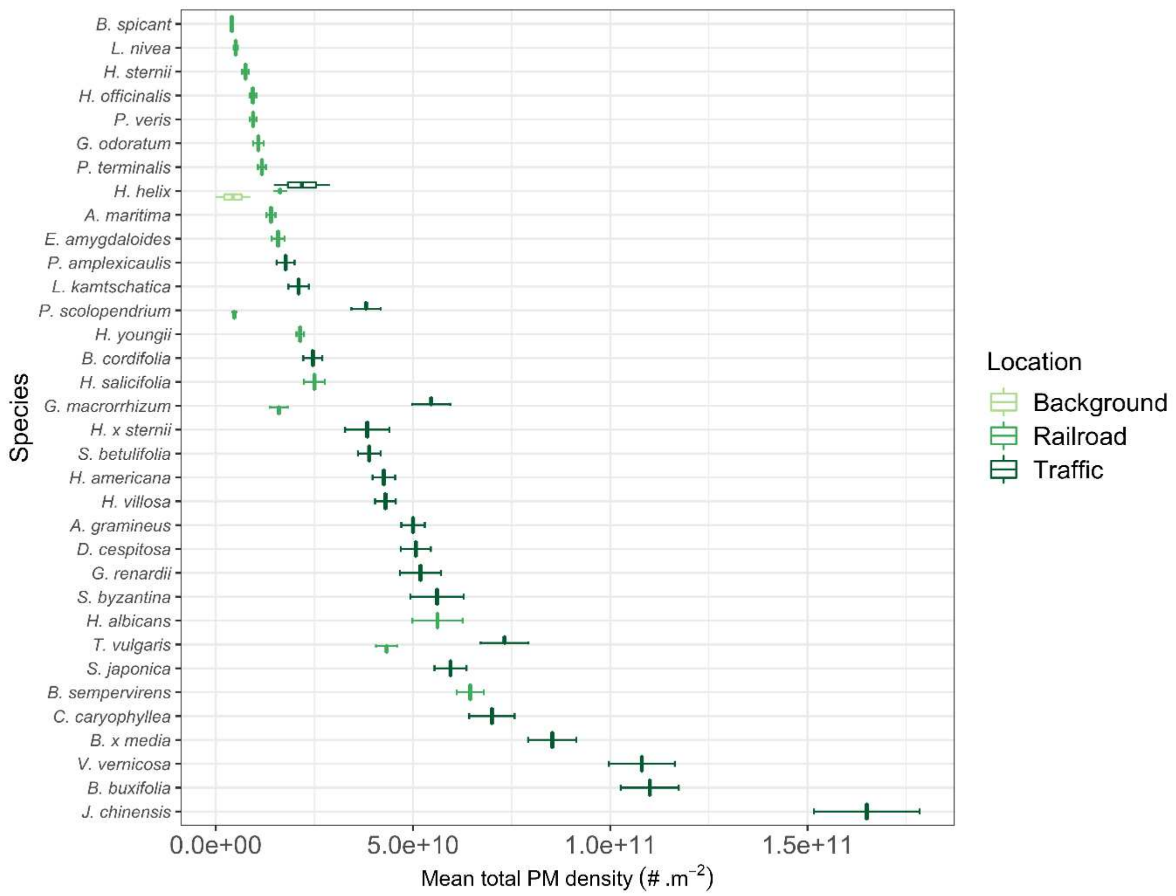


Figure 5: Mean total PM density (number of particles per m^2 leaf area) of different GF and LWS species reported by different authors (Ottelé et al., 2010; Sternberg et al., 2010; Weerakkody et al., 2018a, 2017). The error bars represent the standard deviation. The location at which the GW was placed is categorised according to the pollution level in 'Background' (rural area or woodland), 'Railroad' and 'Traffic' (location with high traffic density with on average 20,000 cars per day).

Microstructure

The impact of leaf micro-morphology (i.e. grooves and ridges, stomata and trichomes) was not conclusive, especially in comparison with tree and shrubs species. Rough leaf surfaces with dense ridges and grooves resulted in more PM capture (Weerakkody et al., 2018b), as was reported in studies on trees and shrubs (Dzierzanowski et al., 2011; He et al., 2020; Sæbø et al., 2012). However, the density of ridges and grooves did not show a significant correlation with PM accumulation (Weerakkody et al., 2018a). The authors of that research paper assigned this contradicting result to the diverse characteristics of grooves and ridges, however this was not found elsewhere in the literature. The stomatal density had a positive effect on PM accumulation (Weerakkody et al., 2018a), in contrast to studies on trees and shrubs who did not report any relationship (Muhammad et al., 2019; Sæbø et al., 2012). A higher epicuticular wax content was suggested to have a positive effect on PM accumulation by GW species (Perini et al., 2017; Weerakkody et al., 2018a, 2017). This was confirmed for trees and shrubs (Dzierzanowski et al., 2011; He et al., 2020; Sæbø et al., 2012), but Paull et al. (2020) found that GW species containing high wax content did not necessarily have the highest PM accumulation. Next, the presence of trichomes did not have a significant influence on PM capture (Paull et al., 2020; Perini et al., 2017), except for PM_{10} on adaxial surfaces (Weerakkody et al., 2018a). This is in contradiction with studies on urban trees and herbaceous plants (Muhammad et al., 2019; Sæbø et al., 2012; Weber et al., 2014). This could be attributed to differences in the nature of the hairs, which is species-specific. Recent research has also identified leaf wettability as an important parameter for PM capture: the more hydrophilic the leaf surface was, the more PM was captured (He et al., 2020; Muhammad et al., 2019). Hence, it is observed that the influence of microstructures on PM accumulation differed between the studies on GW species and studies on tree and shrub species. It is however so that a particular leaf characteristic could have enhanced or limited PM accumulation and, this could have resulted in contradictory results. Therefore, all characteristics of both the macro- and micromorphology should be regarded together to make sound conclusions.

Pollution level

The mean total PM density of *Thymus vulgaris*, *Geranium macrorrhizum* and *Phyllitis scolopendrium* at a high-intensity traffic road were 41, 71 and 88% higher compared with a railroad, respectively. This reflects the higher PM emission from road transport relative to rail transport (Abbasi et al., 2013). A significant relationship between ambient PM concentrations and PM deposition was found for particles larger than 5 µm, but not for particles smaller than 5 µm. More PM was found on the leaves of small linear species (*Nephrolepis exaltata bostoniensis* and *Nematanthus glabra*) with higher atmospheric PM concentrations, while species with a rosette leaf arrangement accumulated less PM at higher atmospheric PM concentrations (*Neomarica gracilis* and *Philodendron Xanadu*). It was suggested that this different relationship was due to leaf trait differences (Paull et al., 2020). More research is needed to determine the influence of ambient PM concentrations on leaf PM deposition. The particle size distribution on the leaves in terms of mass was almost identical for all species with a peak in the range of 0.5-2.5 µm (Paull et al., 2020; Perini et al., 2017) as found for GF. Likewise, Weerakkody et al. (2018b) found that the concentration in terms of particle count was the highest for the smallest size fraction, namely $PM_1 > PM_{2.5} > PM_{10}$, however for some species the amount of PM_{10} and $PM_{2.5}$ were more similar. In line with the findings of Ottelé et al. (2010), PM counts on the leaf adaxial side were generally higher than the abaxial side. Similar findings were published for tree species and hedgerows (Baldacchini et al., 2017; Mo et al., 2015).

Rainfall

Weerakkody et al. (2018c) found significant wash-off of PM of all size fractions for all evergreen species, both for normal (16 mm hr^{-1}) and more intense rainfall (41 mm hr^{-1}). They observed wash-off of the smallest particles, unlike Perini et al. (2017). The reason is probably that the latter author washed the leaves, in contrast to Weerakkody et al. (2018c) who simulated direct rainfall. Anyway, the highest wash-off was observed for PM_{10}, while PM_1 showed relatively low wash-off rates. Inter-species variability was observed, and smooth leaves resulted in more wash-off. The washed-off PM is then immobilised in the soil or is resuspended from paved surfaces. Resuspension is of course not desirable, but some scarce studies have investigated wind or rain driven resuspension for urban green infrastructure at a local scale (Buccolieri et al., 2018; Petroff and Zhang, 2010) and a model-based approach was used to obtain estimations on an urban scale for trees (Nowak et al., 2013).

5 Wind tunnel studies

Wind tunnels are frequently used to study the fluid dynamics of street canyons and coupled transport of an inert gas. The influence of vegetation on air flow and pollutant dispersion is different in street canyons than in open-street environments. This was apparent from the frequently cited wind tunnel experiment by Gromke and Ruck (2005) and later publications, on the impact of urban trees and hedges on pollutant dispersion within an idealised street canyon. The results have been collected in a public database named CODASC (Concentration DAta of Street Canyons) and it is a valuable dataset for model validation (Gromke et al., 2008; Gromke and Ruck, 2012, 2005). The findings of CODASC only cover trees and hedgerows. Wind tunnel studies of green walls were performed to link plant morphological characteristics to aerodynamic parameters (Koch et al., 2019). No studies included dispersion and deposition of PM in a wind tunnel. CODASC only used the tracer gas SF_6 to model traffic emissions instead of real PM, meaning that deposition, resuspension and chemical reactions were not considered. Gromke et al. (2008) claimed this assumption to be acceptable, because the effective filtering potential of PM by urban trees only affects local concentrations for a few percent and the aerodynamic effect is much stronger. This statement does not hold for green walls, since they do not act as a solid barrier as trees do, but they allow polluted air to pass through, so that deposition can take place (Abhijith et al., 2017; Janhäll, 2015). A wind tunnel study with real PM would be of interest to determine the deposition and resuspension velocity adequately. Nevertheless, the models constructed at wind tunnel scale should be validated with data from field studies to check if they are still valid for the complex real-world.

Studies have been reported that use a ventilated room in which PM is generated by combustion of incense to investigate the ability of GW species to capture PM. These studies allow to have more control on the environmental conditions as PM concentration and wind speed, but they do not include the air flow across the GW. Viecco et al. (2018) conducted experiments on LWS species characteristic for a semiarid climate in a ventilated test room with a volume of 60 m^3, a wind speed of 0.4 m s^{-1} and a maximum PM concentration of 140.3 and 139.2 µg m^{-3} for PM_{10} and $PM_{2.5}$, respectively. They discovered that *Sedum palmeri* was significantly better at capturing PM than the other three species studied with a total amount of deposited PM of 6.9 ± 0.4 µg cm^{-1} h^{-1} of which 52% was fixed by the wax of the leaves. The results about the decline of the PM concentration in the test room was reported, but this was not substantiated with a statistical test.

Pettit et al. (2019) studied native Australian plant species of a passive and active LWS in a test room of 22.7 m^3 and a total PM concentration of 400 µg m^{-3}. An active GW makes use of fans to actively draw polluted air towards the GW and significantly lowered PM concentrations by approximately 40% compared to 20% when the passive GW was installed. The active GW was also studied in classroom of 120.2 m^2 located in Beijing (China) with a HVAC system installed that provided an air exchange rate of 2.5 per hour. The PM concentration in the room with the HVAC operating was 101.2 ± 0.3 µg m^{-3}, which lowered by 42.6% when the active GW was installed (significantly different from the case without active GW) (Pettit et al., 2019). Although this study has demonstrated the application of active GW for indoor PM mitigation, this knowledge could be used for outdoor GW applications as well.

6 Modelling studies

6.1 Dispersion

Numerical models have been used to study the effect of urban vegetation on wind flow patterns and pollutant concentrations in urban areas. They have an important advantage in that they provide information in the whole computational domain, in contrast to the point measurements in field and wind tunnel experiments. On the other hand, the evaluation of model performance against measured data is essential for producing reliable model results. Many dispersion models have been described and they can be categorised following their physical or mathematical principles (box, Gaussian, Lagrangian and Computational Dynamics models). The typical vertical spatial scale is often the urban boundary layer, while the horizontal spatial scale varied amongst published research from district or neighbourhood to street canyon scale. An overview of different particle dispersion models was given by Holmes and Morawska (2006) at different spatial scales from local to regional scale and by Vardoulakis et al. (2003) at street canyon scale. Under certain conditions such as open environments and for longer averaging periods, dispersion models of passive (i.e. non-reactive) scalars can be used to model particle transport, but in the complex urban environment gas and particle dispersion behave differently and aerosol dynamics process dynamics should be incorporated into the dispersion models (Holmes and Morawska, 2006). On the other hand, due to the very short distance between the source and the exposed population, only very fast chemical reactions will influence the concentration within a street canyon (Vardoulakis et al., 2003). The summary of Kumar et al. (2011) showed that coagulation, condensation and wet deposition processes are not important on street canyon and neighbourhood scale, while emissions, nucleation, dilution, evaporation and dry deposition are (very) important.

Computational Fluid Dynamics (CFD) models are the preferred way to describe plant-atmosphere interactions in complex geometries such as cities in detail. It uses numerical algorithms to solve the governing fluid dynamics equations. Buccolieri et al. (2018) made an overview of current parametrisations used to model the aerodynamic, deposition, resuspension and thermal effect of urban trees. In CFD, vegetation is mostly explicitly represented, but only with their main shape, in which it is simplified as a uniform, porous medium. Airflow through vegetation is then modelled by additional terms in the momentum and turbulence equations using source (sink) terms describing heat, humidity and momentum exchanges (Buccolieri et al., 2018; De Maerschalck et al., 2010; Morakinyo et al., 2016). Another way of parametrising the aerodynamic effect was described by Koch et al. (2019) based on the Darcy-Forchheimer equation which considers air flow through a porous medium. It is an extension of Darcy's law to account for dissipation of kinetic energy by viscous shear, as in the Navier-Stokes equation, and the Darcy-Forchheimer drag was included to account for turbulent flow.

6.2 Deposition

In models, dry deposition is often simplified as a one-dimensional downward flux to a homogeneous layer of vegetation. Consequently, this method does not take into account the complex physical and geometric aspects of vegetation (Equation 2 in Table 1). The approach is derived from models used to describe deposition on tree canopies (Janhäll, 2015), but was also applied to study the PM mitigating potential of green walls at neighbourhood scale (∼km). While this is sufficiently adequate for modelling at large scale, this approach cannot capture all dynamic processes that are relevant to PM deposition/resuspension at the level of a green wall, especially since the main orientation of green walls is vertical. This is important when modelling the effect of green walls at street canyon scale (∼m). A street canyon is expressed in terms of its aspect ratio, i.e. the building height to street width ratio (H/W). Pugh et al. (2012) assumed deposition to occur to both canyon walls and floor and parametrised dry deposition accordingly (Equation 3). Later publications (Buccolieri et al., 2018) used another approach where dry deposition is parametrised in the transport equations by means of an additional volumetric sink term which is based on the deposition velocity, but includes the dimensions of the green wall in terms of LAD (Morakinyo and Lam, 2016; Qin et al., 2018). In this way, an average value for PM deposition by vegetation is calculated (Equation 4 and Equation 5 in Table 1).

Table 1: Additional sink F_d and source term F_r, added to the PM dispersion equation for modelling PM deposition and resuspension, respectively, by green walls. v_d and v_r represents the deposition and resuspension velocity [m s^{-1}], respectively, v_d^h and v_d^w the deposition velocity to the wall and floor surfaces, respectively, *c* the concentration of PM in the atmosphere [g m^{-3}], *H* and *W* the height and width of a street canyon [m], and *LAD* the leaf area index in [m^2 m^{-3}].

Additional term	Unit	Equation	Reference
$F_d = -v_d c$	[g m^{-2} s^{-1}]	Equation 2	Currie and Bass (2008) Jayasooriya et al. (2017)

$F_d = -c(\frac{2v_d^h}{W} + \frac{v_d^w}{H})$	[g m^{-2} s^{-1}]	Equation 3	Pugh et al. (2010)
$F_d = -LADv_dc$	[g m^{-3} s^{-1}]	Equation 4	Morakinyo et al. (2016) Qin et al. (2018)
$F_r = LADv_rc$	[g m^{-3} s^{-1}]	Equation 5	Qin et al. (2018)

The values of the deposition velocity (v_d) depend on the type of vegetation and PM size. However, most authors have used a constant value for deposition velocity and only Jayasooriya et al. (2017) has used a variable deposition velocity depending on wind speed and the dimensions of the green walls. Resuspension of the intercepted particles can be included in the deposition velocity (Freer-Smith et al., 2005; Litschke and Kuttler, 2008) or parametrised as a volumetric source term in the transport equation of pollutants, similar to deposition, however this has not been applied often (Equation 5) (Hong et al., 2018; Qin et al., 2018). Although both processes are influenced to a different extent by environmental variables such as wind speed, the difference in the result of a model with and without a parametrisation of resuspension has not yet been studied. It should be noted that the equations in Table 1 are still a simplification of the actual dry deposition process. As was apparent from section 3.1, a complete scientific framework should include dry deposition due to gravity and diffusion processes (i.e. Brownian motion), impaction and interception, and subsequent resuspension from the leaf surfaces to the environment. This would require much more computational power and is therefore probably not yet included in current deposition models to vegetation.

6.3 Overview of modelling studies

Table 2 lists the results of the published papers that use numerical models to study the interaction between PM and green walls in terms of a PM reduction efficiency at a particular location. At neighbourhood scale, we have calculated the PM reduction efficiency with data on the amount of PM that was removed during one year (E_M, Equation 6 and at street canyon scale with data on the concentration of PM (E_C, Equation 7).

$$E_M = \sum_{i=1}^{n} \frac{M_{gw} - M_{ref}}{M_{ref}} \times 100\% \qquad \text{Equation 6}$$

$$E_C = \sum_{i=1}^{n} \frac{C_{gw} - C_{ref}}{C_{ref}} \times 100\% \qquad \text{Equation 7}$$

M_{gw} and M_{ref} are the amount of PM removed during one year [kg y^{-1}] by a scenario with green walls and by the current scenario (i.e. reference case), respectively. C_{gw} and C_{ref} are the concentration of PM [µg m^{-3}] in a scenario with a green wall present and with only a bare wall (i.e. reference case), respectively. Most studies did only consider a situation with the wind approaching perpendicularly to a street canyon, as this is often accompanied by high pollutant concentrations on the leeward side (or up-wind side) of the canyon (Vardoulakis et al., 2003).

Neighbourhood scale

The removal of PM by deposition of green walls at neighbourhood scale was calculated with Equation 2 by Currie and Bass (2008) and Jayasooriya et al. (2017). Deposition velocities for PM_{10} were calculated based on deposition velocities reported by Lovett (1994) and take the bark area index (m^2 of bark per m^2 of ground surface covered by the tree crown) and LAI into account. Deposition velocities for $PM_{2.5}$ were obtained from literature and varied with wind speed (Hirabayashi et al., 2012). A range of deposition velocities were described in the model description (iTree Eco Deposition Model) and are shown in Table 2 (Hirabayashi et al., 2012). Currie and Bass (2008) studied a scenario in which existing trees and shrubs were removed and vertical walls of *Juniperus* were added within 3 m of residential houses. It must be noted that *Juniperus* is a tree species which formed a hedge rather than a green wall, which still might be a relevant case to consider here due to the lack of more specific studies on real green walls. This scenario resulted in an PM reduction efficiency of 17% (calculated with Equation 6. Jayasooriya et al. (2017) included vertical walls of 2 m high *Laurus nobilis*, also a tree hedge, around commercial buildings in an industrial area in Australia and computed with the model iTree Eco a PM reduction efficiency, with Equation 7, of 40 and 43% for PM_{10} and $PM_{2.5}$, respectively. They showed that planting new trees could remove substantially more than adding green walls (up to 14 times for PM_{10} and 4 times for $PM_{2.5}$), but the dimensions of the trees was not given so it is hard to compare the two measures. In addition, the model was not validated with experiments, meaning that the reliability of these results cannot be guaranteed. Nevertheless, it shows that planting green walls on a larger scale can have a substantial effect on PM levels at city scale.

Street canyon scale

A CFD model coupled with an atmospheric chemistry model was used by Pugh et al. (2012). The CiTTy-Street model is an idealised model of an infinitely long street canyon, in which only vertical mixing with the urban boundary layer above was considered. The mixing between the components was defined by an air exchange rate, calculated by Liu *et al.* (2005), and modified by the canyon height and above-roof wind speed. Dry deposition was calculated with Equation 3 and deposition was prescribed separately for the green wall (v_d^h, h referring to the height) and ground surface (v_d^w, w referring to the width). Therefore, the influence of the built environment and the green wall on pollutant dispersion was not regarded, which is major drawback. In addition, the PM concentration within the canyon did not change due to deposition and the model could thus overestimate its removal. The deposition velocity was taken from experiments and is reported in Table 2. The authors considered this conservative value for the deposition velocity suitable since it is often used in modelling studies (as e.g. Nowak et al., 2006) and it is comparable with the deposition velocity to grass predicted by the process-based model of Petroff and Zhang (2010) for grass. The results are combined with the results of Qin et al. (2018) on Figure 6 and will be discussed further. It should be noted that the model was only validated for a street canyon without vegetation (Ketzel et al., 2002).

Another CFD model applied to evaluate the role of green walls on pollutant dispersion and removal is the microclimate model ENVI-met (Morakinyo et al., 2016). Deposition was modelled using Equation 4. It was noted that the calculated gravitational settling is valid for particle transport towards a horizontal surface. This is not the case for a vertical surface, where the advective impact through the horizontal flow components is the dominating force. It is, however, not clear to which extent particles will stick to the vertical surface and, therefore, the horizontal gravitational settling was used (Bruse, 2007). However, the parametrisation of deposition can be seen as an average sink term of the vegetation with leaves aligned in different orientations (Buccolieri et al., 2018).

Table 2: Overview of numerical studies on the impact of green walls on atmospheric PM levels including model name, PM fraction [µm], deposition velocity (v_d) [m s^{-1}], GW dimensions as Wall Leaf Area Index (WLAI) [m^2 m^{-2}] or Leaf Area Density (LAD) [m^2 m^{-3}], GW surface area [m^2], species, model scale (H/W is the aspect ratio of a street canyon), wind speed [m s^{-1}], wind direction relative to the street axis [°], PM reduction efficiency based on mass values (E_M) or on concentrations (E_C) [%] and if the models are validated and if so their R^2 value. n.q. - not quantified.

Author	Model	PM fraction [µm]	v_d [cm s^{-1}]	WLAI [m^2 m^{-2}] or LAD [m^2 m^{-3}]	Surface area [m^2]	Species	Model scale	Wind speed [m s^{-1}]	Wind direction [°]	E_M [%][a]	E_C [%][b]	Validated
Currie and Bass (2008)	UFORE	10	0.64	n.q.	12,160,000	*Juniper*	H/W = 1	n.q.		16.6		No
Pugh et al. (2012)	CiTTy-Street	10	0.64	2 m^2 m^{-2}	20	n.q.	H/W = 1 H/W = 2 H/W = 2	2 2 0.5	90 90 90		10.8 32.0 61.9	Only without GW
Morakinyo et al. (2016)	ENVI-met	2.5	0.1	2 m^2 m^{-3}	40; 80	n.q.	Open road	3 1	90 45 0 90 45 0		±65 [c] ±90 [c] ±100 [c] ±70 [c] ±90 [c] ±100 [c]	R^2 = 0.79 (without GW) R^2 = 0.89 (with GW)
Jayasooriya et al. (2017)	iTree eco	10 2.5	0.25 - 1 0.04 ± 0.01 - 9 ± 5	n.q.	288,200	*Laurus nobilis*	City scale	n.q.	90 90	39.6 42.9		No
Qin et al. (2018)	PHOENICS	10	0.64	1.0; 3.5; 6.0 m^2 m^{-3}	300; 600; 900	*Parthenocissus vitacea*	H/W = 0.5 H/W = 1.0 H/W = 2.0	2.1 2.1 2.1	90 90 90		4.9 [d] 9.3 [d] 28.3 [d]	R^2 = 0.910 (6.5 m height) R^2 = 0.974 (1.5 m height)

[a] Calculated with Equation 6 by the authors of this review
[b] Calculated with Equation 7 by the authors of the particular article
[c] Derived from graphs, at 1.4 m height within 1 m behind the GW
[d] Values for a green wall with LAD 1 m^2 m^{-3} and coverage 300 m^2 (all results are given in Figure 6)

Morakinyo et al. (2016) first assessed the model results with measurements in front of, directly behind and 10 m behind a vegetation barrier (VB), which was in fact a row of conifers. The measurements were also done at a reference site at same distances from the source as in the case with the VB. Since they did not study a real green wall, which was also not accompanied with an impermeable wall like in their modelling study, the question rises if this measuring campaign gave proper validation data. Furthermore, the model underestimated the PM concentration behind the VB and overestimated it at all locations for the case without vegetation. This under- and overestimation was attributed to the non-steady behaviour of the wind which was not accounted for in the model. Overall, linear regression between modelled and measured values showed an R^2 of 0.89 and 0.79 for the case with and without vegetation, respectively. Afterwards, the validated model was used to determine the vertical and horizontal dispersion pattern under different prevailing wind directions (parallel, oblique and perpendicular) in an open road condition without other buildings. In this way, the GW served rather as a barrier with the PM filtering properties of vegetation. It appeared that under all wind directions $PM_{2.5}$ was reduced below 5 m, while air quality worsened above this height when oblique and perpendicular wind prevailed. Behind the GW at pedestrian height (1.4 m), $PM_{2.5}$ reductions between 65 and 100 % were observed, because wind was not capable to penetrate the solid wall, instead it was transported aloft to several directions.

Qin et al. (2018) used the CFD model PHOENICS to compare the impact of GR and GW on PM_{10} concentrations in street canyons. In this model, deposition was calculated with Equation 4 and also resuspension was included by using Equation 5. A value of the deposition velocity was reported (Table 2), but not for the resuspension velocity. They first validated their model against measurements conducted in front of a green wall with *Parthenocissus vitacea* in a Beijing residential district. The model results agreed with the average hourly concentrations of PM_{10} with an R^2 of 0.910 and 0.974 at a height of 6.5 m and 1.5 m, respectively. The constructed model framework was administered to study the effects of GW and GR for different aspect ratio's (H/W of 0.5, 1 and 2), different GW surface areas (300, 600 and 900 m^2) and different values of LAD (1.0, 3.5 and 6.0 m^2 m^{-3}). Figure 6 gives the PM_{10} reduction efficiency at pedestrian level (1.5 m) for a coverage of 300 m^2 by Qin et al. (2018) and the in-canyon PM_{10} reduction efficiency by Pugh et al. (2012). It seems that, for a certain LAD, an increasing aspect ratio, i.e. a smaller street, resulted in a higher PM reduction efficiency. In this case, the PM pollution comes in closer contact with the green wall, giving more time for deposition to take place. When the LAD is increased, keeping the H/W constant, also an increase in PM reduction efficiency is observed, although the increase is less pronounced. Pugh et al. (2010) tested a lower above-roof wind speed of 0.5 m s^{-1} compared with 2 m s^{-1} for all other data points on Figure 5 (also the one of Qin et al. (2018)). It showed that a higher residence time in the canyon and thus a higher PM reduction efficiency was obtained for lower wind speeds. Therefore, the literature suggests that the aspect ratio of the canyon and the above-roof wind speed are the key parameters determining PM deposition on green walls in street canyons. Nevertheless, this should be confirmed with other validated models.

When comparing GWs with GRs, GRs performed better than GWs for H/W = 0.5, while for H/W > 0.5, GWs outperformed GRs (Qin et al., 2018). The comparison between GRs and GWs demonstrated that the aerodynamic effect dominated for GRs, especially at H/W = 2.0, which even led to an increase in PM concentrations in the whole domain. It demonstrates the need of in-depth assessment of the local environment in terms of street canyon morphology (H/W).

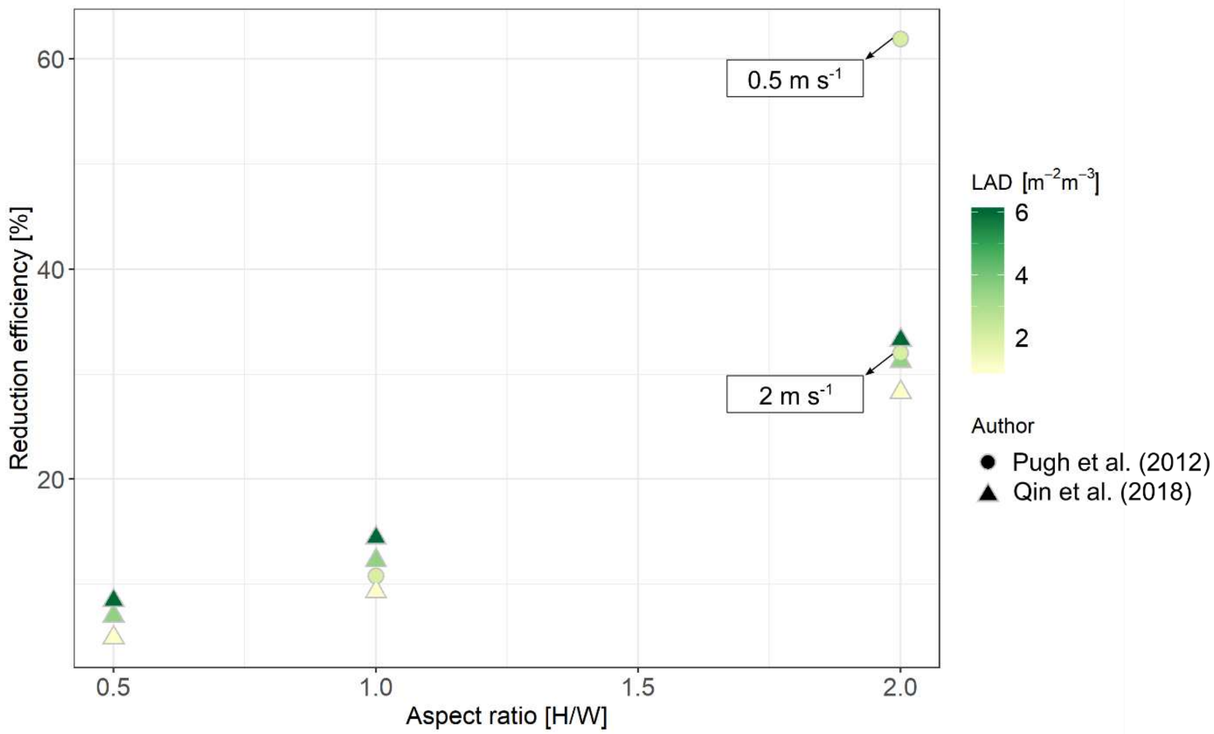


Figure 6: The results of Pugh et al. (2012) and Qin et al. (2018) of the PM_{10} reduction efficiency (E_C) for different values of LAD [m^2 m^{-3}] and wind speed [m s^{-1}] (values in the boxes) as a function of the street canyon aspect ratio (H/W).

7 Discussion and recommendations

The analysis of field and modelling studies described in the literature suggests that the effect of green walls on particle deposition depends on three main parameters: species, pollution level and residence time. The authors of this review already want to stress that owing to the limited amount of studies, these conclusions need to be substantiated with more quantitative field measurement data. Although rainfall was suggested to be unnecessary to sustain PM deposition, it results in wash-off and possible resuspension of PM afterwards and, thus, plays an important role in the PM pathway. In addition, we discuss the similarities with vegetation barriers.

Species

From this literature review, it is apparent that the combination of macro- and microstructure of a plant species determines its PM mitigation potential. While these characteristics should be regarded all together to make sound conclusions, this was not done in most studies. This could have explained the high variation in significant plant characteristics for PM deposition between different GW species and GW species in comparison with trees and shrubs. It should be noted that far more research has been performed on tree and shrub species and only a limited set of species found in GW were investigated. For example, in the case of a green façade (direct or indirect) only *Hedera helix* has been investigated. Therefore, more research is required to conclude which GW species or set of species turn out ideal for PM capture and to clarify the discrepancies listed above. It is key that different green wall types will be investigated by means of modelling studies to investigate the impact of the growing method on PM capture. Furthermore, the climate conditions to which the plants will be subjected should be taken into account, since these climate conditions can have an effect on the plants' PM reduction efficiency. For example, during dry and hot periods, vegetation can become water stressed which can result in plant failure. In addition, high wind velocities can be present at the windward side of tall buildings and can lead to wind-induced mechanical damage of vegetation, possibly leading to plant failure (Hunter et al., 2014). More research is requested to examine the effect of these factors on the PM mitigating potential of GW species. With this knowledge, species that are performing adequately to the prevailing climate conditions can be selected to assure that PM deposition is sustained.

Pollution level

Different studies on GW clearly indicate that a higher atmospheric particle concentration results in higher PM concentration on the plant leaves (Ottelé et al., 2010; Przybysz et al., 2014; Sternberg et al., 2010). On the other hand, the ambient PM concentration had a significant relationship with deposited PM only for particles larger than 5 µm (Paull et al., 2020). Furthermore, the majority of the deposited PM constituted of fine- and ultrafine PM (0.5-2.5 µm) when counting the particles, typically associated with the emission of traffic, while coarse PM represents the largest fraction on mass basis. The accumulation of PM over time was only significant in one study (Przybysz et al., 2014), hence research should focus on the influence of meteorological conditions on the PM content of leaves.

Residence time

Increased residence times of PM in a street resulted in more removal of PM by the present GW (Pugh et al., 2012; Qin et al., 2018). This suggest that green walls have a significant unexploited potential for mitigating PM pollution in urban environments. An active GW, in which the polluted air is actively drawn through the vegetation, was already tested for indoor PM mitigation, but the outdoor application has not yet been considered and more research should be conducted to improve the contact between PM and green wall species outdoors. The construction of the GW could be adapted in such a way that natural airstreams are created. For example, cavities between a green wall and the building envelope may induce a natural chimney effect, resulting in a higher air flow through the green wall. In addition, extensively validated models are required to accurately calculate the impact of green walls on air flow and the PM concentration on site. Only then, well founded decisions can be made on the design of new green wall infrastructures. These models could also be used to investigate how the surface boundary layer next to GW influences air flow and the influence of the vegetation type, type of GW (e.g. structure and material used in case of an LWS) and the wall shape on this boundary layer.

Extensively validated models are also ideal to test new GW designs that would allow more polluted air come in contact with the plants. For this, wind tunnel studies with green wall species are vital, because they are the most suitable experiments to determine the relevant aerodynamic parameters and deposition/resuspension rate of PM on green wall species. However, there should be sufficient variation in boundary conditions (e.g. wind speed and direction), pollution level and plant species (including the LAD) to mimic real environmental conditions. When studying the interaction of PM in streets, the aspect ratio should be varied as well, since it has a lot of influence on the wind patterns and thus the dispersion of pollutants in these streets. Wind tunnel experiments also provide a dataset for validation, so that the performance of different urban dispersion and deposition models can be compared and tested against acceptance criteria that are set beforehand. It would be of interest to include the climbing aid of indirect green façades and the pre-cultivated panels and substrate of LWS in the CFD models as they will influence air flow. Additionally, the use of real PM in wind tunnel experiments has rarely been reported. It will result in more reliable data about PM deposition and resuspension. Nevertheless, the models constructed at wind tunnel scale should be validated with data from field studies to check if they are still valid for the complex real-world.

Rainfall

Both natural and simulated rainfall resulted in a significant wash-off of PM of all size fractions with the highest wash-off for PM_{10}, while PM_1 showed relatively low wash-off rates. Washing leaves to mimic rainfall seemed not to be a good method to test the wash-off effect (Weerakkody et al., 2018c). Next, inter-species variability was observed with smooth leaves showing more PM wash-off. Yet, more research on the effect of rainfall is relevant and it would be of interest to know all the fluxes of deposition and resuspension. For example, wind driven resuspension was studied to a very limited extent (Nowak et al., 2013).

Vegetation barrier

A bit out of context for this review, but still worth mentioning are the roadway barriers that are grown with vegetation, which can be seen as a form of a green wall. While Morakinyo et al. (2016) is one of the few that studied vegetation directly attached to a solid wall, the combination of a solid barrier with a row of trees or shrubs has already been studied in more detail. It was demonstrated in field and modelling studies that the combination of a solid noise barrier with a row of trees or shrubs is able to improve near-road air quality and it does so more effectively than a solid barrier alone (Baldauf et al., 2008; Hashad et al., 2020; Tong et al., 2016). Baldauf et al. (2018) concluded that this type of vegetation barrier should be thick, have a high LAD and the vegetation should be sufficiently higher than the solid barrier to effectively improve near-road air quality along highways. These findings are also valuable for the application of roadway barriers which are grown with vegetation. However, the influence on PM dispersion of the direct attachment of vegetation to the solid barrier needs to be studied in more detail.

8 Conclusions

In general, the (limited) number of studies on the effect of green walls on PM deposition have recognised the PM mitigating potential of green walls in the built environment. Careful species selection is key when designing green walls, since it highly determines PM accumulation with values ranging from 10^{10} to 10^{11} particles per m^2 leaf area along a high intensity traffic road. Species deposition capacity is related to WLAI, leaf morphology (leaf size and shape), and leaf micromorphology (wax, stomatal density, grooves and trichomes). Related to the latter, more research is highly necessary to resolve current contradictory results. Higher PM levels clearly lead to more PM accumulation on leaf surfaces, but it was not conclusive if the PM content was ever increasing after plantation. Modelling studies have shown that the residence time of PM in a street canyon determines the PM reduction efficiency. A higher reduction efficiency was obtained for longer residence times, which are obtained in street canyons with a larger aspect ratio and/or at lower wind speed. Nevertheless, more field studies, wind tunnel studies and validated modelling studies are necessary to eliminate discrepancies about the key parameters (i.e. species, pollution level and residence time) determining PM capture by GW.

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10 Bibliography

Abbasi, S., Jansson, A., Sellgren, U., Olofsson, U., 2013. Particle emissions from rail traffic: A literature review. Crit. Rev. Environ. Sci. Technol. 43, 2511–2544. https://doi.org/10.1080/10643389.2012.685348

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

Amorim, J.H., Rodrigues, V., Tavares, R., Valente, J., Borrego, C., 2013. CFD modelling of the aerodynamic effect of trees on urban air pollution dispersion. Sci. Total Environ. 461–462, 541–551. https://doi.org/10.1016/j.scitotenv.2013.05.031

Baldacchini, C., Castanheiro, A., Maghakyan, N., Sgrigna, G., Verhelst, J., Alonso, R., Amorim, J.H., Bellan, P., Bojović, D.D., Breuste, J., Bühler, O., Cântar, I.C., Cariñanos, P., Carriero, G., Churkina, G., Dinca, L., Esposito, R., Gawroński, S.W., Kern, M., Le Thiec, D., Moretti, M., Ningal, T., Rantzoudi, E.C., Sinjur, I., Stojanova, B., Aničić Urošević, M., Velikova, V., Živojinović, I., Sahakyan, L., Calfapietra, C., Samson, R., 2017. How Does the Amount and Composition of PM Deposited on Platanus acerifolia Leaves Change Across Different Cities in Europe? Environ. Sci. Technol. 51, 1147–1156. https://doi.org/10.1021/acs.est.6b04052

Baldauf, R., McPherson, G., Wheaton, L., Zhang, M.A.X., Cahill, T.O.M., Bailey, C., Hemphill Fuller, C., Withycombe, E., Titus, K., 2013. Integrating Vegetation and Green Infrastructure into Sustainable Transportation Planning. TR News 288, 14–18.

Baldauf, R., Thoma, E., Khlystov, A., Isakov, V., Bowker, G., Long, T., Snow, R., 2008. Impacts of noise barriers on near-road air quality. Atmos. Environ. 42, 7502–7507. https://doi.org/10.1016/j.atmosenv.2008.05.051

Baldauf, R.W., Devlin, R.B., Gehr, P., Giannelli, R., Hassett-Sipple, B., Jung, H., Martini, G., McDonald, J., Sacks, J.D., Walker, K., 2016. Ultrafine particle metrics and research considerations: Review of the 2015 UFP workshop. Int. J. Environ. Res. Public Health 13, 1–21. https://doi.org/10.3390/ijerph13111054

Beckett, K.P., Freer-Smith, P.H., Taylor, G., 2000. The capture of particulate pollution by trees at five contrasting urban sites. Arboric. J. 24, 209–230. https://doi.org/10.1080/03071375.2000.9747273

Beckett, K.P., Freer-Smith, P.H., Taylor, G., 1998. Urban woodlands: Their role in reducing the effects of particulate pollution. Environ. Pollut. 99, 347–360. https://doi.org/10.1016/S0269-7491(98)00016-5

Bruse, M., 2007. Particle filtering capacity of urban vegetation: A microscale numerical approach. Berliner Geogr. Arb. 109, 61–70.

Buccolieri, R., Santiago, J.L., Rivas, E., Sanchez, B., 2018. Review on urban tree modelling in CFD simulations: Aerodynamic, deposition and thermal effects. Urban For. Urban Green. 31, 212–220. https://doi.org/10.1016/j.ufug.2018.03.003

Castanheiro, A., Samson, R., De Wael, K., 2016. Magnetic- and particle-based techniques to investigate metal deposition on urban green. Sci. Total Environ. 571, 594–602. https://doi.org/10.1016/j.scitotenv.2016.07.026

De Maerschalck, B., Maiheu, B., Janssen, S., Vankerkom, J., 2010. CFD-Modelling of complex plant-atmosphere interactions: direct and indirect effects on local turbulence, in: CLIMAQS Workshop 'Local Air Quality and Its Interactions with Vegetation.' pp. 839–842.

Dzierzanowski, K., Popek, R., Gawrońska, H., Saebø, A., Gawroński, S.W., 2011. Deposition of particulate matter of different size fractions on leaf surfaces and in waxes of urban forest species. Int. J. Phytoremediation 13, 1037–1046. https://doi.org/10.1080/15226514.2011.552929

EEA, 2017. Air quality in Europe - 2017 report, European Environment Agency.

https://doi.org/doi:10.2800/413142

Fowler, D., Skiba, U., Nemitz, E., Choubedar, F., Branford, D., Donovan, R., Rowland, P., 2003. Measuring aerosol and heavy metal deposition on urban woodland and grass using inventories of 210Pb and metal concentrations in soil. Water, Air Soil Pollut. Focus 4, 483–499.

Freer-Smith, P.H., Beckett, K.P., Taylor, G., 2005. Deposition velocities to Sorbus aria, Acer campestre, Populus deltoides × trichocarpa "Beaupré", Pinus nigra and × Cupressocyparis leylandii for coarse, fine and ultra-fine particles in the urban environment. Environ. Pollut. 133, 157–167. https://doi.org/10.1016/j.envpol.2004.03.031

Gallagher, J., Baldauf, R., Fuller, C.H., Kumar, P., Gill, L.W., McNabola, A., 2015. Passive methods for improving air quality in the built environment: A review of porous and solid barriers. Atmos. Environ. 120, 61–70. https://doi.org/10.1016/j.atmosenv.2015.08.075

Gromke, C., Buccolieri, R., Di Sabatino, S., Ruck, B., 2008. Dispersion study in a street canyon with tree planting by means of wind tunnel and numerical investigations - Evaluation of CFD data with experimental data. Atmos. Environ. 42, 8640–8650. https://doi.org/10.1016/j.atmosenv.2008.08.019

Gromke, C., Ruck, B., 2012. Pollutant Concentrations in Street Canyons of Different Aspect Ratio with Avenues of Trees for Various Wind Directions. Boundary-Layer Meteorol. 144, 41–64. https://doi.org/10.1007/s10546-012-9703-z

Gromke, C., Ruck, B., 2005. Die Simulation atmosphärischer Grenzschichten in Windkanälen, in: Fachtagung "Lasermethoden in Der Strömungsmesstechnik." pp. 1–8.

Grote, R., Samson, R., Alonso, R., Amorim, J.H., Cariñanos, P., Churkina, G., Fares, S., Thiec, D. Le, Niinemets, Ü., Mikkelsen, T.N., Paoletti, E., Tiwary, A., Calfapietra, C., 2016. Functional traits of urban trees: air pollution mitigation potential. Front. Ecol. Environ. 14, 543–550. https://doi.org/10.1002/fee.1426

Hashad, K., Yang, B., Baldauf, R.W., Deshmukh, P., Isakov, V., Zhang, K.M., 2020. Enhancing the local air quality benefits of roadside green infrastructure using low-cost, impermeable, solid structures (LISS). Sci. Total Environ. 717. https://doi.org/10.1016/j.scitotenv.2020.137136

He, C., Qiu, K., Alahmad, A., Pott, R., 2020. Particulate matter capturing capacity of roadside evergreen vegetation during the winter season. Urban For. Urban Green. 48. https://doi.org/10.1016/j.ufug.2019.126510

HEI, 2010. Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects, Special Report 17.

Hirabayashi, S., Kroll, C.N., Nowak, D.J., 2012. i-Tree Eco Dry Deposition Model Descriptions 35.

Hofman, J., Maher, B.A., Muxworthy, A.R., Wuyts, K., Castanheiro, A., Samson, R., 2017. Biomagnetic Monitoring of Atmospheric Pollution: A Review of Magnetic Signatures from Biological Sensors. Environ. Sci. Technol. 51, 6648–6664. https://doi.org/10.1021/acs.est.7b00832

Hofman, J., Wuyts, K., Van Wittenberghe, S., Samson, R., 2014. On the temporal variation of leaf magnetic parameters: Seasonal accumulation of leaf-deposited and leaf-encapsulated particles of a roadside tree crown. Sci. Total Environ. 493, 766–772. https://doi.org/10.1016/j.scitotenv.2014.06.074

Holmes, N.S., Morawska, L., 2006. A review of dispersion modelling and its application to the dispersion of particles: An overview of different dispersion models available. Atmos. Environ. 40, 5902–5928. https://doi.org/10.1016/j.atmosenv.2006.06.003

Hong, B., Qin, H., Lin, B., 2018. Prediction of wind environment and indoor/outdoor relationships for PM2.5 in different building-tree grouping patterns. Atmosphere (Basel). 9. https://doi.org/10.3390/atmos9020039

Hunter, A.M., Williams, N.S.G., Rayner, J.P., Aye, L., Hes, D., Livesley, S.J., 2014. Quantifying the thermal performance of green façades: A critical review. Ecol. Eng. 63, 102–113. https://doi.org/10.1016/j.ecoleng.2013.12.021

Jacobsen, M.Z., 2005. Fundamentals of atmospheric modelling, 2nd ed. Cambridge University Press.

Janhäll, S., 2015. Review on urban vegetation and particle air pollution - Deposition and dispersion. Atmos. Environ. 105, 130–137. https://doi.org/10.1016/j.atmosenv.2015.01.052

Jimoda, L. a., 2012. Effects of particulate matter on human health, the ecosystem, climate and materials: A review. Facta Univ. Work. Living Evniromental Prot. 9, 27–44. https://doi.org/10.5124/jkma.2007.50.2.175

Kardel, F., Wuyts, K., Maher, B.A., Hansard, R., Samson, R., 2011. Leaf saturation isothermal remanent magnetization (SIRM) as a proxy for particulate matter monitoring: Inter-species differences and in-season variation. Atmos. Environ. 45, 5164–5171. https://doi.org/10.1016/j.atmosenv.2011.06.025

Ketzel, M., Berkowicz, R., Muller, W.J., Lohmeyer, A., 2002. Dependence of street canyon concentrations on above-roof wind speed - implications for numerical modelling. Int. J. Environ. Pollut. 17, 356. https://doi.org/10.1504/IJEP.2002.000678

Kim, K.H., Kabir, E., Kabir, S., 2015. A review on the human health impact of airborne particulate matter. Environ. Int. 74, 136–143. https://doi.org/10.1016/j.envint.2014.10.005

Koch, K., Samson, R., Denys, S., 2019. Aerodynamic characterisation of green wall vegetation based on plant morphology: An experimental and computational fluid dynamics approach. Biosyst. Eng. 178, 34–51. https://doi.org/10.1016/j.biosystemseng.2018.10.019

Koch, K., Ysebaert, T., Denys, S., Samson, R., 2020. Urban heat stress mitigation potential of green walls: A review. Urban For. Urban Green. 55, 1618–8667. https://doi.org/10.1016/j.ufug.2020.126843

Kumar, P., Ketzel, M., Vardoulakis, S., Pirjola, L., Britter, R., 2011. Dynamics and dispersion modelling of nanoparticles from road traffic in the urban atmospheric environment - A review. J. Aerosol Sci. 42, 580–603. https://doi.org/10.1016/j.jaerosci.2011.06.001

Lelieveld, J., Evans, J.S., Fnais, M., Giannadaki, D., Pozzer, A., 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature 525, 367–371. https://doi.org/10.1038/nature15371

Leonard, R.J., McArthur, C., Hochuli, D.F., 2016. Particulate matter deposition on roadside plants and the importance of leaf trait combinations. Urban For. Urban Green. 20, 249–253. https://doi.org/10.1016/j.ufug.2016.09.008

Litschke, T., Kuttler, W., 2008. On the reduction of urban particle concentration by vegetation - A review. Meteorol. Zeitschrift 17, 229–240. https://doi.org/10.1127/0941-2948/2008/0284

Liu, C.H., Leung, D.Y.C., Barth, M.C., 2005. On the prediction of air and pollutant exchange rates in street canyons of different aspect ratios using large-eddy simulation. Atmos. Environ. 39, 1567–1574. https://doi.org/10.1016/j.atmosenv.2004.08.036

Lovett, G.M., 1994. Atmospheric Deposition of Nutrients and Pollutants in North-America - an Ecological Perspective. Ecol. Appl. 4, 629–650. https://doi.org/10.2307/1941997

Manso, M., Castro-Gomes, J., 2015. Green wall systems: A review of their characteristics. Renew. Sustain. Energy Rev. 41, 863–871. https://doi.org/10.1016/j.rser.2014.07.203

Mo, L., Ma, Z., Xu, Y., Sun, F., Lun, X., Liu, X., Chen, J., Yu, X., 2015. Assessing the capacity of plant species to accumulate particulate matter in Beijing, China. PLoS One 10, 1–18. https://doi.org/10.1371/journal.pone.0140664

Morakinyo, T.E., Lam, Y.F., 2016. Simulation study of dispersion and removal of particulate matter from traffic by road-side vegetation barrier. Environ. Sci. Pollut. Res. 23, 6709–6722. https://doi.org/10.1007/s11356-015-5839-y

Morakinyo, T.E., Lam, Y.F., Hao, S., 2016. Evaluating the role of green infrastructures on near-road pollutant dispersion and removal: Modelling and measurement. J. Environ. Manage. 182, 595–605. https://doi.org/10.1016/j.jenvman.2016.07.077

Muhammad, S., Wuyts, K., Samson, R., 2019. Atmospheric net particle accumulation on 96 plant species with contrasting morphological and anatomical leaf characteristics in a common garden experiment. Atmos. Environ. 202, 328–344. https://doi.org/10.1016/j.atmosenv.2019.01.015

Nowak, D.J., Crane, D.E., Stevens, J.C., 2006. Air pollution removal by urban trees and shrubs in the United States. Urban For. Urban Green. 4, 115–123. https://doi.org/10.1016/j.ufug.2006.01.007

Nowak, D.J., Hirabayashi, S., Bodine, A., Hoehn, R., 2013. Modeled PM2.5 removal by trees in ten U.S. cities and associated health effects. Environ. Pollut. 178, 395–402. https://doi.org/10.1016/j.envpol.2013.03.050

Ottelé, M., van Bohemen, H.D., Fraaij, a. L. a, 2010. Quantifying the deposition of particulate matter on climber vegetation on living walls. Ecol. Eng. 36, 154–162. https://doi.org/10.1016/j.ecoleng.2009.02.007

Paull, N.J., Krix, D., Irga, P.J., Torpy, F.R., 2020. Airborne particulate matter accumulation on common green wall plants. Int. J. Phytoremediation 22, 594–606. https://doi.org/10.1080/15226514.2019.1696744

Perini, K., Ottelé, M., Giulini, S., Magliocco, A., Roccotiello, E., 2017. Quantification of fine dust deposition on different plant species in a vertical greening system. Ecol. Eng. 100, 268–276. https://doi.org/10.1016/j.ecoleng.2016.12.032

Petroff, A., Mailliat, A., Amielh, M., Anselmet, F., 2008a. Aerosol dry deposition on vegetative canopies. Part I: Review of present knowledge. Atmos. Environ. 42, 3625–3653. https://doi.org/10.1016/j.atmosenv.2007.09.043

Petroff, A., Mailliat, A., Amielh, M., Anselmet, F., 2008b. Aerosol dry deposition on vegetative canopies . Part II : A new modelling approach and applications. Atmos. Environ. 42, 3654–3683. https://doi.org/10.1016/j.atmosenv.2007.09.043

Petroff, A., Zhang, L., 2010. Development and validation of a size-resolved particle dry deposition scheme for application in aerosol transport models. Geosci. Model Dev. 3, 753–769. https://doi.org/10.5194/gmd-3-753-2010

Pettit, T., Irga, P.J., Torpy, F.R., 2019. The in situ pilot-scale phytoremediation of airborne VOCs and particulate matter with an active green wall. Air Qual. Atmos. Heal. 12, 33–44. https://doi.org/10.1007/s11869-018-0628-7

Przybysz, A., Sæbø, A., Hanslin, H.M., Gawroński, S.W., 2014. Accumulation of particulate matter and trace elements on vegetation as affected by pollution level, rainfall and the passage of time. Sci. Total Environ. 481, 360–369. https://doi.org/10.1016/j.scitotenv.2014.02.072

Pugh, T.A.M., MacKenzie, A.R., Whyatt, J.D., Hewitt, C.N., 2012. Effectiveness of green infrastructure for improvement of air quality in urban street canyons. Environ. Sci. Technol. 46, 7692–7699. https://doi.org/10.1021/es300826w

Qin, H., Hong, B., Jiang, R., 2018. Are green walls better options than green roofs for mitigating PM10 pollution? CFD simulations in urban street canyons. Sustainability 10. https://doi.org/10.3390/su10082833

Riley, B., 2017. The state of the art of living walls: Lessons learned. Build. Environ. 114, 219–232. https://doi.org/10.1016/j.buildenv.2016.12.016

Roupsard, P., Amielh, M., Maro, D., Coppalle, A., Branger, H., Connan, O., 2013. Measurement in a wind tunnel of dry deposition velocities of submicron aerosol with associated turbulence onto rough and smooth urban surfaces. J. Aerosol Sci. 55, 12–24. https://doi.org/10.1016/j.jaerosci.2012.07.006

Sæbø, A., Popek, R., Nawrot, B., Hanslin, H.M., Gawronska, H., Gawronski, S.W., 2012. Plant species differences in particulate matter accumulation on leaf surfaces. Sci. Total Environ. 427–428, 347–354. https://doi.org/10.1016/j.scitotenv.2012.03.084

Samson, R., Moretti, M., Amorim, J.H., Branquinho, C., Fares, S., Morelli, F., Niinemets, Ü., Paoletti, E., Pinho, P., Sgrigna, G., Stojanovski, V., Tiwary, A., Sicard, P., Calfapietra, C., 2019. Towards an integrative approach to evaluate the environmental ecosystem services provided by urban forest. J. For. Res. 30, 1981–1996. https://doi.org/10.1007/s11676-019-00916-x

Sternberg, T., Viles, H., Cathersides, A., Edwards, M., 2010. Dust particulate absorption by ivy (Hedera helix L) on historic walls in urban environments. Sci. Total Environ. 409, 162–168. https://doi.org/10.1016/j.scitotenv.2010.09.022

Tallis, M., Taylor, G., Sinnett, D., Freer-Smith, P., 2011. Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments. Landsc. Urban Plan. 103, 129–138. https://doi.org/10.1016/j.landurbplan.2011.07.003

Tong, Z., Baldauf, R.W., Isakov, V., Deshmukh, P., Max Zhang, K., 2016. Roadside vegetation barrier designs to mitigate near-road air pollution impacts. Sci. Total Environ. 541, 920–927. https://doi.org/10.1016/j.scitotenv.2015.09.067

van Bohemen, H.D., Fraaij, a L. a, Ottelé, M., 2008. Ecological engineering, green roofs and the greening of vertical walls of buildings in urban areas. Ecocity World Summit 2008 Proc. 1–10. https://doi.org/10.1016/j.envpol.2010.10.029

Vardoulakis, S., Fisher, B.E.A., Pericleous, K., Gonzalez-Flesca, N., 2003. Modelling air quality in street canyons: A review. Atmos. Environ. 37, 155–182. https://doi.org/Pii S1352-2310(02)00857-9

Vos, P.E.J., Maiheu, B., Vankerkom, J., Janssen, S., 2013. Improving local air quality in cities: To tree or not to tree? Environ. Pollut. 183, 113–122. https://doi.org/10.1016/j.envpol.2012.10.021

Weber, F., Kowarik, I., Säumel, I., 2014. Herbaceous plants as filters: Immobilization of particulates along urban street corridors. Environ. Pollut. 186, 234–240. https://doi.org/10.1016/j.envpol.2013.12.011

Weerakkody, U., Dover, J.W., Mitchell, P., Reiling, K., 2019a. Topographical structures in planting design of living walls affect their ability to immobilise traffic-based particulate matter. Sci. Total Environ. 660, 644–649. https://doi.org/10.1016/j.scitotenv.2018.12.292

Weerakkody, U., Dover, J.W., Mitchell, P., Reiling, K., 2019b. Topographical structures in planting design of living walls affect their ability to immobilise traffic-based particulate matter. Sci. Total Environ. 660, 644–649. https://doi.org/10.1016/j.scitotenv.2018.12.292

Weerakkody, U., Dover, J.W., Mitchell, P., Reiling, K., 2018a. Quantification of the traffic-generated particulate matter capture by plant species in a living wall and evaluation of the important leaf characteristics. Sci. Total Environ. 635, 1012–1024. https://doi.org/10.1016/j.scitotenv.2018.04.106

Weerakkody, U., Dover, J.W., Mitchell, P., Reiling, K., 2018b. Evaluating the impact of individual leaf traits on atmospheric particulate matter accumulation using natural and synthetic leaves. Urban For. Urban Green. 30, 98–107. https://doi.org/10.1016/j.ufug.2018.01.001

Weerakkody, U., Dover, J.W., Mitchell, P., Reiling, K., 2018c. The impact of rainfall in remobilising particulate matter accumulated on leaves of four evergreen species grown on a green screen and a living wall. Urban For. Urban Green. 35, 21–31. https://doi.org/10.1016/j.ufug.2018.07.018

Weerakkody, U., Dover, J.W., Mitchell, P., Reiling, K., 2017. Particulate matter pollution capture by leaves of seventeen living wall species with special reference to rail-traffic at a metropolitan station. Urban For. Urban Green. 27, 173–186. https://doi.org/10.1016/j.ufug.2017.07.005

WHO, 2016a. Urban Health.

WHO, 2016b. Ambient air pollution: a global assessment of exposure and burden of disease.