Science of the Total Environment 635 (2018) 1012–1024

Contents lists available at ScienceDirect

Science of the Total Environment

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

Quantification of the traffic-generated particulate matter capture by plant species in a living wall and evaluation of the important leaf characteristics

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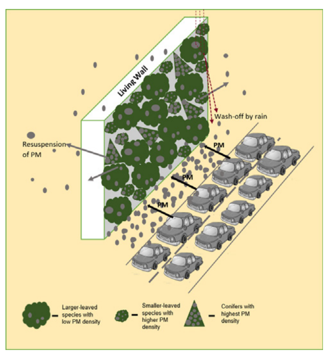
HIGHLIGHTS

- Traffic-based PM is a serious threat to human health, mainly in urban settings.
- Living walls can potentially provide a solution to atmospheric PM pollution.
- PM captured by living wall plants was evaluated using Scanning Electron Microscopy.
- Living wall species showed a great potential to capture and retain traffic-based PM.
- Smaller-leaved plants were particularly good at immobilizing traffic-based PM.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 23 February 2018
Received in revised form 27 March 2018
Accepted 7 April 2018
Available online xxxx

Editor: P. Kassomenos

Keywords:
Green infrastructure
Air pollution
Traffic-based pollution
Leaf characteristics

ABSTRACT

Traffic-generated particulate matter (PM) is a significant fraction of urban PM pollution and little is known about the use of living walls as a short-term strategy to reduce this pollution. The present study evaluated the potential of twenty living wall plants to reduce traffic-based PM using a living wall system located along a busy road in Stoke-on-Trent, UK. An Environmental Scanning Electron Microscope (ESEM) and ImageJ software were employed to quantify PM accumulation on leaves (PM_1, $PM_{2.5}$ and PM_{10}) and their elemental composition was determined using Energy Dispersive X-ray (EDX). Inter-species variation in leaf-PM accumulation was evaluated using a Generalized Linear Mixed-effect Model (GLMM) using time as a factor; any differential PM accumulation due to specific leaf characteristics (stomatal density, hair/trichomes, ridges and grooves) was identified. The study showed a promising potential for living wall plants to remove atmospheric PM; an estimated average number of $122.08 \pm 6.9 \times 10^7$ PM_1, $8.24 \pm 0.72 \times 10^7$ $PM_{2.5}$ and $4.45 \pm 0.33 \times 10^7$ PM_{10} were captured on 100 cm^2 of the living wall used in this study. Different species captured significantly different quantities of all particle sizes; the highest amount of all particle sizes was found on the leaf-needles of *Juniperus chinensis* L., followed by smaller-leaved species. In the absence of an apparent pattern in correlation between PM accumulation and leaf surface characteristics, the study highlighted the importance of individual leaf size in PM capture irrespective of their variable micro-morphology. The elemental composition of the captured particles showed a strong correlation with traffic-based PM and a wide range of important heavy metals. We conclude that the use of living walls that consist largely of smaller-leaved species and conifers can potentially have a significant impact in ameliorating air quality by removing traffic-generated PM pollution to improve the wellbeing of urban dwellers.

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https://doi.org/10.1016/j.scitotenv.2018.04.106
0048-9697/

1. Introduction

Epidemiological studies have revealed short and long-term impacts of PM and found increased levels of, hospital admissions, morbidity and mortality around the world (Pascal et al., 2014; Pope III et al., 2011; Seaton et al., 1995). Traffic-generated particulate matter (PM) is known to be responsible for a significant portion of urban particulate pollution (Pant and Harrison, 2013; Ranft et al., 2009). Globally, 25% of $PM_{2.5}$ (PM with <2.5 μm aerodynamic diameter) and PM_{10} (PM with <10 μm aerodynamic diameter) were estimated as being generated from road traffic (Karagulian et al., 2015) and in Europe road traffic is known to be responsible for more than 50% of PM_{10} (Künzli et al., 2000). Some studies found direct links between traffic-based PM and detrimental health effects (Brook et al., 2010; Hyun Cho et al., 2005; Ranft et al., 2009). Long-term exposure to these particles is known to cause premature death and various illnesses such as cardio-pulmonary diseases, lung cancer, allergies, brain damage and neuro-degenerative diseases (Brook et al., 2010; Pascal et al., 2014; Pope III et al., 2011; Seaton et al., 1995; Maher et al., 2016), and have even been linked to cognitive impairments in elderly people (Ranft et al., 2009). Pascal et al. (2014) also found a considerable rate of cardiovascular, cardiac, and ischemic mortality following short-term exposure to PM. Vehicular emission of $PM_{0.1}$ in the ultrafine range was recently highlighted as being important due to its higher toxicity and larger numbers compared to other size fractions (Lin et al., 2005). PM such as elemental carbon, hydrocarbons, metals, oxides of nitrogen, sulfates, ammonia (Fauser, 1999; Sharma et al., 2005) from vehicle exhaust, and various non-exhaust emissions from brake wear, tyre wear, clutch wear, abrasives, and road dust, are responsible for this pollution (Mulawa et al., 1997; Slezakova et al., 2007; Thorpe and Harrison, 2008; Timmers and Achten, 2016; Wåhlin et al., 2006).

Despite several initiatives taken to mitigate this pollution, such as reducing emission levels and separating high emission zones from populous areas (Pugh et al., 2012), particulate levels in air still remain problematic for human health and the environment (e.g. reducing visibility, affecting urban thermal environment) (Han et al., 2012; Yan et al., 2016). Since plants are known to filter these pollutants, the ability of vegetative barriers to reduce near-road PM levels has recently been studied under different environmental and weather conditions using various techniques (Abhijith et al., 2017; Blanusa et al., 2015; Gautam et al., 2005; Maher et al., 2008; Mori et al., 2015; Šíp and Beneš, 2016; Tong et al., 2015; Weber et al., 2014; Weerakkody et al., 2017). The potential of vertical greenery systems is frequently cited as a possible short-term solution due to their smaller land utilization, quick installation, reduced dependency on existing soil conditions, and additional ecosystem services (Cheetham et al., 2012; Dover, 2015; Johnston and Newton, 2004). Previous research has mainly focused on the use of climbing species to capture PM with most not specifically relating to road traffic (Ottelé et al., 2010; Sternberg et al., 2010; Tiwary et al., 2008; Xia et al., 2011) but see Dover and Phillips (2015). Except for the work of Perini et al. (2017), who studied two shrub species and two climbing species in a green façade located above street level, a small-scale study on shrubs (which included few living wall species) by Shackleton et al. (n.d.), and work by Weerakkody et al. (2017), relating to PM generated by rail traffic, the value of living wall plants in the reduction of motor traffic-based PM has not been evaluated.

Living walls are vertical greenery systems holding multiple species of plants usually grown at ground level, and contrasts with façade systems using climbers; living walls require piped irrigation systems which typically also deliver nutrients (Dover, 2015). The present study evaluated the potential of different living wall plants to capture and retain near-road PM which are mainly derived from traffic pollution. Inter-species variation in capture and retention of PM under the same environmental and weather conditions were evaluated to identify the best species to use as near-road PM filters. Leaf micro-morphological variations suspected to control their ability to capture and retain PM (Dzierzanowski et al., 2011; Kardel et al., 2012; Leonard et al., 2016; Räsänen et al., 2013; Sæbø et al., 2012; Wang et al., 2011; Weerakkody et al., 2018) were also investigated. The elemental composition of captured particles was analysed to identify their links to traffic-generated PM and potential health effects.

2. Material and methods

2.1. Site description

An experimentally manipulable, freestanding, modular living wall system was employed in this research. The wall was donated, designed, and installed by Nemec Cascade Garden Ltd., Czech Republic, in June 2016. The wall was erected 6 m from the edge of Leek Road, a busy 'A' road adjacent to Staffordshire University, Stoke-on-Trent, UK (Fig. 1). The road has an average daily traffic flow of 20,251 vehicles (Department for Transport, 2017). Stoke-on-Trent is a city located in central England with a population density of 6640 people/km^2. The local mortality burden attributed to anthropogenic $PM_{2.5}$ in Stoke-on-Trent was estimated at 5.6% in 2009 (Gowers et al., 2014).

This living wall was a first-generation prototype, having two 3.98 m × 2.09 m planting areas, one on each side of the wall. The planting areas were separated from the ground by a 0.5 m tall concrete platform encased in metal. This was an artificially irrigated system equipped with water and thermal sensors for easy maintenance. As traffic pollution is of concern, only the planting area of the front side (facing the road) is described here. Ten plants per species of twenty different species (Table 1), both evergreen and deciduous species, with various leaf morphotypes (size, shape and micromorphology) were planted as ten rows and twenty columns using a Latin Square design.

2.2. Leaf sampling

Samples were only taken from the middle six rows of the wall, avoiding the upper most two rows (based on accessibility) and the bottom two rows to avoid ground-level contaminations. Prior to sampling, plants were washed using a watering hose connected to a pressure head to remove existing particles from the leaves. Plants were left undisturbed for ten weeks (23rd of June 2016 to 1st September 2016) allowing continuous exposure to weather changes to minimize the effect of any variability in baseline PM levels. Sampling was carried out on six days during September and October 2016 under dry weather conditions. Thirty-six leaves from *Thymus vulgaris* and 18 leaves from rest of each species were taken in total. Three leaves were randomly taken from each species on every sample day (i.e. 6 days × 3 leaves/day = 18 leaves) with the exception of *T. vulgaris* which had 6 leaves/day removed. All species were sampled on every sample day. Sampled leaves were arranged in clean plastic containers using blue tac on their petioles, avoiding cross contamination between leaves or with container surfaces. Subsequently, containers were sealed and transferred to the laboratory for analysis. Samples were analysed fresh or stored at 9 °C in a refrigerator in the same storage containers until analysed (within 2 days of sampling) (Weerakkody et al., 2017).

2.3. Imaging leaves using a scanning electron microscope (SEM)

Sample preparation and imaging followed the same approach as in Weerakkody et al. (2017). An Environmental Scanning Electron Microscope (ESEM) (Model: JSM-6610LV) was employed to image the particulates captured on leaves and the leaf micromorphology. Six leaf sections (5.0 mm × 5.0 mm), three from each adaxial and abaxial surface were excised from each of the leaves larger than 2.5 cm^2 in area. Smaller leaves (apart from *T. vulgaris*) were cut into halves, one half to visualize adaxial surface, and one for the abaxial surface and mounted without further cropping. Leaves of *T. vulgaris* and leaf needles (*J. chinensis*) were scanned without cropping. *T. vulgaris* was too small to