Evaluation of respiratory deposition doses in the presence of green infrastructure

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Graphical abstract

Abstract

Green infrastructure (GI) is effective in reducing PM concentrations in near-road environments, but how such reductions in concentration compared with relative respiratory deposition doses (RDD) is rarely discussed. We quantified variations in RDD in the presence of three GI types (trees, hedges, and tree-hedge combinations), and compared them with PM reduced by the GI under different wind directions and seasons through the assessment of data

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collected during multiple field campaigns. We also studied three scenarios (sitting, walking, running) to investigate RDD doses in adults and children during different possible activities in the presence of GI at public parks or gardens or in front of houses. Finally, we illustrated particle mass distribution before and after different GI configurations to explore the reasons for variations in RDD. Changes in RDD displayed a trend of $\% \Delta RDD_{PM_{10}} > \% \Delta RDD_{PM_{2.5}} = \% \Delta RDD_{PM_1}$, compared to the changes in PM concentrations of $\% \Delta PM_1 > \% \Delta PM_{10} > \% \Delta PM_{2.5}$. A maximum reduction (25%) in RDD was observed for PM_{10} in the presence of the tree-hedge combination, and this combination emerged as the most effective GI type in lowering the RDD dose. The changes in ratios of mass median diameter and deposition fraction of roughly ± 0.2 before and after the GI led to differences between $\% \Delta PM$ and $\% \Delta RDD$. Cross-winds (perpendicular to road direction) led to greater variations between $\% \Delta PM$ and $\% \Delta RDD$, whereas parallel winds (along the road) led to similar variations in $\% \Delta RDD$ and $\% \Delta PM$. Particle mass distributions revealed the absence of a peak around particle diameter $2.5 \mu m$ in the presence of GI. The highest difference in RDD behind GI was observed in the presence of a hedge-tree combination during different physical activities.

Keywords: Green infrastructure; Respiratory doses; Human exposure; Roadside greening; Particulate pollution

1. Introduction

Exposure to particulate matter (PM) adversely affects human health and causes seven million deaths per year (WHO, 2018). Road traffic is a significant contributor to PM pollution in the UK in near-road environments (DEFRA, 2017). Elevated ambient PM concentrations near roadways amplify concerns about the wellbeing and health of people living or working close to highways, and prolonged exposure to PM could deteriorate the health of these people (HEI, 2010; Karner et al., 2010; Kimbrough et al., 2018). Epidemiological studies have

reported associations between PM exposure and a higher risk of cardiovascular morbidity and mortality (Brook et al., 2010, 2004; Guo et al., 2009; Ma et al., 2011; Pope III et al., 2002; Samet et al., 2000). Green infrastructure (GI) is one passive control measure to reduce exposure to high PM concentrations close to busy roads (Tomson et al., 2021; Abhijith et al., 2017; Baldauf, 2017; Gallagher et al., 2015; Janhall, 2015). Several studies have reported reductions in PM concentrations of ~2% to 52% due to vegetation barriers (Abhijith and Kumar, 2020, 2019; Deshmukh et al., 2018; Ottosen and Kumar, 2020). Such reductions in PM concentrations in near-road environments lower the exposure of individuals by modifying the airflow around GI and removing PM by deposition. Reduced exposure due to the presence of GI could diminish the health risk, which also depends on PM concentration level, frequency and duration of exposure, and the quantity of PM entering the body. Cyclists, pedestrians and runners using footpaths next to busy roads have increased inhalation rates due to physical activity, resulting in higher inhaled doses and lung deposition of PM (de Nazelle et al., 2012; Int Panis et al., 2010; Kumar et al., 2018; Luo et al., 2018; McNabola et al., 2008; Nyhan et al., 2013; Tan et al., 2017). These physical activities, although typically performed for short periods (<1 hour), elevate the exposure of individuals to traffic emissions, can intensify existing pulmonary and cardiovascular illness (Chen et al., 2017; Hemmingsen et al., 2015; Lanki et al., 2008; McCreanor et al., 2007; Mehta et al., 2013; Paulin and Hansel, 2016; Peters et al., 2013; Provost et al., 2016; Shields et al., 2013; Weichenthal, 2012).

Numerous studies have assessed exposure to PM and other traffic pollutants and quantified the related inhalation dose or respiratory deposition dose (RDD) (de Nazelle et al., 2012; Int Panis et al., 2010; Joodatnia et al., 2013; Kumar et al., 2018, 2017; Kumar and Goel, 2016; Luo et al., 2018; McNabola et al., 2008; Nyhan et al., 2013; Rivas et al., 2017; Tan et al., 2017). Most of these studies compared the RDD of commuters in different traffic microenvironments, either while walking, cycling, in cars, on buses, or trains. They highlight that inhalation doses of

pedestrians are generally higher than those of commuters in other traffic microenvironments (Kumar et al., 2018; Luo et al., 2018; Nyhan et al., 2013; Tan et al., 2017). These studies have also reported that well-designed and appropriately placed GI can reduce PM exposure (Abhijith and Kumar, 2020, 2019; Deshmukh et al., 2018; Ottosen and Kumar, 2020). However, it is unclear how these concentration reductions may translate into a decrease in RDD in near-road environments, such as on footpaths, in residential buildings, parks, and recreational areas close to busy roads. Moreover, wind flow conditions and seasonal variation could influence RDD behind GI. Finally, PM mass distribution behind GI may change due to removal through deposition and dispersion, influencing RDD behind GI.

To address these uncertainties and to understand the additional health benefits of GI, the overall goal of this work is to answer the question: what are the relative impacts of near-road GI on reduced PM concentrations and corresponding exposure doses? The specific objectives are: to (i) quantify changes in RDD and PM levels with and without three types of GI; (ii) to assess the influence of wind direction on RDD variations in the presence of GI; (iii) to investigate the relationship between morphological changes in GI across different seasons and related implications for RDD, taking a hedge as an example; (iv) to create hypothetical scenarios for understanding RDD variations during various physical activities by adults and children in the presence of GI; and (v) to illustrate PM mass distribution before and after different GI types to understand variations in RDD due to GI.

2. Methodology

2.1 Site description

This study utilises data collected during two field campaigns conducted at six sampling sites in a typical UK town (Guildford, Surrey) from May 2017 to early September 2017 (spring-summer) and, at one of the sampling sites, from October 2018 to early November 2018 (autumn). The sampling sites consisted of three types of GI: hedge (H), tree (T), and a

combination of tree and hedge (TH). Table S1 in the Supplementary Information (SI) provides a summary of the relative positions of instruments, measurement locations, instrument set-up and GI characteristics of each site, and further details of the sampling sites are available elsewhere (Abhijith and Kumar, 2020, 2019). Depending upon the distance from the road, the sites were classified as 'close-road' (<1m from the road) and 'away-road' (>2m from the road). There was one PM monitoring point behind the GI at each. For the 'close-road' sites, the second PM monitoring point was established at an adjacent clear area due to a lack of space for the instrument in front of the GI, and this set-up was defined as 'clear area and behind (CB)'. The 'away-road' sites included enough space for the instruments to be placed in front of the GI and were defined as 'in front and behind (IB)'.

The two sites that contained only hedges, Stoke Road-Hedge (H_{IB}) and Aldershot-Hedge (H_{CB}), were adjacent to two-lane roadways next to a children's park and near residential buildings, respectively. The H_{IB} site consisted of a well-maintained beech (*Fagus sylvatica*) hedge, 2.2m in height and 1.5m in width, with a leaf area index (LAI) of 6.6-6.9 mm^2/mm^2 and 4.5-4.7 mm^2/mm^2 during spring-summer and autumn seasons, respectively, as seen in Table S1 (Ottosen and Kumar, 2020, Abhijith and Kumar, 2020, 2019). H_{CB} was a mixed hedge of hawthorn (*Crataegus monogyna*) and common ivy (*Hedera helix*); it was smaller in height (1.2m) and width (1m) than H_{IB} , with a LAI of 6.6 mm^2/mm^2 . One of the sites that contained only trees, Aldershot-Tree (T_{CB}), was along the same road as H_{CB} . T_{CB} contained a single row of common lime (*Tilia x europaea*) trees, roughly 10m in height and 6m in crown diameter, with an LAI of ~4.3 mm^2/mm^2 (Table S1). The other trees-only site, Sutherland-Tree (T_{IB}), had multiple rows of trees (up to four rows) that consisted of common lime (*Tilia x europaea*), field maple (*Acer campestre*), black poplar (*Populus nigra*), and bird cherry (*Prunus padus*). This GI was next to a public park and was around 7m high and 9m wide with an average LAI of 4.6 mm^2/mm^2 . The nearby trees and hedge site, Sutherland-GI (TH_{IB}), contained a well-

maintained, 1.7m tall, mixed hedge of hawthorn (*Crataegus monogyna*) and common ivy (*Hedera helix*) and a single row of common ash (*Fraxinus excelsior*) behind the hedge, forming a combined vegetation barrier with a width, height, and LAI of 7m, 5m, and 3.4 mm²/mm², respectively (Table S1). The other trees and hedge site, Shalford-GI (TH_{CB}), bordered a public park along a busy two-lane road and contained a blackthorn (*Prunus spinosa*) hedge with trees including red pine (*Pinus resinosa*) and London plane (*Platanus x hispanica*) embedded in the hedge. This combined vegetation barrier was 3.5m tall and 4m wide, with an average LAI of 4.1 mm²/mm². Further details including the coordinates and traffic volumes of these sites are provided in Abhijith and Kumar (2019).

2.2 Instrumentation and data collection

The data obtained from the two optical particle spectrometers (OPC; models 1.107 and 11-C) were used for RDD calculation and plotting the mass distribution of PM at both the monitoring points for all sites. The OPC uses a light scattering principle to measure the size-segregated mass distribution of PM from 0.22 to 34μm and provides concentrations of PM₁, PM_{2.5}, and PM₁₀. These instruments have been widely used in PM exposure monitoring (Hagler et al., 2009; Kumar et al., 2018, 2017; Rivas et al., 2017; Viippola et al., 2018). Before the commencement of both field campaigns for this study, instruments were factory calibrated. During data collection, the OPC instruments were mounted on tripod stands of 1.5m height, mimicking breathing height with a recording time base of 6s, which was averaged to 1m for data analysis. Both field campaigns collected five days of measurements, starting at 08:00 and ending at 18:00 (local time) at each site. One of the tripods was erected behind the GI at each site, whereas the other tripod was kept in front of the GI (sites H_{IB} and T_{IB}) or at an adjacent clear area (sites H_{CB}, T_{CB}, and TH_{CB}) due to lack of space between road and GI and for the general safety of field workers and members of the public (Abhijith and Kumar, 2020, 2019). During both field campaigns, instruments were run collocated for 30 minutes before and after

data collection to ensure accuracy in PM concentration measured by the OPCs and the interoperability of both instruments. These quality control measures reported good agreement between both OPCs, as discussed in previous works (Abhijith and Kumar, 2019; 2020). The LAI of the GI at each site was measured using a handheld Ceptometer (AccuPAR LP-80, Meter Environment). The LAI of the hedge at the Stoke Park site (H_{IB}) was recorded in both spring-summer and autumn seasons.

The collected data was divided into three wind direction categories to understand the influence of wind flow conditions, defined as ‘cross-road,’ ‘cross-vegetation,’ and ‘along-road.’ Under ‘cross-road’ and ‘cross-vegetation’ conditions, winds flow perpendicular to GI from the road and to the road from the area behind GI, respectively. Both consist of two 60^0 circular sectors on either side of the perpendicular axis of GI. The ‘along-road’ conditions represented winds that travel from either end of the GI, flowing parallel to the longitudinal axis of the GI and the road. It has two 30^0 circular sections on either side of the longitudinal axis.

2.3 Exposure assessment

To evaluate the health benefits of GI beyond ambient concentration changes, the total respiratory lung deposition dose (total RDD in thoracic, tracheobronchial, alveolar regions) was estimated both with and without the presence of GI. The RDD at each monitoring point was calculated using Eq. (1), which is adapted from the International Commission on Radiological Protection (ICRP, 1994) and has been employed in numerous previous studies (Joodatnia et al., 2013; Kumar et al., 2018, 2017; Kumar and Goel, 2016; McNabola et al., 2008; Rivas et al., 2017). RDD is the product of particle mass concentration (PMC), deposition fraction (DF), and ventilation rate (VR) (Hinds, 1999). The PMC varies in different environmental conditions and according to the presence or absence of GI. The DF is mainly influenced by particle size and other characteristics, and it is proportional to particle diameter.

Finally, VR depends on age, sex, and the activity of a person. We used ventilation rates provided by US-EPA (2009).

$$RDD \text{ of } PM(\text{fractions}) = VR_j \times DF_i \times PM_i \quad (1)$$

Where VR_j is ventilation rate for the j^{th} individual; DF_i and PM_i represents DF and PMC for each of the i^{th} PM fractions (PM_1 , $PM_{2.5}$, PM_{10}). DF s are calculated using the mass median diameter ($d_p, \mu m$) of PM fractions following Eqs. (2) and (3), provided by (Hinds, 1999).

$$DF = IF \left(0.058 + \frac{0.911}{1 + \exp(4.77 + 1.485 \ln d_p)} + \frac{0.943}{1 + \exp(0.508 - 2.58 \ln d_p)} \right) \quad (2)$$

Where inhalable fraction (IF) is calculated as follows:

$$IF = 1 - 0.5 \left(1 - \frac{1}{1 + 0.00076 d_p^{2.8}} \right) \quad (3)$$

The d_p for each PM fraction was derived from plotting particle diameter versus percentage cumulative PM concentrations, which was calculated by adding the percentage mass collected in all size bins under the corresponding PM fraction. The d_p for PM_1 , $PM_{2.5}$ and PM_{10} size fractions were calculated from PM mass collected in different size bins, following an approach used in our previous work (Kumar and Goel, 2016). Thereafter, the percentage of PM mass collected in each size bin was quantified for all these three fractions. Plots for all three PM fractions, showing particle diameter versus the cumulative percentage of PM mass collected for different particle diameters were drawn. The d_p was then determined by reading the particle diameter, corresponding to a cumulative percentage of 50% PM mass. The d_p (mass median diameter) for PM_1 , $PM_{2.5}$, PM_{10} were calculated from PM mass collected in size bins under each size fraction. Then the percentage of PM mass collected in each size bin was quantified for all these three fractions. Plots for all three PM fractions, showing particle diameter vs cumulative percentage of PM mass collected under particle diameter were drawn. The d_p mass

~~median diameter~~ was determined by reading the particle diameter corresponding to the cumulative percentage of PM mass of 50%. The use of optical diameter recorded by OPCs instead of aerodynamic diameter (Chien et al., 2016; Sanders et al., 2003) and avoiding hygroscopic properties of particles inside the lungs (Vu et al., 2017) may result in variability in the calculated DF . However, the study investigated and discussed relative changes in RDD to cancel out such effects and allow comparison with previous exposure studies that used optical diameter for calculation of RDD (de Nazelle et al., 2012; Joodatnia et al., 2013; Kumar et al., 2018; Kumar and Goel, 2016; Rivas et al., 2017; Tan et al., 2017).

2.4 Scenarios

Most of the GI sites used for assessing related changes in PM concentrations and RDD were situated along the boundaries of public recreational areas (e.g. cricket or football pitches) or footpaths where people undertake different physical activities including running and walking. For example, the H_B site borders a children's play area at Stoke Park, providing us with reasoning to quantify relative differences in RDD of adults and children. Varying levels and types of physical activity, such as sitting, walking, running/playing games, are undertaken behind these GI barriers. Therefore, we considered a range of physical activities (sitting, walking, and running) to represent the breathing rate of light, mild, and high intensities, respectively. We quantified the RDD of adults (31-41 years, males and females) and children (3-6 years, female) during the above-noted physical activities. The changes in ventilation rates during different activity levels of various gender and ages can have a prominent influence on RDD calculation, unlike the DF that are a function of particle size distributions. The ventilation rates of adults (both female and male) and children (female), during various physical activities, were adopted from US-EPA (2009) and are shown in SI Table S5.

3. Results and discussion

3.1 Comparison of overall reduction in RDD and PM

The percentage reductions in RDD and PM concentration with the presence of GI is shown in Fig. 1, and a summary of the estimation of RDD, including d_p , IF , DF , and PM concentration, is provided in SI Table S2. For conciseness, the quantified RDD is presented in SI Table S2, as well as percentage differences (Fig. 1) considering the ventilation rate of females during the light activity, following a previous study (Rivas et al., 2017). The differences in RDD between sexes while performing various levels of activity are discussed in Section 4. In general, variations in $\% \Delta RDD$ followed the $\% \Delta PM$. Abhijith and Kumar (2019) reported an overall trend in $\% \Delta PM$ following the order of $\% \Delta PM_{2.5} < \% \Delta PM_{10} < \% \Delta PM_1$. Here, we observed a maximum variation of 27% in $\% \Delta RDD_{PM10}$ at the TH_{IB} site, whereas the greatest variation in $\% \Delta RDD_{PM2.5}$ and $\% \Delta RDD_{PM1}$ was 25%, observed at TH_{IB} and H_{IB} , respectively. This showed an overall trend of $\% \Delta RDD_{PM10} > \% \Delta RDD_{PM2.5} = \% \Delta RDD_{PM1}$ while considering maximum variations across investigated sites. In most cases, the tree and hedge combination (TH) emerged as the most effective GI type in terms of health benefit, exhibiting a greater reduction in RDD than in all ΔPM fractions. While comparing $\% \Delta PM$ of different size fractions with corresponding $\% \Delta RDD$, no differences between $\% \Delta RDD_{PM1}$ and $\% \Delta PM_1$ were observed for any GI type for particles less than $1 \mu m$. Some anomalies were observed, which were predominantly in the comparison between $\% \Delta RDD_{PM2.5}$ and $\% \Delta PM_{2.5}$. For example, we observed a threefold greater reduction in $RDD_{PM2.5}$ than $PM_{2.5}$ at both T_{IB} and TH_{IB} , and a ~9% increase in lung deposition behind H_{IB} despite a reduction of 14% in $PM_{2.5}$ concentration at the same location. These observed anomalies may have arisen from the changes in DF , which are dependent on the mass median diameter variations occurring in the presence of GI.

To understand the influence of DF and d_p on RDD, their ratios before and after GI were plotted (Fig 2). When the ratios of d_p and DF were close to harmony at any GI site, $\% \Delta RDD$ was close or equal to $\% \Delta PM$, as reported for the PM_1 fraction (Fig 1). We observed that whenever the

presence of GI resulted in no considerable change in mass median diameter, there was no variation in DF before and after GI. This absence of change in DF was mainly seen for the PM_{10} fraction at each site. Moreover, lung deposition is least for particles with diameters in the range of $0.1\mu m$ to $1\mu m$ (Hinds, 1999). When the impact of GI on ratios of d_p and DF resulted in a variation of ± 0.2 from one, the changes in $\% \Delta RDD$ differed considerably from $\% \Delta PM$. The aforementioned threefold improvement in $\% \Delta RDD$ on $\% \Delta PM$ at T_{IB} and TH_{IB} in the $PM_{2.5}$ fraction was caused by the lower d_p ($d_{p\ INF} / d_{p\ BHD} = 0.86$) and DF ($DF_{INF} / DF_{BHD} = 0.82$) ratios behind the GI. By contrast, higher ratios of d_p and DF of 1.2 and 1.3 for the $PM_{2.5}$ fraction (increase in d_p behind GI) resulted in increased lung deposition in H_{IB} despite a $PM_{2.5}$ concentration reduction behind the hedge. Similarly, the lower $\% \Delta RDD_{PM_{10}}$ compared to $\% \Delta PM_{10}$ at all sites except TH_{IB} (Fig. 1) was due to higher ratios (<1) of d_p and DF (Fig. 2). These findings indicate that the health benefits of GI depend on the mass median diameter of the particles and the concentration of PM behind the GI. Previous studies assessing ultrafine particle (UFP) removal by GI have established a relationship between UFP removal efficiency and particle size that varies with the plant species of GI (Neft et al., 2016; Wang et al., 2019), which was not included in this work. Similarly, higher reductions in PM_{10} and PM_1 than $PM_{2.5}$ by GI have been reported by numerous previous studies (Abhijith and Kumar, 2019; Brantley et al., 2014; Chen et al., 2015; Viippola et al., 2018; Yli-Pelkonen et al., 2017). These size-dependent variations in PM and UFP concentrations in the presence of GI could lead to an increase or decrease in RDD behind the GI. To understand and accurately quantify the lung deposition of PM behind GI, size-dependent DF s for different PM fractions and size-resolved particle number concentrations for UFP deposition in lungs are needed. Thus, combined PM and UFP studies investigating lung deposition would lead to precise and comprehensive quantifications of the health benefits provided by GI.

The influence of DF on $\% \Delta RDD$ in the presence of GI was further investigated by plotting hourly averaged variation in the ratios of DF , $\% RDD$ and $\% PM$ for all size fractions, as shown in SI Fig. S1 (PM_1), Fig. 3 ($PM_{2.5}$) and Fig. 4 (PM_{10}), respectively. The hourly averaged variation for the PM_1 size fraction showed coinciding lines of $\% \Delta RDD$ and $\% \Delta PM$ for all sites and a ratio of DF equal to one, resulting in a similar or close $\% \Delta RDD$ and $\% \Delta PM$. This indicated negligible changes in the mass median diameter of particles less than $1 \mu m$ in the presence of GI. Conversely, the greatest differences between hourly averaged $\% \Delta RDD$ and $\% \Delta PM$ were observed for the $PM_{2.5}$ size fraction (Fig. 3). Moreover, the ratio of DF s was less than one in most cases for particles less than $2.5 \mu m$, resulting in higher $\% \Delta RDD_{PM_{2.5}}$ than $\% \Delta PM_{2.5}$ (Fig. 3). The ratio of DF s for PM_{10} at most GI sites was slightly above one, resulting in lower $\% \Delta RDD_{PM_{10}}$ than $\% \Delta PM_{10}$ (Fig. 4), although a low value in the ratio of DF of about 0.8 led to the highest increase in hourly average $\% RDD_{PM_{10}}$ compared to $\% \Delta PM_{10}$ at TH_{IB} site (Fig. 4). Overall, this analysis revealed that when the ratio of DF was <1 , the observed $\% \Delta RDD$ was higher than $\% \Delta PM$ at sites H_{CB} , T_{IB} , T_{CB} , TH_{IB} (Fig. 3), and TH_{IB} (Fig. 4). The opposite trend was seen when the ratio of DF was >1 at sites H_{IB} (Fig. 3), H_{CB} , T_{IB} , T_{CB} , and TH_{CB} (Fig. 4). Furthermore, when DF was $\cong 1$, the $\% \Delta RDD$ was close to $\% \Delta PM$, as observed at H_{CB} (SI Fig. S1) and TH_{CB} (Fig. 3). Finally, an inverse trend between the ratio of DF and $\% \Delta RDD$ was observed, especially for the $PM_{2.5}$ size fraction. For instance, the lowest point in the ratio of DF corresponded to the highest value in $\% \Delta RDD$ (Figs. 3c, 3f) and the vice-versa (Figs. 3b).

3.2 Effect of wind direction on RDD

To extend the current understanding of the relationship between $\% \Delta PM$ and $\% \Delta RDD$, the influence of wind flow directions on their relative variations was assessed by categorising the data under three wind flow conditions (*along-road*, *cross-road*, and *cross-vegetation*). The $\% \Delta PM$ and $\% \Delta RDD$ at all six sites under these various wind conditions are presented in Fig.

5, with a statistical summary provided in SI Table S3. Irrespective of wind direction, for particles less than $1\mu\text{m}$, the $\%\Delta\text{RDD}$ followed the $\%\Delta\text{PM}$ at all GI sites. Moreover, the ratio of d_p and DF was close to one at all sites for the three investigated wind conditions (SI Fig. S2). This indicates that the wind flow conditions had a negligible influence on d_p and DF of the submicron particle fraction behind GI. A comparison of the impacts of different wind directions showed a smaller difference between the observed $\%\Delta\text{RDD}$ and $\%\Delta\text{PM}$ under along-road conditions than under cross-road or cross-vegetation conditions. However, considerable variation in $\%\Delta\text{RDD}$ against $\%\Delta\text{PM}$ under along-road conditions was observed for the PM_{10} size fraction. Along-road wind conditions generally result in higher PM concentration reductions due to the sweeping effect of such winds along the road direction, enabling less PM to cross the GI barrier (Abhijith and Kumar, 2019). This may explain the lower variation in the ratios of d_p and DF under along-road wind conditions, as presented by SI Figure S1.

Higher differences between $\%\Delta\text{RDD}$ with $\%\Delta\text{PM}$ were observed for both cross-road and cross-vegetation wind flow conditions (Fig. 5). The greatest improvement (69%) in $\%\Delta\text{RDD}_{\text{PM}_{2.5}}$ was observed at the T_{CB} site during cross-road winds. Particles less than $2.5\mu\text{m}$ in diameter displayed a higher reduction in RDD than PM at most of the sites under cross-road and cross-vegetation winds (Fig. 5). By contrast, the PM_{10} size fraction showed less improvement in $\%\Delta\text{RDD}$ than $\%\Delta\text{PM}$ under both perpendicular wind flow conditions, with a maximum increase of 32% in lung deposition behind GI at H_{CB} during cross-vegetation winds. Moreover, the ratios of d_p and DF under both perpendicular conditions were above one, leading to higher lung deposition behind GI (Fig. 5) and resulting in lower improvements in RDD. These results indicate possible particle agglomeration or development in particle size when winds flow perpendicular to GI, in addition to enhanced dispersion and removal through deposition in the presence of GI canopies. In addition, the resuspension of particles from the leaf deposition, pollen and other biogenic material from the GI could also influence the particle size distribution

behind the GI. Further studies are required to verify these results, by investigating changes in mass median diameter in the presence of GI under different wind conditions and their influences on RDD. Finally, the study observed noticeable differences between $\% \Delta \text{RDD}$ and $\% \Delta \text{PM}$ in the presence of GI when winds flew perpendicular to GI barriers than under parallel wind conditions.

3.3 Effects of seasonal changes in GI on RDD

To assess the effects of seasonal changes in GI on $\% \Delta \text{RDD}$ and $\% \Delta \text{PM}$, one of the hedge sites (H_{IB} , which borders a children's park) was selected, and relative percentage changes in RDD and PM were estimated (Fig. 6). PM concentration data from field campaigns conducted in the spring-summer (Abhijith and Kumar, 2019) and autumn (Abhijith and Kumar, 2020) were used for this analysis. In comparing periods of leaf growth (spring-summer) with maturity/senescence (autumn), we observed more significant reductions in both RDD and PM in the summer season (SI Table S4). One of the reasons could be the higher average LAI during spring-summer ($6.94 \text{ mm}^2/\text{mm}^2$) than during autumn ($4.89 \text{ mm}^2/\text{mm}^2$), as shown in SI Figure S3. A greater improvement in RDD behind the hedge for all size fractions of PM was seen during the autumn than in the summer. Moreover, the $\% \Delta \text{RDD}$ followed the $\% \Delta \text{PM}$ for the size fractions PM_1 and PM_{10} in both seasons. Conversely, an increase of 9% in $\text{RDD}_{\text{PM}_{2.5}}$ was observed for the summer season, despite a greater concentration reduction. This increase may be attributable to a higher ratio of d_p and DF (>1) behind the hedge in the summer for the size fraction $\text{PM}_{2.5}$ (Fig. 6). On the contrary, a slight increase (1%) in $\% \Delta \text{RDD}_{\text{PM}_{2.5}}$ compared to $\% \Delta \text{PM}_{2.5}$ was observed for the autumn season due to a lower ratio of d_p and DF (<1) behind the hedge. However, no differences were observed between $\% \Delta \text{RDD}$ and $\% \Delta \text{PM}$ in the submicron PM fraction during both seasons, demonstrating the insignificant impact of GI in changing d_p and DF , and thereby resulting in negligible variation in RDD.

3.4 RDD during physical activity

SI Table S5 provides the estimated RDD in adult females, adult males, and children (female) during different physical activities for all PM size fractions and at each GI site. This table also tabulates differences in RDD between locations behind GI and in-front of GI or in a clear area. For the PM_{10} size fraction, the $RDD_{PM_{10}}$ variation during different physical activities ranged $0.5\text{--}4.3\ \mu\text{gh}^{-1}$, $0.6\text{--}5.2\ \mu\text{gh}^{-1}$, and $0.5\text{--}1.9\ \mu\text{gh}^{-1}$ for an adult female, an adult male, and children, respectively (SI Table S5). The estimated variation in $RDD_{PM_{2.5}}$ was $1.2\text{--}17.9\ \mu\text{gh}^{-1}$ for adult females, $1.5\text{--}21.7\ \mu\text{gh}^{-1}$ for adult males, and $1.2\text{--}13.8\ \mu\text{gh}^{-1}$ for children performing various activities at GI sites. Finally, the $RDD_{PM_{10}}$ variation was $8.2\text{--}61.7\ \mu\text{gh}^{-1}$, $10.1\text{--}75.4\ \mu\text{gh}^{-1}$, and $8.1\text{--}47.9\ \mu\text{gh}^{-1}$ for an adult female, an adult male, and children (female), respectively (SI Table S5). The RDD in adult females was 23% to 33% lower than in adult males, while it was 1% to 22% higher than the RDD of children. These differences are due to differences in ventilation rates between each group.

The range of $RDD_{PM_{10}}$ of $23\text{--}42\ \mu\text{gh}^{-1}$ for adult males while walking at various GI sites is slightly lower than the $47\text{--}73\ \mu\text{gh}^{-1}$ reported by Kumar et al. (2018) for near-traffic walking. However, the $RDD_{PM_{2.5}}$ range of $3.3\text{--}12.2\ \mu\text{gh}^{-1}$ for adult males while walking is comparable to the $5\text{--}6\ \mu\text{gh}^{-1}$ range reported by Kumar et al. (2018) and the average $RDD_{PM_{2.5}}$ values of $7\ \mu\text{gh}^{-1}$ and $6.8\ \mu\text{gh}^{-1}$ reported by Kumar and Goel (2016) and de Nazelle et al. (2012), respectively. This agreement with previous studies underlines the significance of the relative reduction in RDD behind different GI (Fig. 7). The relative difference in $RDD_{PM_{10}}$ of PM_{10} behind GI compared to in front of GI or in an adjacent clear area was less than $1\ \mu\text{gh}^{-1}$ for all types of GI, with TH_{CB} and H_{IB} showing the highest $RDD_{PM_{10}}$ differences of $0.93\ \mu\text{gh}^{-1}$ and $0.79\ \mu\text{gh}^{-1}$, respectively, in adult males undertaking intense physical activity (Fig. 7). By contrast, the $RDD_{PM_{2.5}}$ reduction for adult males behind TH_{IB} for the $PM_{2.5}$ size fraction was $5.4\ \mu\text{gh}^{-1}$. The maximum decrease of $14.7\ \mu\text{gh}^{-1}$ in $RDD_{PM_{10}}$ was observed at TH_{IB} for adult males during running. The comparison of relative differences in RDD for all size fractions, across the adult

male, adult female, and children groups and at all GI sites, displayed a similar trend (Fig. 7), and variations at a GI site when undertaking the same physical activity were proportional to ventilation rates. Overall, the tree and hedge combination affected the greatest reductions in RDD for all PM size fractions. These relative differences in RDD of PM could be significant, as the individual inhaled dose of $PM_{2.5}$ from short-term exposure has been linked with airway inflammation, reduced lung function, and alteration of blood pressure (Chang et al., 2012; Wu et al., 2014; Xu et al., 2018; Yin et al., 2017; Yoda et al., 2014). Appropriately designed GI along the peripheries of public parks, boundaries of households, and between roads and footpaths could lower individual RDD and result in associated health benefits by reducing exposure to PM concentrations.

3.5 Variations in PM mass distribution

To clarify the differences between $\% \Delta PM$ and $\% \Delta RDD$ and the dependency of RDD on DF and d_p , the particle mass distributions (PMDs) before and after GI were investigated and are illustrated for all six sites in Fig 8. All PMDs at monitoring points in clear areas and in front of GI in away-road and close-road conditions displayed a similar distribution, with two peaks around the particle diameter ranges of $0.25\text{--}0.35\mu m$ and $2\text{--}3\mu m$ (Fig. 8). Conversely, the PMDs at monitoring points behind GI showed a peak at around $0.3\mu m$. On the other hand, for particle diameters greater than $1\mu m$, a peak between $2\text{--}3\mu m$ was absent (resulting in a flatter curve at most sites) or shifted to a range of $5\text{--}9\mu m$ (Fig. 8). We repeatedly observed no difference between $\% \Delta PM$ and $\% \Delta RDD$ for the submicron PM fraction under different wind conditions and during the two seasons. This could be due to the closely similar PMDs for both monitoring points at GI sites, resulting in negligible variation in mass median diameter. Thus, RDD variations depended only on changes in PM_1 concentrations in the presence of GI.

The observed difference in $\% \Delta PM$ and $\% \Delta RDD$ for $PM_{2.5}$ and PM_{10} at the GI sites could be due to variations in corresponding PMDs (Fig. 8). The H_{CB} site showed the greatest

deterioration in RDD behind GI, which coincided with a peak in PMD at around 6.4 μ m. Similarly, the relatively small increases in RDD_{PM10} behind GI at T_{CB} and TH_{CB} (Fig. 1) were associated with small peaks occurring at around the 6.4 μ m diameter area (Fig. 8). In addition to the absence of a prominent peak at around 2.5 μ m, a large difference between PMDs at monitoring points in front of and behind GI at T_{IB} and T_{CB} (Fig. 8) resulted in a threefold improvement in RDD when compared to the % Δ PM (Fig 1). The study found similar trends between % Δ PM and % Δ RDD of H_{IB} during the two seasons, spring-summer and autumn, as indicated by PMDs shown in Fig. 9. These observed variations in PMDs led to changes in the mass median diameter behind GI, which resulted in differences between % Δ PM and % Δ RDD. This work attempted to draw a relationship between PMDs and variations in % Δ RDD, but further research is required to develop knowledge on the impacts of GI in changing RDD behind GI barriers, ensuring associated health benefits. Furthermore, investigations capturing the full-range of high-resolution PM size distributions, including particle number distributions in the ultrafine size range, can elucidate the GI's influence on the RDD.

4. Summary and conclusions

This study investigated RDD reductions in the presence of GI and compared results with concomitant changes in PM concentrations, estimating % Δ RDD and % Δ PM at six different GI sites. The effects of wind direction and seasonal changes in GI on RDD were also quantified, as well as differences in RDD during various levels of physical activity. Finally, particle mass distributions in the presence of GI were illustrated, and a relationship between PMDs and RDD was explored. The following conclusions were drawn:

- In most cases, % Δ RDD followed % Δ PM and its variation displayed a trend of a % Δ RDD_{PM10} > % Δ RDD_{PM2.5} = % Δ RDD_{PM1}, as compared to the PM order of change of % Δ PM_{2.5} < % Δ PM₁₀ < % Δ PM₁. GI types consisting of a combination of hedges and trees were identified as most effective in reducing RDD for all PM size fractions.

- 408 • The study observed significant differences between $\%\Delta\text{PM}$ and $\%\Delta\text{RDD}$ when ratios

409 of mass median diameter and deposition fraction before and after GI exceeded a range

410 of 1 ± 0.2 .
- 411 • Hourly averaged data illustrated the impact of the ratio of DF on $\%\Delta\text{PM}$ and $\%\Delta\text{RDD}$.

412 When the ratio of DF was < 1 , we observed a higher $\%\Delta\text{RDD}$ than $\%\Delta\text{PM}$, whereas a

413 lower $\%\Delta\text{RDD}$ than $\%\Delta\text{PM}$ was observed with a ratio of $DF > 1$. The ratio of DF is

414 inversely proportional to the $\%\Delta\text{RDD}$.
- 415 • No differences between $\%\Delta\text{PM}$ and $\%\Delta\text{RDD}$ were observed for the submicron PM

416 fraction at any of the GI sites, under different wind flow conditions or different seasons.

417 *Along-road* wind conditions, which represented winds that flow parallel to the road,

418 resulted in the least variation between $\%\Delta\text{PM}$ and $\%\Delta\text{RDD}$ at all GI sites, when

419 compared with both *cross-road* and *cross-vegetation* wind conditions.
- 420 • Negligible seasonal variation between $\%\Delta\text{PM}$ and $\%\Delta\text{RDD}$ was observed at the hedge

421 site H_{IB} during spring-summer and autumn seasons, except for in the $\text{PM}_{2.5}$ size fraction.

422 This indicated that the influences of GI on DF and IF were consistent across seasons.
- 423 • The PMDs illustrated the absence of a peak at around $2.5\ \mu\text{m}$ diameter behind GI, as

424 compared to in front of GI and at an adjacent clear area. No difference in PMDs was

425 observed for the submicron particle diameter in the presence of GI.
- 426 • The most remarkable difference in RDD behind the GI, across all PM size fractions,

427 was observed for the GI type entailing a combination of hedge and trees. The relative

428 differences in RDD behind GI, as compared to in front of GI or at an adjacent clear

429 area, were $1\ \mu\text{gh}^{-1}$, $5.4\ \mu\text{gh}^{-1}$, and $14.7\ \mu\text{gh}^{-1}$ for PM_1 , $\text{PM}_{2.5}$, and PM_{10} , respectively.

430 This study provided insights into the relative changes in RDD in the presence of different types

431 of GI under real-world conditions and compared findings with corresponding reductions in PM

432 concentrations. Although this study gathered scientific evidence for the efficacy of GI in

reducing inhaled doses of PM, it is important to undertake and assess long-term, unattended, combined measurements of PM and UFPs in order to estimate the inhaled doses. This would enable an accurate understanding and quantification of the lung deposition of PM and UFPs in the presence of GI across seasons, and support the development of prudent GI implementation guidelines for health benefits.

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Figure 1. Percentage change in RDD and PM concentration with different GI types. The red and blue bars show %ΔPM and %ΔRDD, respectively. Percentage changes are calculated as $\% \Delta RDD = ((RDD_{PM\ Fraction - INF} - RDD_{PM\ Fraction - BHD}) / RDD_{PM\ Fraction - INF}) \times 100$ and $\% \Delta PM_{Fraction} = ((PM_{Fraction - INF} - PM_{Fraction - BHD}) / PM_{Fraction - INF}) \times 100$.

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The dashed grey line shows the ratio of $DF=1$.

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Figure 7. The relative difference in RDD of male adults, female adults, and female children during different physical activities at various GI sites.

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Figure 9. Particle mass distributions (PMDs) in front of and behind the HIB GI during two seasons: spring-summer and autumn. The red and green lines show PMDs at the monitoring point in front of and behind the hedge, respectively.