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Topographical structures in planting design of living walls affect their ability to immobilise traffic-based Particulate Matter

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Abstract

Traffic-generated particulate matter (PM) pollution is a serious threat to human health and the environment, especially in urban settings. Recent studies have revealed the effectiveness of living walls in the reduction of this pollution; these systems use variable planting designs and their topographical dynamics might have an impact on PM dry deposition. This present study, employing an experimentally manipulable living wall system using box (*Buxus sempervirens* L.) plants, examined whether plants arranged in a design with heterogeneous topography have a differential PM removal capacity compared to plants in a design with homogenous topography. Two planting designs using 'short' and 'tall' plants, were simultaneously used on this living wall and equally exposed to traffic-based PM for 5 consecutive days. PM accumulation on leaves were estimated using an Environmental Scanning Electron Microscope and ImageJ image analysis software. The experiment was replicated four times changing the position of each design on the wall, and any variation in PM capture levels on leaves belonging to different designs were identified using a Generalised Linear Mixed-effect Models (GLMM). The planting design with topographical heterogeneity resulted in significantly higher PM densities (PM_{10}, $PM_{2.5}$ and PM_1) on leaf surfaces compared to a design with homogenous topography, indicating that topographical heterogeneity has a strong positive impact on the ability of plants to immobilise PM.

Key words: Green Infrastructure; green wall designs; air quality; vertical greenery system

1. Introduction

Atmospheric particulate matter (PM) pollution has been linked to various health effects, premature mortality, emergency room visits, and hospital admissions (Atkinson *et al.*, 2001; Halonen *et al.*, 2008;

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Pope and Kanner, 1993; Schwartz, 1996; Shaughnessy *et al.*, 2015). WHO (2005) identified traffic-based PM to be the most toxic class of PM and in the UK traffic-generated pollution has become the major source of PM in the air (DEFRA, 2017). The use of green walls in mitigating near-road PM pollution has recently been highlighted due to their ability to overcome most of the challenges in urban greening including limited land space, poor soil fertility, sub-surface infrastructure and potential building-shading effects (Dover, 2015; Pérez-Urrestarazu *et al.*, 2015; Weerakkody *et al.*, 2018). In our recent studies we demonstrated a great potential of living wall systems for reducing traffic-generated PM (Weerakkody *et al.* 2017; Weerakkody et al. 2018b). Living walls are an advanced type of Vertical Greenery System (VGS) which facilitate the growth of a wide variety of plant species; they are artificially irrigated and many are hydroponic (Dover, 2015).

The literature on PM dry deposition on large forest canopies and on other urban surfaces indicates that vegetation topography influences surface resistance and surrounding airflow patterns, hence producing different levels of turbulence which, in turn, results in differential PM deposition rates (Abhijith *et al.*, 2017; Davidson and Wu, 1990; Gallagher *et al.*, 2012; Janhall, 2015; Slinn, 1982). Living wall systems comprise a diverse collection of species and they are delivered in variable planting designs. Consequently, their topographical dynamics may have a similar impact as forest canopies in the reduction of PM by changing the surrounding airflow patterns. However, any such influence of planting design on the ability of PM immobilisation has not been explored in previous research (Pereni *et al.*, 2017; Weerakkody *et al.*, 2017; Weerakkody *et al.*, 2018) and due to their vertical configuration, their aerodynamic behaviour cannot be predicted based on predictions or findings on large forest canopies. Studies that focused on PM capture and retention by different species of plants grown on vertical greenery (Dover and Phillips, 2015; Perini *et al.*, 2017; Ottelé *et al.*, 2010; Sternberg *et al.*, 2011; Weerakkody *et al.*, 2017; Weerakkody *et al.*, 2018), did not consider any variable influence of planting

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design on PM reduction. This influence can be explored by creating topographical variation in wall vegetation using a single plant species to standardise the impact of species characteristics. As the planting designs can be predicted to be important in optimising the capture of PM by living walls or other vertical greenery systems, the present study evaluated this impact using box, *Buxus sempervirens* L., one of the species commonly used in living walls and shown to be an efficient PM trap (Weerakkody *et al.*, 2017).

2. Material and methods

A modular living wall system (Nemec Cascade Garden Ltd., Czech Republic), was employed in this research. The double-sided wall was located facing a busy road (Leek Road), 6 m from the road-side, in Stoke-on-Trent, UK. Only the planting area facing the road (3.98 m x 2.09 m) was used in this study (Fig. 1).

Plants of *B. sempervirens* were purchased from the Hedge Nursery, UK in two commercially available heights of 10-20 cm and 30-40 cm (referred to as ‘short’ and ‘tall’ plants respectively). As PM deposition is a function of weather, planting designs used in this research were required to be exposed to the same weather conditions to avoid any differential influence on different designs. The number of planting designs used were limited to two due to the relatively compact dimensions of the wall. Equal halves of the road-facing side of the living wall (through its mid-vertical axis) had different planting designs imposed on them. One half of the wall was planted creating a variable (heterogeneous) topography by having plants of both heights in a random order, the ‘random design’. The other half was planted as a ‘cluster design’ having two distinct groups of plants, each group with plants all of the same height to create two areas with homogeneous topography (one height at the top and the other at the bottom of the wall) (Fig. 1). This experiment was replicated four times during the period June - August 2017 and in each of the replicates, the allotted side for each planting design and the arrangement of clusters (top or bottom) were changed in a random order (Fig. 1). The hypotheses for this study were:

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1. If increased turbulence caused by topographical heterogeneity increases PM deposition, plants allocated to the 'random' design should collect more PM than plants allocated to the more homogeneous 'cluster' design.

2. Increased PM levels are predicted to occur on leaves of plants at the interface (edge) between tall and short plants in the cluster design due to increased turbulence.

Once the plants were installed for each experimental trial, they were washed by spraying water on leaves using a hose in order to remove existing particles, and 20 leaves from the short plants and 20 leaves from the tall plants were randomly collected from each design (a total of 80 leaves) to quantify the baseline PM levels. Leaves were stored in plastic containers, avoiding any cross contamination, and sealed to minimise particles falling-off the leaves; sample storage and transfer followed the same protocol used in Weerakkody *et al.* (2017). Subsequently, baseline PM (PM_{10}, $PM_{2.5}$ and PM_1) levels on the leaves were quantified using an Environmental Scanning Electron Microscope (ESEM) and imageJ software following the same procedure described in Weerakkody *et al.* (2017).

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Figure 1. Images showing two random arrangements of two planting designs of *Buxus sempervirens* planted on the living wall located along Leek Road, Stoke-on-Trent.

Leaves were sectioned into halves in order to visualise adaxial and abaxial surfaces and mounted on aluminium stubs using carbon sticky tabs for visualisation using the ESEM. Nine micrographs from each leaf half were taken (avoiding the leaf margins and tips) using back-scattered electrons in a low vacuum. The number of PM_{10}, $PM_{2.5}$, and PM_1 on the micrographs were quantified using the particle analyser in ImageJ. The density of each PM size fraction on leaf surfaces was estimated as particle numbers per 1 mm^2. Densities of each PM size fraction on individual leaves were estimated by totalling the PM densities on the adaxial and abaxial surfaces of the leaves. Any significant difference in baseline PM levels, between tall and short plants, and between the two planting designs, were identified using Student's t-test following application of the Shapiro-Wilk test to confirm normality.

Subsequently, plants were left untouched and exposed to pollution (mainly generated from traffic on Leek Road) for five consecutive rain-free days. Before the first replicate, in order to identify any potential edge-effect at the interface between short and tall plant clusters in cluster design, leaves were

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randomly collected from the middle and edges of the clusters (20 leaves from each category). The density of PM on these leaves were quantified employing the ESEM/ImageJ approach. Any edge-effect at the interface between short and tall plant clusters was identified by comparing PM densities on the leaves taken from the middle and edges of the clusters, using Student's t-test (R Development Core Team, 2016).

Forty leaves from each planting design, i.e. 20 leaves from each height per design, were sampled to assess any differential impact of topography. PM accumulation on leaves in each experimental trial were quantified following exactly the same exposure time and experimental procedure. At the beginning of each experiment (after plants were re-allocated for the experiment) plants were washed with a watering hose to remove existing PM trapped in the previous trial and any variability in baseline PM levels (even after wash-off) were identified using Student's t-test after normality testing.

At the completion of all four experimental trials, any significant differences in densities of PM_1, $PM_{2.5}$, and PM_{10} on the leaves taken from different designs were identified using a Generalised Linear Mixed-effect Model (GLMM) (R Development Core Team, 2016). As these leaves were sampled in different experimental trials, time was included as a random factor in the model to avoid any variable influence of weather in different replicates. Any variability in PM accumulation on the leaves of plants with different heights, within the same design, was also identified using a GLMM using time as a factor.

3. Results

There were no significant differences in baseline PM densities after washing the leaves off (Table 1), and hence they were not included in the analyses following the 5-day exposure periods. PM densities on the leaves taken from the middle of the clusters and from the edges were not significantly different from each other for any particle size fraction (Fig. 2) and hence, the sampling location within the cluster was random in all the sampling attempts (i.e. no guard rows were used when selecting leaves for sampling).

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Table 1. Results of Student's t-test in the analysis of baseline PM densities on the leaves of *B. sempervirens* plants used in random and cluster planting designs of the living wall located along Leek Road, Stoke-on-Trent (n=20).

Plant height	**Tall plants**			**Short plants**		
PM size fraction	**PM_1**	**$PM_{2.5}$**	**PM_{10}**	**PM_1**	**$PM_{2.5}$**	**PM_{10}**
Prior to replicate 1	t= 1.83 p=0.07	t= 1.60 p=0.11	t= 0.89 p=0.37	t= 0.74 p=0.46	t= 0.81 p=0.43	t= 0.63 p=0.53
Prior to replicate 2	t= 0.12 p=0.89	t= 1.16 p=0.25	t= 0.97 p=0.38	t= 0.12 p=0.89	t= 0.96 p=0.32	t= 0.18 p=0.79
Prior to replicate 3	t= 0.006 p=0.99	t= 0.78 p=0.44	t= 1.30 p= 0.19	t= 0.97 p= 0.41	t= 1.72 p= 0.09	t= 0.07 p= 0.93
Prior to replicate 4	t= 0.92 p=0.36	t= 0.53 p=0.59	t= 0.87 p=0.39	t= 1.69 p= 0.10	t= 1.09 p=0.26	t= 0.05 p=0.96

The GLMM revealed significantly higher densities of PM_{10}, $PM_{2.5}$, and PM_1 on the leaves sampled from the random planting design compared to the leaves taken from the cluster design, for both short and tall plants (Fig. 3 and Fig. 4). The densities of PM on the leaves of short and tall plants within the same (random and cluster) design, were not significantly different for any PM size fraction (Fig. 4 and Fig. 5).

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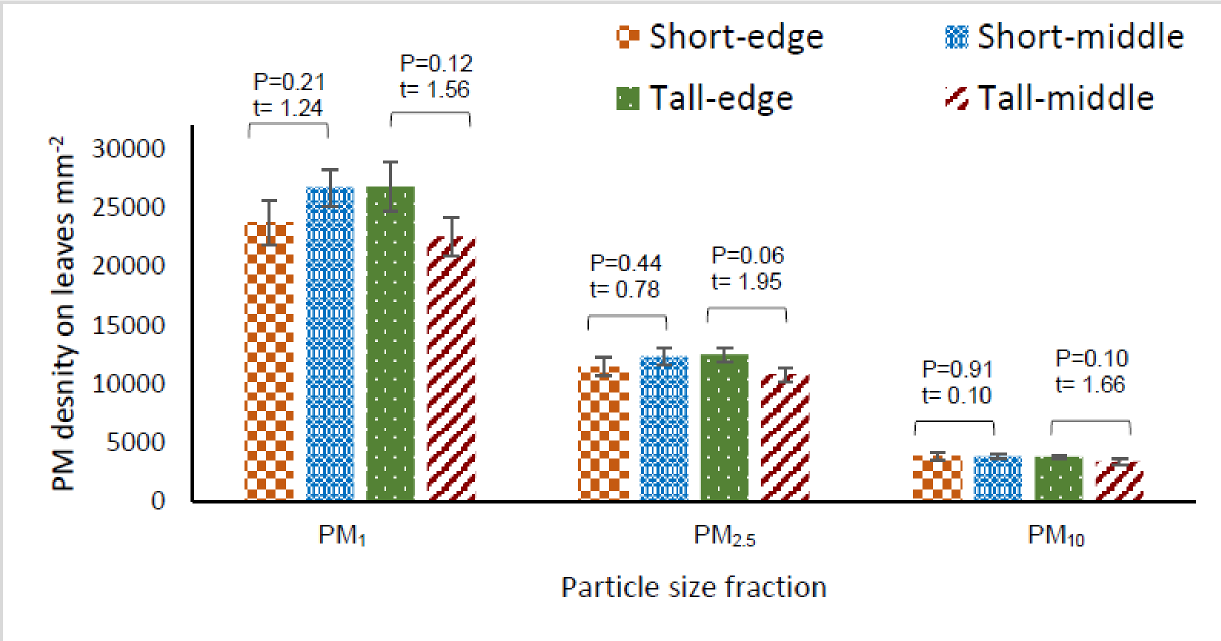

Figure 2. The mean PM density ± SE on leaves taken from the edges and middle of plant clusters (plants of the same height were grouped together to form a homogeneous topography) of *B. sempervirens* in the living wall located along Leek Road, Stoke-on-Trent. *Short-edge and short-middle: leaves taken from edges and middle of the short plant clusters; tall-edge and tall-middle: leaves taken from edges and middle of the tall plant clusters.*

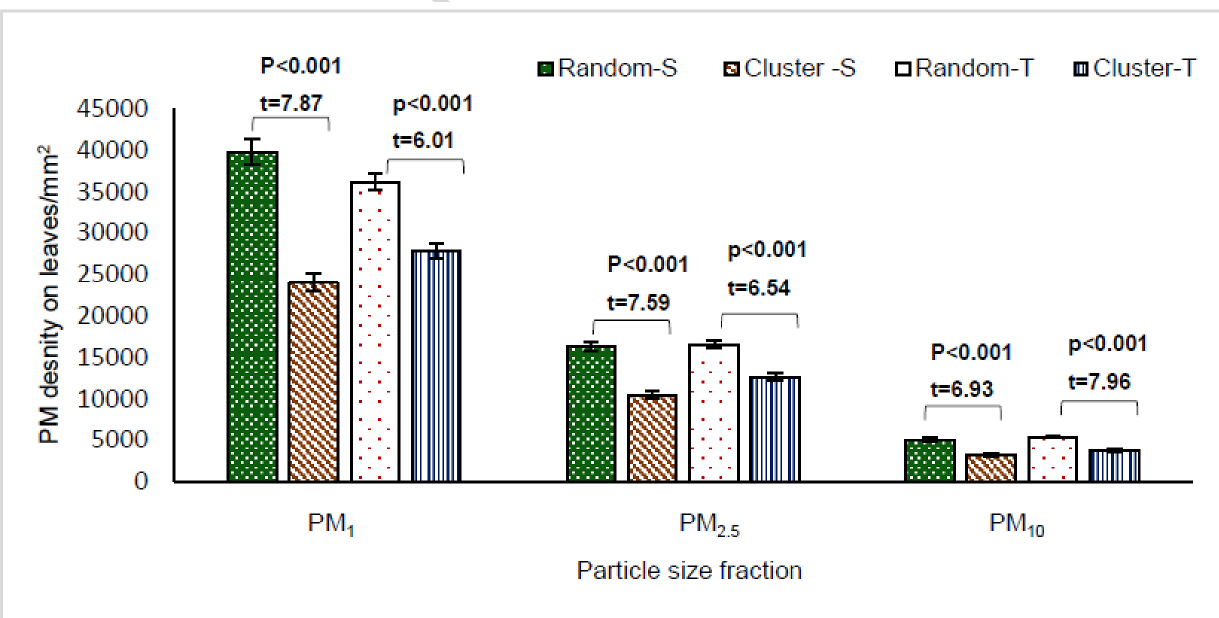

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Figure 3. The mean PM density ± SE on leaves of *B. sempervirens* plants in the living wall system located along Leek Road, Stoke-on-Trent in planting designs where plants of the same height were grouped together to form a homogeneous topography 'Cluster' or interspersed with tall plants to form a heterogeneous topography 'Random'. *(Random-S: short plants in random design, Cluster-S: short plants in cluster design, Random-T: tall plants in random design, Cluster-T: tall plants in cluster design*).

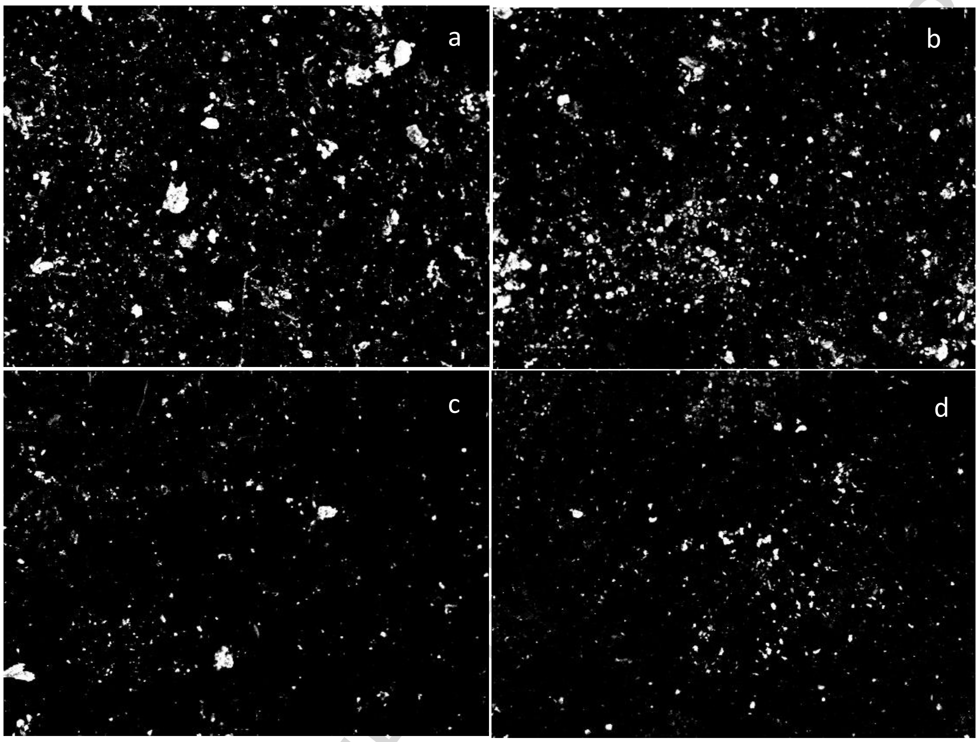

Figure 4. Sample ESEM micrographs (x450) showing PM captured on leaves of *B. sempervirens* a) short plants in a random design b) tall plants in a random design c) short plants in a cluster design d) tall plants in a cluster design on the living wall system located along Leek Road, Stoke-on-Trent;

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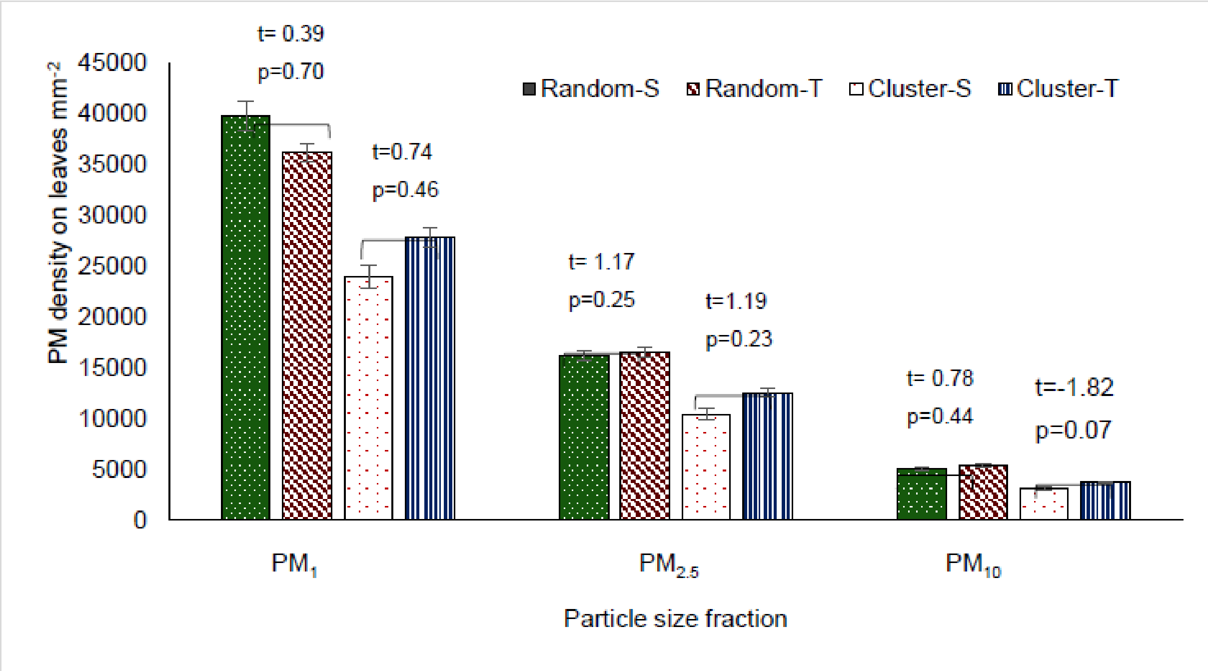

Figure 5. The mean PM density ± SE on leaves of short and tall plants of *B. sempervirens* used in the random planting design with heterogeneous topography and in the 'cluster' planting design with homogeneous topography on the living wall system located along Leek Road, Stoke-on-Trent.

4. Discussion

Significantly higher PM densities were found on leaves of the plants in the random design compared to those in the cluster design, for both tall and short plants, and demonstrated the higher efficiency of a planting design with topographical heterogeneity to capture and retain particulates. The random arrangement of plants with two different heights created an uneven wall-surface whereas the cluster design had a more level surface in each cluster and, hence, less topographical variation. It is likely that the more complex deposition surface of the random design with topographical heterogeneity, with a greater surface roughness, increased turbulence in the surrounding airflow resulting in higher PM accumulation on the leaves. Some researchers made similar predictions on having high PM dry deposition on forests or large tree canopies with high surface roughness (Manning and Feder, 1980),

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using deposition velocity models (Davidson and Wu, 1990; Petroff *et al.*, 2008b; Slinn, 1982). Since there was no variability in PM accumulation on the plants with different heights within the random design, use of plants of slightly different heights (i.e. 10-20 cm and 30-40 cm in this study), is unlikely to negatively affect the PM capture ability of each other by shielding. Similarly, in the cluster design, the absence of any variability in PM capture between short and tall plant clusters suggests the importance of overall topography in PM accumulation rather than plant height *per se*.

Whilst higher PM levels were predicted to occur on leaves collected from the edges of the clusters compared to the middle of the clusters due to greater turbulence at the interface between short and tall plantings, no such difference was detected. The absence of any significant variability between leaves on the edges and the middle of clusters possibly indicates that there was insufficient turbulence created at the interface and, hence, no differential accumulation of PM. This may have resulted from a boundary layer effect or back wind pressure, similar to that found with pesticide drift deposition at the base of hedges (Davis *et al.*, 1994) or be attributable to the relatively small dimensions of these plant clusters.

Our previous work showed a great potential of living wall systems to capture and retain both road and rail traffic-based PM emphasing the important impact of inter-species variation and individual leaf traits (Weerakkody *et al.* 2017; Weerakkody *et al.* 2018a; Weerakkody *et al.* 2018b). All the species used in these systems captured a wide range of elements, including important heavy metals (e.g. Ag, Cr, Co,

Cu, Fe, Mn, Sb, Sn, Ti, Zr and V) irrespective of their differential PM capture potential; their compositions were strongly correlated to road and rail traffic (Weerakkody *et al.* 2017; Weerakkody *et al.* 2018b). The results of this experiment suggest an important impact of planting design on the performance of living wall species in the capture of PM; for a purpose-built living wall to reduce atmospheric PM, use of a design that optimises topographical variation would be beneficial. As living walls typically comprise a

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diverse collection of species, interspersing plants that are morphologically different may also increase topographical heterogeneity of the planting area resulting in higher PM capture levels.

5. Conclusion

The findings of this study showed that the use of a planting design with heterogeneous topography, created by interspersing plants of different heights, has a significantly greater impact on immobilising atmospheric PM compared to a design with homogenous topography comprising plants of similar heights. Therefore, use of a planting design with complex topography should enhance the PM reduction potential of living walls.

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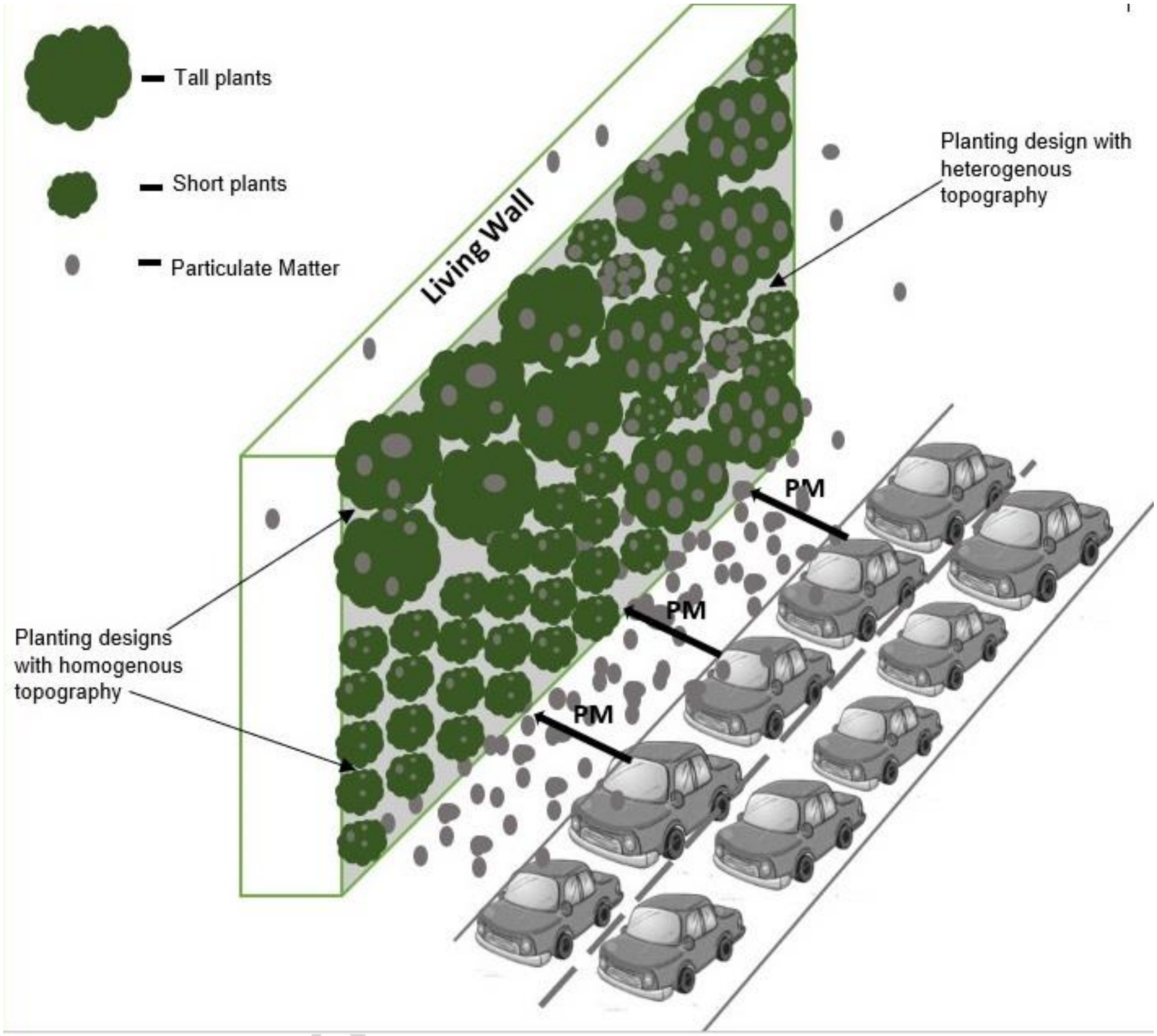

Graphical abstract

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Highlights

- Planting design of a living wall has an important influence on PM immobilisation
- Topographical heterogeneity of a planting design improves the leaf PM accumulation
- Interspersing species or using the same species with variable morphology improves PM deposition

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