Urban Forestry & Urban Greening 30 (2018) 98–107

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

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

Evaluating the impact of individual leaf traits on atmospheric particulate matter accumulation using natural and synthetic leaves

Udeshika Weerakkody*, John W. Dover, Paul Mitchell, Kevin Reiling

The Green Wall Centre, Department of Biological Sciences, School of Life Sciences and Education, Staffordshire University, Stoke-on-Trent, Staffordshire, ST4 2DF, United Kingdom

A R T I C L E I N F O

Keywords:
Traffic-generated pollution
Living walls
Green walls
Green infrastructure
Leaf shape
Leaf size
Micromorphology

A B S T R A C T

The ability of vegetation to capture and retain atmospheric Particulate Matter (PM) is directly dependent on the interactions between PM and plant surfaces. However, the impact of individual leaf traits in this respect is still under debate due to variations in published findings. This study employed standardised experimental designs with natural and synthetic leaves in three experiments to explore the impact of individual leaf traits on traffic-generated PM accumulation whilst other influential variables were controlled. The impact of leaf size on PM deposition was explored using synthetic leaves of different sizes (small, medium and large) but with the same shape and surface characteristics (n = 20 for each category). The impact of leaf shape was examined using another set of synthetic leaves of different shape (elliptical, palmately-lobed and linear) but with the same surface area and the same surface characteristics (n = 20 for each category). PM accumulation (PM_1, $PM_{2.5}$ and PM_{10}) on these leaves was quantified using an Environmental Scanning Electron Microscope (ESEM) and ImageJ software. Any differences in PM capture levels due to leaf size and leaf shape were identified using one-way Anova and Tukey's pairwise comparison. In a subsequent experiment, equal-sized, square-shaped leaf sections obtained from four plant species (n = 20 for each species) with different micromorphology were exposed to traffic-generated pollution and any PM capture differences due to leaf micromorphology identified employing the same SEM/ImageJ and statistical approach. The results of all three experiments showed significant differences in PM accumulation between different leaf sizes ($p < 0.001$), between different leaf shapes ($p < 0.001$) and between different leaf micromorphology ($p < 0.001$) suggesting that all these characters are influential in the capture and retention of PM on leaves. Smaller leaves and complex leaf shapes (lobed leaves) showed a greater potential to capture and retain PM. Leaf surfaces with hair/trichomes, epicuticular wax, and surface-ridges accumulated more PM compared to smooth surfaces; of these characters, leaf hairiness/presence of trichomes was found to be the most important. Species sharing most of these important leaf traits are recommended as effective PM filters.

1. Introduction

Three different size fractions of Particulate Matter (PM) are of particular concern based upon their ability to be inhaled and toxicity: coarse particles/PM_{10} (aerodynamic diameter $\leq 10\,\mu m$), fine particles/$PM_{2.5}$ (aerodynamic diameter $\leq 2.5\,\mu m$) and ultra-fine particles/$PM_{0.1}$ (aerodynamic diameter $\leq 0.1\,\mu m$) (Chow et al., 2006; Solomon et al., 2012). Long-term exposure to coarse particles diminishes lung function and increases cardiovascular mortality (Gilmour et al., 1996). $PM_{2.5}$ can reach the narrower spaces in lungs (Brunkeef and Holgate, 2002) and cause lung cancer and cardio-vascular mortality associated with acute ischemic events (Solomon et al., 2012). Ultra-fine particles are more dangerous than the other size ranges as they can cross cell membranes and influence intracellular functions (Riddle et al., 2009). According to Seaton et al. (1995), $PM_{0.1}$ can cause systemic inflammatory changes by entering the blood stream or influence phagocytosis by accumulating in alveolar macrophages. They can also enter the brain via the olfactory nerves (Solomon et al., 2012) which may cause central nervous system disorders (e.g. Alzheimer's disease and Parkinson's disease) depending on their chemical composition and toxicity (Allsop et al., 2008; Maher et al., 2013).

Vegetation has been known as a sink for atmospheric PM for some time (Smith, 1977; Zulfacar, 1975) and the PM filtering behaviour of different types of vegetation has been studied using a range of different techniques (Beckett et al., 2000; Dover, 2015; Freer-Smith et al., 2004; Leonard et al., 2016; Maher et al., 2013; McDonald et al., 2007; Ottelé

* Corresponding author.
E-mail address: udeshika.w@research.staffs.ac.uk (U. Weerakkody).

https://doi.org/10.1016/j.ufug.2018.01.001
Received 12 September 2017; Received in revised form 13 December 2017; Accepted 1 January 2018
Available online 06 January 2018
1618-8667/

et al., 2010; Sternberg et al., 2010; Terzaghi et al., 2013; Zhang et al., 2017). Vegetation has been found to be more effective in removing PM from air compared to other building/land surfaces due to high air turbulence created by their complex morphology and large surface area (Roupsard et al., 2013; Tallis et al., 2011).

Dry deposition of PM on vegetation takes place via sedimentation under gravity, impaction (via turbulent transfer), interception, and diffusion (Slinn, 1982; Wang et al., 2006); processes antagonistic to deposition include aerodynamic resistance (resistance exerted on particles by the air), boundary layer resistance (reduced ability to cross the laminar air layer immediately adjacent to the deposition surface) and surface resistance (due to the properties of the deposition surface) (Davidson and Wu, 1990). The aerodynamic behaviour of different particle size fractions has been studied comprehensively under different meteorological conditions (Legg and Powell, 1979; Slinn, 1982; Petroff et al., 2008b). Wind speed, wind turbulence, humidity and rainfall all had a considerable influence on PM deposition on vegetation (Litschke and Kuttler, 2008; Tomasevic et al., 2005). PM deposition is also driven by the interactions between the particles and plant surfaces including the latter's geometrical properties such as shape, size, orientation and surface morphology (Chen et al., 2016; Freer-Smith et al., 2005; Leonard et al., 2016; Litschke and Kuttler, 2008; Petroff et al., 2008a; Tomasevic et al., 2005). Understanding the impact of such leaf traits on particulate deposition is thus crucial in the design and use of vegetation as an environmental control filter of particulate pollution. Legg and Powell (1979) modelled coarse particle impaction and sedimentation using fungal spores, and found that collection efficiency depended on the nature of the deposition surface. When the inertia of particles is too high to follow the wind flow deviations in the mean air flow around an object, they collide with it and deposit via impaction which can be, again, influenced by surface characteristics (Petroff et al., 2008a). When particles with smaller inertia, which thus follow the wind flow deviations in the mean airflow, pass over plant surfaces with less than half a diameter distance between the centre of the particle and the plant surface they can deposit via interception; this process is also influenced by the micro-topography of the plant (Slinn, 1982). Despite several studies that have examined these interactions, there remains much debate on the relative importance of different leaf characteristics on PM capture.

For example, coniferous species with leaf needles have been frequently cited as being good PM filters compared to broad-leaved species (Beckett et al., 2000; Dzierzanowski et al., 2011; Wang et al., 2011), and Shackleton et al. (2010) found "grass-like" (linear leaved) species to be the best PM filters out of the 16 species they tested. In contrast, Leonard et al. (2016) found significantly higher PM levels on lanceolate leaves compared to needle-like or linear leaves. The effects of epicuticular wax and leaf hairs have also produced mixed results. According to Dzierzanowski et al. (2011), the relationship between PM deposition and epicuticular wax does not depend on the amount of wax but on the structure and composition of the wax. Liu et al. (2012) found a negative impact of epicuticular wax in capturing particles but identified stomata, deep grooves, and leaf size as critically important characters. In contrast, Sæbø et al. (2012) found that PM deposition was a function of epicuticular wax content. Hairy leaves were found to be effective in accumulating PM in several different studies (Beckett et al., 2000; Kardel et al., 2012; Ram et al., 2012); conversely, Perini et al. (2017) found a negative impact of leaf hair on PM capture.

These discrepancies in findings could be attributed to various interactive effects of different leaf traits on PM capture. Standardising the influence of non-target leaf variables should facilitate the investigation of the impact of each leaf character on PM accumulation. Assuming that positive characteristics are at least additive, and at best synergistic, in value, species carrying a collection of such leaf traits should result in high PM capture efficiency and hence be most appropriate to employ as PM filters. As these characters are inherent and not manipulatable in natural leaves, use of leaf models or synthetic leaves can help in standardising the influence of non-target variables. We therefore explored the individual impact of leaf size, shape and micromorphology on PM accumulation on leaves using manipulative experimental designs with natural and synthetic leaves whilst controlling for the influence of additional variables. We believe this is the first attempt to use such standardised designs in the evaluation of the impact of individual leaf characters on PM accumulation. This study is a contribution to the optimisation of living walls (vertical, irrigated, greenery systems typically carrying multiple non-climbing or twining plant species) as urban PM filters (Weerakkody et al., 2017) and hence the experimental designs employed relate to the configuration of vertical greenery systems. Since traffic-generated pollution has become the major source of PM in the UK (DEFRA, 2015) and categorised as the most toxic class of PM globally (WHO, 2005), PM generated through road traffic was focused on in this study.

2. Materials and method

2.1. Site description

Stoke-on-Trent is a city located in Staffordshire, United Kingdom with an estimated population of 259,140 and population density of 6640 persons/km^2 (UKpopulation, 2017). Leek Road is one of the busiest single carriageways in Stoke-on-Trent, categorised as an A Road (Fig. 1), with a traffic density of 20,251 Average Daily Flow in 2016 (Department for Transport, 2017). Given the continuous pollution generation due to road traffic, a linear, grassed area, 11.5 m in width at Staffordshire University, located parallel to Leek Road (4.5 m distance from the road) (Fig. 1) was selected to erect experimental rigs.

2.2. Manufacturing the synthetic leaves and sampling natural leaves

Synthetic leaves used in these experiments were hand-made, using stiffened Poplin. A 1.0 m × 1.4 m section of commercially available Poplin (125.0 gm^{-2}), was stiffened by painting a sago solution (15 g of sago boiled in 1 L of water) on the fabric to ensure synthetic leaves had no pleats or folds. Cardboard templates of different sizes and shapes (sizes and shapes are detailed in Sections 2.4 and 2.5) were used to outline and cut the leaves from the fabric as required. Commercially available floral stems (plastic-paper covered stem wire, Handicrafts Ltd.) were stuck on one side of each of the leaves using fabric glue (Hobby glue gun- 230 V,15 W, Powerbox International Ltd.) and dried for 20 min. Using the same fabric, without any pleats or folds, produced artificial leaves with exactly the same surface characteristics and roughness (Fig. 2). Natural leaves required for the experiments were obtained from a free-standing living wall system (an experimentally manipulated system designed for our work on PM pollution, manufactured and installed by Nemec Cascade Garden Ltd., Czech Republic) (Fig. 1) located at the same site, facing Leek Road. Sampling and experiments were conducted on several occasions during March and April 2017. The mean temperature, mean humidity and mean wind speed of the study site was recorded as 12.8 °C, 68% and 2.3 m s^{-1} during this period.

2.3. Scanning electron microscope (ESEM)/ImageJ approach to quantifying PM densities on natural and artificial leaves

PM accumulation on both natural and synthetic leaves used in this study were quantified using an Environmental Scanning Electron Microscope (ESEM) (Model: JSM-6610LV) (Ottelé et al., 2010; Sternberg et al., 2010; Weerakkody et al., 2017) and ImageJ image analysis software (Collins, 2007). Sampling numbers and methods of each experiment are detailed in the relevant sections below. In experiments where complete leaves were exposed to pollution all the leaves were synthetic (Sections 2.4 and 2.5) and three leaf sections (5 mm × 5 mm) from every leaf blade were cropped out and mounted