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Particulate matter pollution capture by leaves of seventeen living wall species with special reference to rail-traffic at a metropolitan station

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ABSTRACT

Atmospheric Particulate Matter (PM) constitutes a considerable fraction of urban air pollution, and urban greening is a potential method of mitigating this pollution. The value of living wall systems has received scant attention in this respect. This study examined the inter-species variation of particulate capture by leaves of seventeen plant species present in a living wall at New Street railway station, Birmingham, UK. The densities of different size fractions of particulate pollutants (PM_1, $PM_{2.5}$ and PM_{10}) on 20 leaves per species were quantified using an Environmental Scanning Electron Microscope (ESEM) and ImageJ image-analysis software. The overall ability of plant leaves to remove PM from air was quantified using PM density and LAI (Leaf Area Index); any inter-species variations were identified using one-way Anova followed by Tukey's pairwise comparison. This study demonstrates a considerable potential for living wall plants to remove particulate pollutants from the atmosphere. PM capture levels on leaves of different plant species were significantly different for all particle size fractions ($P < 0.001$). Smaller-leaved *Buxus sempervirens* L., *Hebe albicans* Cockayne, *Thymus vulgaris* L. and *Hebe x youngii* Metcalf showed significantly higher capture levels for all PM size fractions. PM densities on adaxial surfaces of the leaves were significantly higher compared to abaxial surfaces in the majority of the species studied (t-test, $P < 0.05$). According to EDX (Energy Dispersive X-ray) analysis, a wide spectrum of elements were captured by the leaves of the living wall plants, which were mainly typical railway exhaust particles and soil dust. Smaller leaves, and hairy and waxy leaf surfaces, appear to be leaf traits facilitating removal of PM from the air, and hence a collection of species which share these characters would probably optimize the benefit of living wall systems as atmospheric PM filters.

1. Introduction

Outdoor air pollution caused an estimated 3.7 million premature deaths worldwide in 2012, mainly due to atmospheric Particulate Matter (PM) less than 10 µm in aerodynamic diameter (PM_{10}), ozone, nitrogen dioxide and sulphur dioxide (WHO, 2014). The European Environment Agency (EEA, 2016) estimated that in the 2012–2014 period 50–63% and 85–91% of the urban population in Europe were exposed to levels of PM_{10} and $PM_{2.5}$ (respectively) which exceeded the recommended World Health Organisation (WHO) annual limits (PM_{10}: 20 µg m^{-3} and $PM_{2.5}$: 10 µg m^{-3}). EEA (2016) also estimated that 467,000 premature deaths in Europe could be attributed to $PM_{2.5}$ (PM less than 2.5 µm in aerodynamic diameter) in 2013. Out of 40,000 annual deaths estimated to be caused by outdoor air pollution in the UK, 29,000 were caused by PM pollution (Royal College of Physicians, 2016). Long-term exposure to airborne PM is directly associated with potentially fatal childhood diseases including post-neonatal infant mortality (Laden et al., 2006), Sudden Infant Death Syndrome (SIDS) (Woodruff et al., 2006) and various other diseases which affect all segments of the community such as cardiopulmonary diseases, lung cancer (Pope et al., 2011) atherosclerosis (Araujo, 2011) and asthma (Anderson et al., 2013). Ultrafine particles ($PM_{0.1}$), PM less than 0.1 µm

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in aerodynamic diameter can cause serious damage by entering the liver, spleen, kidney and the brain (via the olfactory nerves) (Solomon et al., 2012). They can also reach the lower respiratory system and change alveolar macrophage functions due to toxic chemicals carried by the particles (e.g. polycyclic aromatic hydrocarbons (PAHs) and heavy metals) (Riddle et al., 2009). On entering the human bloodstream, they can create systemic inflammatory changes, which can lead to serious complications in blood coagulability (Seaton et al., 1995). The annual cost to society due to particulate pollution in the UK has been estimated at £16 billion (COMEAP, 2010).

Coarse particles can originate from natural sources and anthropogenic activities, while fine particles mainly originate from vehicle emissions (gasoline and diesel), combustion, and industrial processes (Chow et al., 2006). Ultra-fine particles mostly originate from transport and photochemical reactions in the atmosphere (Chow et al., 2006). These particles contain toxic compounds such as heavy metals, PAHs, polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs) and polychlorinated biphenyls (PCBs), making them more hazardous and carcinogenic (Dzierzanowski et al., 2011). The International Agency for Research on Cancer (IARC) classified diesel exhaust as a Group 1 (carcinogenic to humans) carcinogen (Silverman et al., 2012). The railway network is one of the main sources of air pollution in the UK due to diesel and electric train emissions (Thornes et al., 2016). In addition to particles generated via rail traffic exhaust, particles can also be generated due to wheel friction, friction with overhead cables and when applying brakes; the particles generated in these circumstances fall mainly within the ultrafine range (Thornes et al., 2016).

Particulate levels in many large cities in the UK exceed both the WHO guidelines and EU safe limits; air pollution mitigation approaches such as emission reduction, enhancing atmospheric dispersion and building high emission sources away from currently polluted or highly populated areas (Pugh et al., 2012) are unlikely to have any impact on city PM levels generated from transport. Increasing surface deposition has been identified as an effective short-term strategy to reduce atmospheric particulate pollutants (Pugh et al., 2012), especially those locally produced within cities due to transportation systems. Since vegetation can act as a sink for particulates (Beckett et al., 2000; Fowler et al., 2004; Freer-Smith et al., 2005) it has the potential to have a high impact in this respect. Trees are often the main source of greening considered in urban landscapes, however, there are several limitations and barriers to achieving urban greening purely by using trees, including (but not limited to): prevailing soil conditions, space utilisation, sub-surface infrastructure, availability of sunlight and the size of the trees compared to the adjacent buildings (Johnston and Newton, 2004). Green walls (vertical greening) could overcome most of these limitations by transforming building walls to greenery while minimizing land-take and providing additional benefits including thermal insulation, noise reduction and conservation of urban biodiversity and rewilding of cityscapes (Alexandri and Jones, 2007; Chiquet et al., 2013; Dover, 2015; Jepson, 2016; Johnston and Newton, 2004). Previous studies on green walls have focused more on the value of climbing plants, such as ivy, in reducing PM pollution and little information is available on the value of living walls in this respect (Cheetham et al., 2012) though see Perini et al. (2017) and Shackleton et al. (undated). Living walls are vertically growing hydroponic green wall systems which facilitate the growth of a variety of plant species with a potential for greater artistic expression than simply using climbing species (Dover, 2015). PM filtering behavior of living wall systems with reference to different PM size fractions of particulates and the optimal species composition for living wall systems to act as effective particulate matter traps are not well understood. This study explores the role of living wall systems in the reduction of PM pollution; in contrast to the work of Perini et al. (2017), particulate capture is investigated at street level adjacent to a pedestrian walkway.

In early research different technical approaches were taken to quantify particulate capture by vegetation, including comparison of dust-fall measurements between the canopy area and open space (Dochinger, 1980), atmospheric aerosol screening (Bache, 1979; Wiman, 1985) and deposition velocity models (Bache, 1979). The gravimetric method, which collects particulate matter in water by washing material off the leaves followed by filtering and weighing the residue has frequently been used (Beckett et al., 2000; Freer-Smith et al., 2005; Ram et al., 2012). However, there are several drawbacks to the latter technique: particulates held on the epicuticular wax or microstructures of leaves may not be washed-off and hence may not be weighed. In some research chloroform was used as the solvent to dissolve epicuticular wax and collect the PM trapped in the wax component (Dzierzanowski et al., 2011; Sæbø et al., 2012; Song et al., 2015). However, as chloroform is used as a solvent to dissolve non-polar molecules and the soluble fraction of PAHs (Castelli et al., 2002) eluting with such solvents has the potential to dissolve some particulates comprised of non-polar materials. In addition, according to pulmonary toxicity studies, the particle surface area and particulate count are more appropriate measures for smaller particles than particle mass (Sager and Castranova, 2009). Ottelé et al. (2010) quantified the number of particulates captured by leaves of *Hedera helix* by using a Scanning Electron Microscope (SEM) to image the particulates in situ and used an image analysis program to count and size-range the particles deposited on the leaves. However, SEM scanning areas are much smaller compared to leaf surface area; and hence, a representative number of micrographs should be taken to draw any conclusions on PM levels on leaves using this approach.

Removal of atmospheric particulates by vegetation is mainly driven by the interactions between the particles and plant surfaces including their morphological properties such as shape, size and orientation (Petroff et al., 2008). Particulate deposition on plants is thought to be influenced by particle diameter and the micro-roughness or micro-topography of the plant (Slinn, 1982). However, there is much debate on the impact of leaf size and morphology on particulate capture. Therefore, this study examined inter-species variation in PM removal by living wall species in order to understand the best species combinations to capture PM employing a SEM/image analysis approach. Particulate densities (the number of particulates deposited per unit area of leaf surface) on the adaxial (upper) and abaxial (under) surfaces of the leaves were also examined to understand any variation due to leaf size or morphology. Further to this, the elemental composition of the captured particulates was also studied to detect the elements which can be removed using living wall plants.

2. Material and methods

2.1. Site selection

Birmingham is a large city located in the West Midlands of England (Fig. 1) with a population of over 1.1 million (Birmingham City Council 2014). In Birmingham, PM accounted for 6.4% of the premature mortality rate in 2009 (Gowers et al., 2014). Birmingham New Street railway station is one of the busiest railway stations in the UK, with up to 140,000 commuters and staff passing through daily (Thornes et al., 2016). Approximately 1,000 trains/day (comprising equal numbers of diesel and electric powered trains) pass through this station (Thornes, 2016) and $PM_{2.5}$ levels of up to 58 $\mu g\ m^{-3}$ for hourly intervals have been reported within the station (Zulkifli, 2015 cited in Thornes et al., 2016). Given the amount of pollution generated in and around the station, a free-standing modular living wall located on it's north side, 5 m above the railway (which is sunk below street level) and 3.2 m from the closest platform (Fig. 1) (52°28′41.2″ N 10°53′48.7″ W) was selected as the experimental site. The living wall was manufactured by ANS Global in 2012 and was subsequently managed by Network Rail; the structure is 77 m long and varies in height from 4.5 m near the station to 3.5 m at its furthest point (300 m^2 in total) and hosted twenty different species of plants (Table 1). A low (0.5 m) stone-clad planter