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Demonstrating multi-benefits of green infrastructure to schools through collaborative approach

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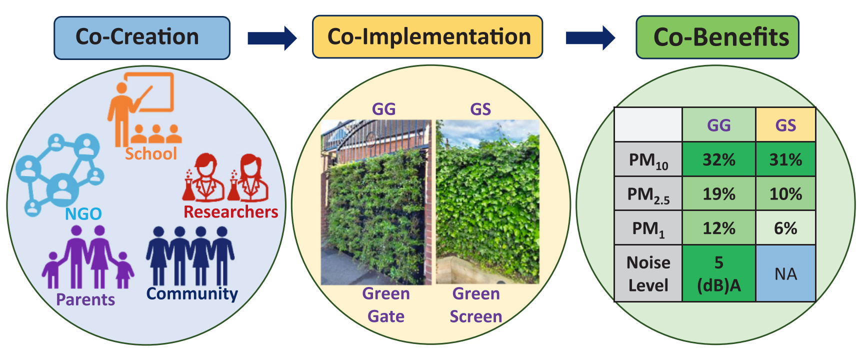
HIGHLIGHTS

- This co-designed and participatory study installed the first living green gate and hedges around the school perimeter.
- Green gate reduced PM_{10}, $PM_{2.5}$, PM_1 and noise by 32 %, 19 %, 12 % and 5 dB (A), respectively.
- Green screen reduced PM_{10}, $PM_{2.5}$, and PM_1 by 31 %, 10 %, and 6 %, respectively.
- PM reduction decreased with distance and had no impact from GI after 25-36 m.
- PM reduced by 44 % (wind flowing away from green gate) and 42 % (wind flowing parallel to green screen).

GRAPHICAL ABSTRACT



	GG	GS
PM_{10}	32%	31%
$PM_{2.5}$	19%	10%
PM_1	12%	6%
Noise Level	5 (dB)A	NA

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ABSTRACT

Green infrastructure (GI) is known to reduce road air pollution exposure, but their implementation in schools and associated benefits remain under-researched. In this study, two GI solutions, green screen and green gate, were co-designed and installed at a primary school in Guildford using collaborative and participatory methods. By assessing changes in air pollution levels, noise, and public perception before and after GI installation, we aimed to understand their impact on reducing children's exposure and evaluate other co-benefits. Without considering wind direction's effect, a maximum reduction of up to 32 %, 10 % and 12 % in the average daily concentration of PM_{10} (green gate), $PM_{2.5}$ (green screen) and PM_1 (green gate), respectively, when compared with in-front concentration. The decay in concentration decreases with distance from the GI, and different wind directions result in varying percentage reductions in PM concentration. For the green screen, 'parallel to the screen' and for the green gate, 'away from the gate' wind directions provided the highest PM reduction. The horizontal

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abatement efficiency of GI varied with PM size, with the highest being PM_{10}. Continuous monitoring behind the green screen revealed a decrease in PM concentration after installation, and this relative concentration varied from 0.29 to 0.90 compared to before installation. The green gate effectively lowered noise by 5 dB(A), and the green screen did not report a noticeable impact on noise levels. Most parents perceived the installation of GI in school as significantly decreasing air pollution exposure and slightly reducing noise levels, resembling the changes in their levels observed in monitoring. The successful co-creation and co-implementation of GI interventions and resulting co-benefits underscore the importance of community engagement and participatory approaches in urban planning and environmental management. This study paves the way for the wider-scale application of innovative strategies involving local communities, stakeholders, and policymakers in implementing GI projects to ensure their sustainability and effectiveness.

Table 1
Summary of past research studies for assessing the impact of GI on school air quality.

Location (year)	Objective	Methodology	Research findings	Study (year)
Taiwan (2022)	To find the effect of greenery and air pollutants in urban areas at the community scale	Local air quality data around urban communities were collected using an IoT based sensor. Total of 15 land-use types, including schools, parks, residential etc. were studied. The land-use regression (LUR) model was applied to study the impact of surrounding land-use types and green metrics on measured PM2.5 concentrations. Green View Index (GVI) from Google Street View (GSV) images were used as greenness metrics.	The higher greenness metrics within the 500 m buffer area of studied land use type showed lower PM2.5 concentration. Evergreen species were found to be better in air quality improvement.	Tang et al. (2024)
U.K (2022)	To assess the effectiveness of GI on the reduction of local, traffic-generated PM concentration.	The study used magnetic and microscopy methods to quantify the amount of local, traffic-derived PM deposited on the leaves of pre-installed hedges. A two-dimensional turbulent mixing model was developed to show the pattern of dispersion of differently sized PM on the front and back sides of the tredge (trees serving as hedges)	A total reduction of 78 % was found in PM_{10} concentration (63 % in the playground and 40 % behind the tredge), and 82 % in $PM_{2.5}$ concentration (behind the tredge) was found as compared to roadside air.	Sheikh et al. (2023)
U.K. (2021)	To assess the effectiveness of different interventions to improve school air quality to reduce students' exposure to air pollutants.	The study investigated three interventions; green screens, air purifiers and school streets. An ivy screen was installed along the school fence, and the effectiveness of the screen was assessed with respect to wind direction.	The green screen along the fences of the school reduced the PM concentration by up to 44 % in the playground depending upon the wind direction.	Abhijith et al. (2022)
U.K. (2021)	To find out the effectiveness of green infrastructure barriers on NO_2 and PM, concentration in a school environment.	Pre and post-green wall installation monitoring was carried out in a school. $PM_{2.5}$ and NO_2 concentration change was evaluated after GI installation near the school playground. Three methods of assessment were used; 1) continuous monitoring with fixed devices, 2) monthly monitoring with diffusion tubes and 3) intermittent monitoring with a mobile device.	13 % and 2 % reduction was observed in NO_2 and $PM_{2.5}$ concentration in the school playground after two years of green barrier installation. The concentration reduction due to low traffic volume was higher than that due to GI installation.	Bermúdez et al. (2023)
Argentina (2021)	To examine the potential and constraints of site-specific GI implementation in urban schoolyards where air pollution levels are high.	A green fence was used in a schoolyard as barrier infrastructure. The effect was assessed by a series of interviews and narratives of stakeholders to find out the barriers to GI implementation	The study categorised the GI implementation barriers into seven different categories (institutional, engagement, political, socio-cultural, built environment and natural landscape, knowledge base and financial) and suggested an expanded model of GI for air quality and multi-dimensional co-benefits.	Redondo Bermúdez et al., 2022a)
U K. (2019)	To find out air quality improvement by roadside vegetation through air quality and leaf magnetic measurement in three schools located near heavily-trafficked roads.	Tredges and ivy screens were installed in three schools (ivy screen, western red cedar tredge and roadside tredges) to find out the effect of PM and BC reduction by tredges in playgrounds and near road locations.	PM deposition on the western red cedar tredge removed 49 % of BC, and 46 % and 26 % of the $PM_{2.5}$ and PM_1, respectively.	Maher et al. (2022)
U.S.A (2018)	Developing a project-based learning module that provides learning opportunities for students with their interaction with a green wall installed inside a classroom.	A green wall workshop was organised that acted as the plant-growing lab to create a learning environment for school children. A green wall was incorporated into a classroom and students were involved while installing the wall and studying the living wall and plants' use as a component of the classroom interior environment.	The project-based learning outcomes resulted in exposure of students to nature-based solutions to classroom interior environments. The module or curriculum incorporating project-based learning has the potential to reduce the effects of directed attention fatigue and to improve students' behaviour.	McCullough et al. (2018)
U.S.A (2014)	To investigate the impact of greening the schoolyards on stress reduction and developing resilience in students	Different methods such as videography, reflective interviews and surveys were used as tools to collect data about students' behaviour and their experience about greening of their school premises.	Students showed improvement in their attention and positive moods, reduced stress	Chawla et al. (2014)

1. Introduction

Air pollution is the fourth leading risk factor for premature death of children worldwide and, therefore, poses a severe threat to public health (State of Global Air Report, 2020). Since children spend a significant amount of their daytime at school (Children's Commisioner Report, 2024), air quality in and around the building greatly influences their health and well-being. Children's developing lungs, increased physical activities, and high breathing rates elevate their susceptibility to the adverse impact of exposure to air pollution (RCP, 2016; Brockmeyer and D'Angiulli, 2016). Additionally, 2092 educational institutes and childcare facilities in the UK are within 150 m of busy roads (Dowler and Howard 2017), where traffic-related air pollutant concentrations are higher than their background levels. A considerable number of schools in the UK have ambient $PM_{2.5}$ concentrations exceeding WHO annual guidelines (GLA Report, 2017; Dowler and Howard, 2017; Osborne et al., 2021) due to the proximity of schools to nearby traffic, the increase in the volume of traffic, rapid urbanisation, and vehicle drop-off and idling, which in turn affects the total exposure of the children (Richmond-Bryant et al. 2009, 2011; Reche et al., 2015; Minguillón et al., 2015; Alzuhairi et al., 2016; Fuller et al., 2017; Adams and Requia, 2017). Controlling emissions at the source by using cutting-edge emission reduction strategies is considered the most effective intervention to lower the exposure (Hewitt et al., 2020). A study by Kurniawan et al., 2024 suggests that desulfurisation technology can reduce >98 % of SO_2 in fuel gas, whereas using thermal incinerators can eliminate 99 % of gaseous pollutants; however, reducing emissions from traffic sources and industries is very costly and time-consuming (when successful) for policymakers. Therefore, policymakers and researchers are turning their efforts to developing and strategising interventions to reduce students' exposure to harmful air pollutants. As a result, in recent years, many technological, behavioural, structural and policy-related interventions (Rawat and Kumar, 2023) have been used in schools.

Green infrastructure (GI) is a passive intervention measure for school premises that can potentially reduce exposure to particulate matter (PM) and gaseous pollutants (Kumar et al., 2020; Abhijith et al., 2022; Barwise and Kumar, 2020; Kumar et al., 2024a; Corada et al., 2021) (Jennings et al., 2021; Kumar et al., 2020b). In addition, GI implementation in schools has gathered significant research attention in the last few years (Sheikh et al., 2023; Tremper and Green, 2018) for its effectiveness in improving air quality in and around schools (Table 1). For example, GI has decreased NO_2 and PM concentrations up to 25 % and 44 %, respectively, in UK schools (Redondo-Bermúdez et al., 2022; Abhijith et al., 2022) and a 14 % reduction in particle number concentrations (Maher et al., 2022). The pollutants are removed by GI through various mechanisms depending upon the surrounding local geometry and meteorological conditions (Donateo et al., 2021), type and characteristics of vegetation, type of pollutants and spatial scale (local or regional) (Venter et al., 2024). GI in urban areas removes gaseous pollutants by absorption through leaf stomata or plant surfaces whereas porous or less dense GI can influence nearby pollutant concentrations by altering the wind flow around it. The aerodynamic effects produced by GI also affect nearby pollutant concentration. In open road environments, GI, as a combination of trees, bushes and hedges, can act as barriers to improving air quality behind them by the mechanism of diffusion and dispersion (Abhijith et al., 2017). Apart from improving the air quality, the wider co-benefits of GI include reducing traffic-generated noise and school building energy consumption by lowering the ambient temperature in summer season, as well as improving local flora and fauna biodiversity supporting local ecosystems (Gago et al., 2013; Perez et al., 2014; Irga et al., 2015; Kremer et al., 2015; Tiwari et al., 2021; Addo-Bankas et al., 2021). The presence of GI on school premises is positively correlated to improvements in academic achievements, physical and mental well-being, enhanced social and community interactions, and improved cognitive development (Bates et al., 2018; Bikomeye et al., 2021). Moreover, strategically implemented GI plans may lead to positive short-term socio-environmental impacts, promote longer-term education and awareness-raising initiatives, and provide solutions to the rising levels of air pollutants in urban environments (Redondo Bermúdez et al., 2022). Apart from numerous benefits, there are certain limitations associated with GI practices. An effective GI implementation requires proper site investigation and a large land area, which can further challenge getting approval or permits from the regulatory authorities. Also, GI is susceptible to seasonal changes and requires extra precautions to prevent the leaves from dying prematurely (Jayasooriya et al., 2017), their pollutants removal efficiency is affected adversely with low wind speed and higher vegetation density (Wania et al., 2012) and higher levels of pollutants' concentration (Bottalico et al., 2016). Therefore, proper care should be taken before implementing GI practices in the field so that their optimum benefits can be achieved.

GI may include different types of networks of vegetation, such as trees, hedges, living walls, green screens and green roofs (Tomson et al., 2021a; Kumar et al., 2024a; Kumar et al., 2024b). Successful implementation of GI in schools depends on the scientific design and planning of GI, the value of GI to the school community, and their engagement, involvement, and reciprocation with the project (Onori et al., 2018; Kumar et al., 2020; Kumar et al., 2020a). As a participatory research method, citizen science enables different levels of public involvement ranging from data collection to total involvement, analysis and interpretation, problem definition, dissemination of the study, and public health action (English et al., 2018; Mahajan et al., 2020). A successful citizen science initiative requires efficient collaboration and communication among partners, finding a middle ground between scientific rigour and community involvement, and integrating local context and knowledge seamlessly into the project's design process. Community engagement should be given utmost importance in the development of GI (Jennings et al., 2021). Guildford has a thriving citizen science community consisting of Guildford Living Lab (GLL), Sandfield Primary School community, Zero Carbon Guildford (ZCG), a local resident group and a parent group from the school. Past collaboration between researchers, local residents, volunteers of ZCG and school communities have delivered citizen science projects in Guildford and around the school, enhancing public awareness and understanding of air pollution levels (Kumar et al., 2023; Abhijith et al., 2024). The current collaboration identified the high air pollution concentration risk at Sandfield Primary School due to its proximity to two major roads along its boundaries (Kumar et al., 2023). Inspired by our past citizen science projects and continuing collaborative activities, this citizen science initiative co-developed and secured funding for a project to implement GI around the school to reduce air pollution exposure in and around the premises. This collaboration between GLL, Sandfield Primary School, ZCG, the parent group, the resident group, and local councilors aimed to demonstrate multiple co-benefits of GI intervention along the roads facing the school perimeter. We installed a green screen along the fence to implement GI along the road and a living green gate at the entrance.

In recent years, many studies have been conducted based on citizen science approaches for air quality monitoring, which is the process of increasing public participation and awareness (Mahajan et al., 2020; Varaden et al., 2021; Kumar et al., 2023; Barros et al., 2023; Toftum and Clausen, 2023). Most of these studies are based on citizen-science techniques such as reflective interviews, public perception surveys and questionnaires. This study is a unique effort to understand and implement the wider benefits of GI in schools because (1) the study is based on co-designed activities from the planning, development and implementation phase to the assessment of GI's impact on school air quality and public perception about it; (2) the variation of PM in different places and its decay with respect to the horizontal distance from the GI in a school environment has not been previously explored; (3) the living green gate (GG) is a unique solution to pollution entering the school through gate openings without interfering with the function of the gate or any change in the ease of opening and closing which has been co-developed and co-assessed for the first time in a scientific study. The specific objectives of this study are to: (1) co-design and co-assessment of the multi-benefits of a green screen (GS) and a GG, including changes in air quality and noise levels, (2) understand the decay of PM from GI along the fence, (3) assess the changes in perception of the school community about the benefits of GI, (4) engage the students in the implementation of GI and the qualitative change in biodiversity, and (5) provide recommendations for adopting these co-created GI solutions in schools elsewhere.

2. Methodology

2.1. Study design

GLL, under the University of Surrey's Global Centre for Clean Air Research (GCARE), coordinates citizen science and public engagement activities and collaborates with local authorities, citizen groups and other organisations on topics such as air quality and climate change, and urban heat island mitigation (Guilford Living Lab (GLL), 2021; Guilford Living Lab (GLL), 2023; Mahajan et al., 2020; Car Free Day, 2021; Kumar et al., 2023; Abhijith et al., 2024; Kumar et al., 2020; Kumar et al., 2023a). This study was collaboratively designed with the researchers from the GLL, Sandfield Primary School, ZCG, the parent group, the community group and the local councilor. The study partners have worked in earlier community-led projects such as RealAir (Abhijith et al., 2024) and Heat-Cool (Kumar et al., 2023a) and identified the need to improve the air quality on the Sandfield Primary School premises. Fig. 1 illustrates the involvement and responsibilities of GLL, Sandfield Primary School, the parent group, and ZCG volunteers in various stages of the study and their roles in the co-designing and co-implementation of this project. Primarily, we focused on tackling air pollution exposure in a primary school located at the intersection of two adjacent busy roads (Stoke Road and York Road) using two sets (GS and GG) of GI (Fig. 2). Additionally, we aimed to demonstrate co-existing multi-benefits from the implementation of GI. To establish engagement, participation, and mutual collaboration among the school community and other project stakeholders, we incorporated surveys to understand the perception of GI implementation, communal co-creation of the GG, and biodiversity surveys of students around GI.

The various stages shown in Fig. 1 present citizen science concepts of

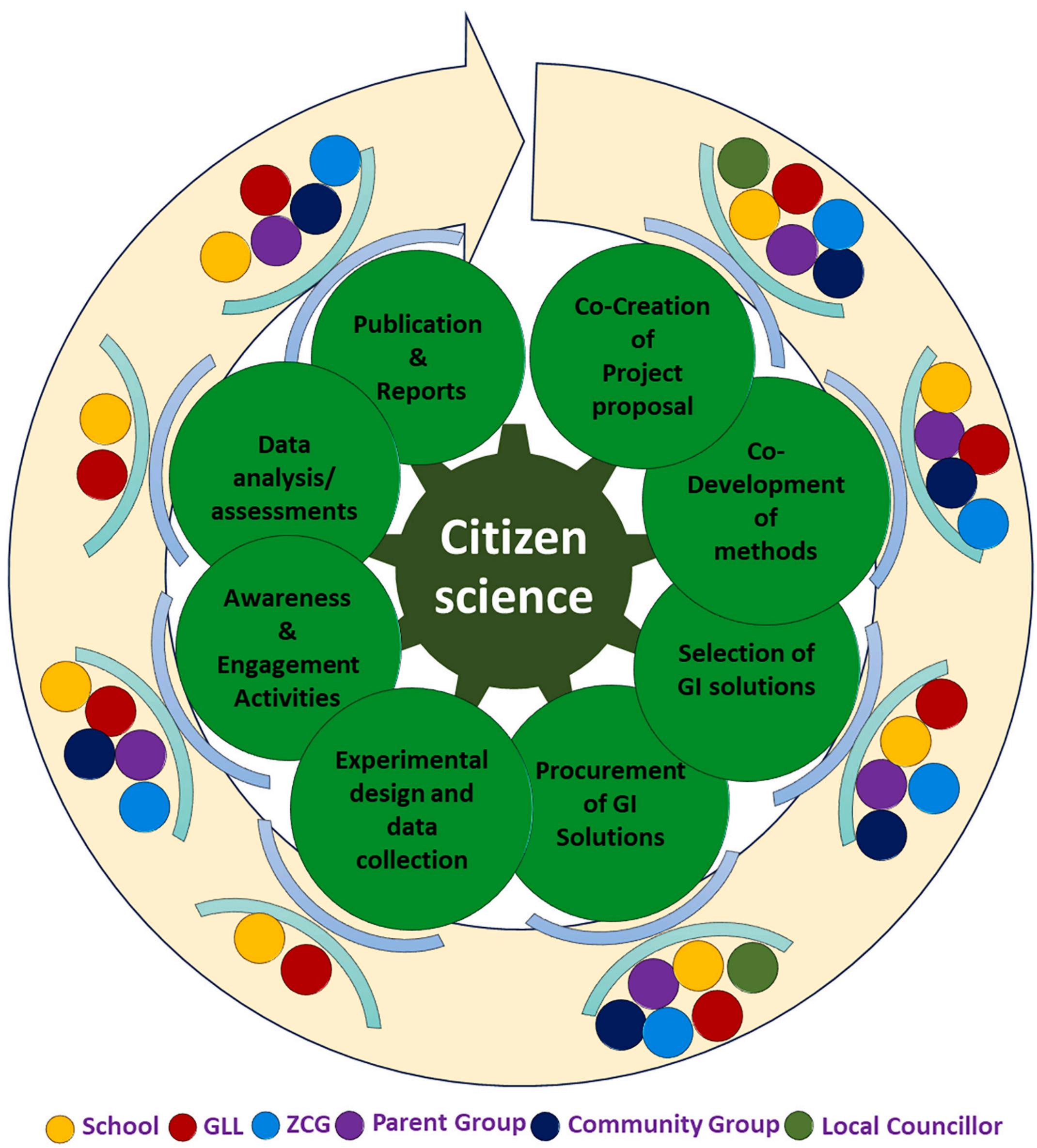

Fig. 1. The schematic representation of citizen science activities and the contributions and involvements of partners. Involvement and roles are marked with circles in each stage of the study.

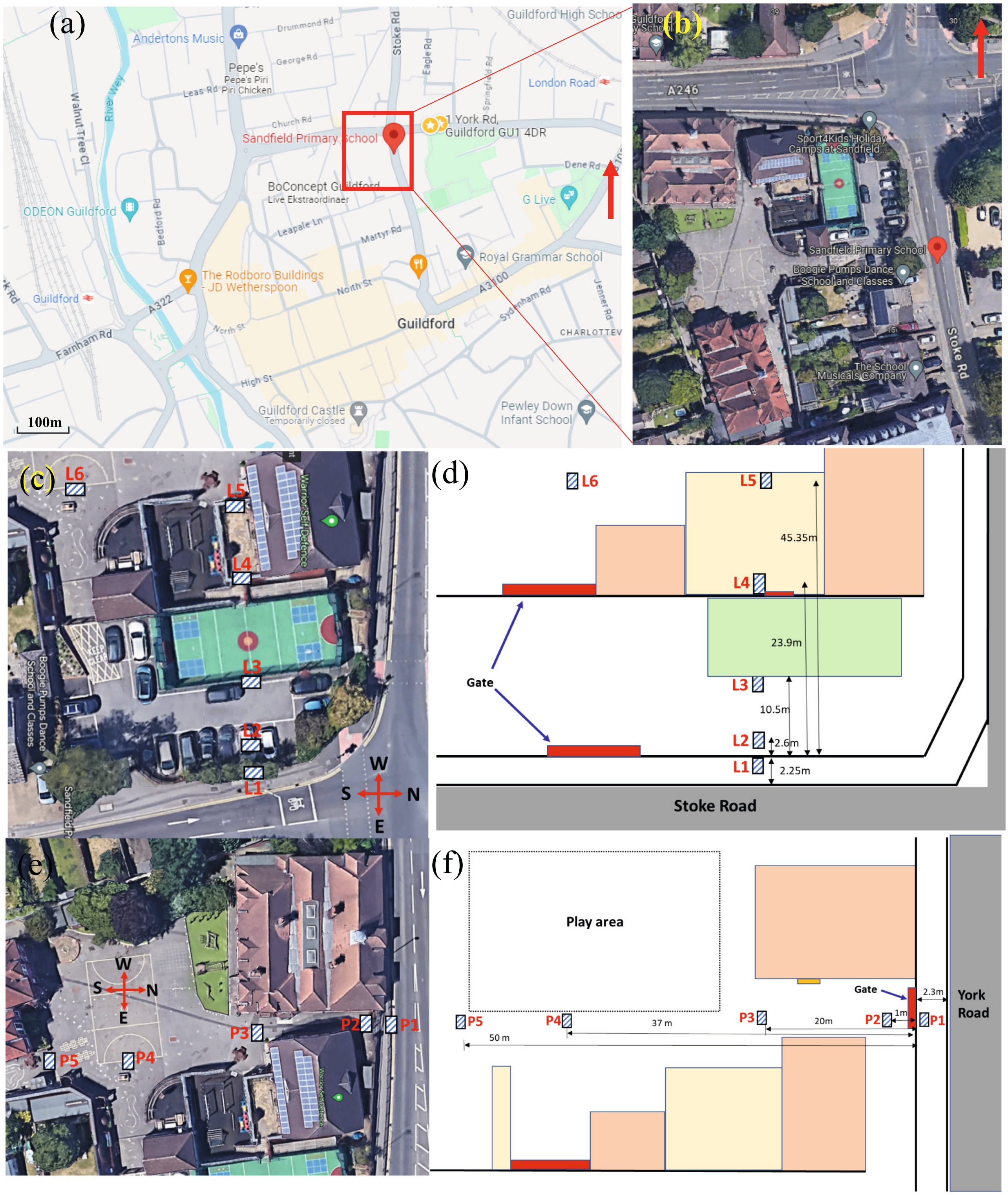

Fig. 2. Location of the study site in a primary school in Guildford (shown in the red box, a), located at the junction of heavily trafficked roads (b). Monitoring points in front (L1) of the fence and behind (L2-L6) where a GS is constructed on the edge of the car park (c). A schematic representation is shown in (d). Monitoring points in front (P1) and behind (P2–5) of GG (e) and its schematic representation (f).

inclusion, collaboration, and reciprocation (Mahajan et al., 2020). The successful co-design of the project and co-writing of the proposal started with informal meetings with all project partners, as presented in Fig. 1. After securing the funding, the project team had regular meetings to assess various GI implementation strategies to curb traffic-generated air pollutants (mainly PM) entering the school from busy roads on two adjacent sides of the school compound (Fig. 2). One of the local residents designed the logo for the project to promote the project among local community group, as an example of an early co-creation activity. We discussed scientific aspects of GI solutions, site-specific conditions for implementation, and considerations from the school and evaluation methods. The outcome of our initial biweekly meeting was to set up a GS made of ivy along the car park to provide a barrier to the pollution coming from Stoke Road and design a unique GI solution to block air and noise pollution entering the school through the gate, the only opening on York road. The school, ZCG, and GLL contacted various suppliers for GI solutions, arranged site visits and finalised procurement. Through consultations with suppliers, the idea of the living green gate emerged, which was first in the UK, probably in the world. School parent and resident groups led negotiations with suppliers and finalised implementation dates. Further, we planned to collect data before and after implementing GI interventions. This study aimed to capture the spatial variation of PM in school premises, investigating the impact of distance from the road on concentration levels. PM is considered as a common proxy indicator for air pollution (WHO, 2024) and has been associated with the negative health impacts especially, children and other vulnerable population groups. In addition, the To understand parents' perceptions of GI solutions, the school conducted surveys before and after implementing GI. The school wanted to integrate the project into students' experience and learning. This resulted in each student planting a plant on the GG and the Year 5 students conducting a biodiversity survey. This showcases an example of 'collective making' where stakeholders are actively involved in the design and delivery of the project (Brandsen et al., 2018; Langley et al., 2018). This collaborative approach was essential in successfully implementing GI as a natural base solution and integrating it into the communities, delivering co-benefits, as pointed out in previous studies (Frantzeskaki, 2019; Sarabi et al., 2019).

2.2. Site description

The effect of the green infrastructure GS and GG were evaluated in a primary school located at the junction of two busy roads in Guildford, United Kingdom (Fig. 2). The main source of air pollution in the area is vehicles, both exhaust and non-exhaust emissions. The emissions from other sources and secondary pollutants are less significant in understanding GI impact on a school at various locations in near-road road environments. Frequent congestion of roads at the traffic junction, specifically at pick-up and drop-off times, leads to poor air quality surrounding the school premises. The sampling sites consisted of two types of GI configurations: (i) GS at the school boundary near the car park area and (ii) GG fixed at the school gate. The selection of sampling points (SPs) in these two locations was based on the availability of space for placing instruments behind the GI, at the adjacent clear area, in front of the GI, and in the open area in the school (e.g., playgrounds). Fig. 2 shows a schematic representation of SPs along with the locations of the GI, the distance from the edge of the road and the school boundary to SPs. The location of the GG and GS was selected to ensure maximum protection against incoming PM generated by traffic sources and to provide green cover on the exposed area of the school boundary. The gradient of concentration decay of pollutants was measured at different monitoring locations covering playgrounds and the maximum possible open area in the school premises with no obstruction to airflow and taking into account practical constraints such as the schedule of the school and movement of children during play time, movement of traffic around the sampling locations during drop-off and pick-up hours.

- Green screen: The GS consists of intertwined Ivy (*Hedera helix*), an evergreen species on a steel wire; each panel has a height of 1.8 m and a width of 1.2 m. These panels are grown in a nursery in a coconut fibre root container filled with potting soil and planted into the soil next to the fence. Raised soil beds were created for planting in a small area next to the gate, which had an asphalt surface. A 20 m long GS was placed in the car park. This was added to the existing single-row tree, providing a breathing height barrier. The sampling site at the car park area consists of 6 monitoring points (Fig. 2 c and d). SI Table S1 provides further information about the location, distance from the road and instrument set-up at each sampling point. The sampling points were selected to cover the maximum possible area, including front, behind the GS and playgrounds. All the sampling points were stationed linearly except point 6, located in playground 2, due to a lack of further feasible points linear to sampling point 5. The playgrounds were included in the monitoring to quantify the concentration reduction effect of the GS installed at the school boundary. The SP in the front of the GS is labelled L1, while the SPs behind the GS are labelled L2-L6, covering the area from the GS up to the playground.
- Green Gate: This GG is a light green wall made of fabric-based material that holds small plants and attaches them to the existing gate. The custom-made GG was built by attaching a wood frame to both gate leaves. A thick fabric base with pouches was screwed to the wooden frame. The metal-facing side of this base was insulated to avoid corrosion of the gate leaves. The fabric base houses a concealed automated drip irrigation system. Three types of plant species (40 % hedera, 35 % lonicera, 25 % Erigeron) were inserted into the pouches, forming a uniform vegetation layer. Additional soil was used to fill any remaining space in the pouches. Due to the use of lightweight materials, the finished product does not hinder the gate's functionality, and there is no change in the serviceability of the gate after converting it to a GG. It also has an automated and concealed irrigation system to keep plants watered. Further safety measures were taken to avoid black ice formation in winter or the development of algal growth in summer at the gate's base. The completed installation had dimensions of 2 m height and 3 m width. The instrument setup, distance from the road and locations at the GG monitoring site are shown in Figs. 2 e and f; details are provided in SI Table S1. The geometric characteristics behind the GG consisted of a passage surrounded by school buildings on both sides, with the width of the passage being slightly less than the height of the buildings on both sides. The monitoring area included drop-off and pick-up points for school children, and it remained quite busy during school's start and finish times. Also, the students used this area to run and play during lunch hours. Therefore, the sampling points were selected to prevent any accidents. The SP in front of the GG is labelled P1, and the SPs behind the GG are labelled P2-P5 (Fig. 2 e and f). It is worth mentioning that the kitchen and dining area for the students were situated between the SPs P2 and P3. P2 was at the starting point and P3 at the far end of the passage, whereas P4 and P5 were in the playground open area.

2.3. Instrumentation

The monitoring set-up included GRIMM-11D, GRIMM-11C, GRIMM EDM 107 EDM-180, OPCs, QTraks and noise level monitors. These instruments have been used widely in different scientific studies (Rivas et al., 2017; Kumar et al., 2018; Abhijith and Kumar, 2021). EDM-180 measured mass fractions of PM_{10}, $PM_{2.5}$ and PM_1 at a minute interval, along with wind speed, wind direction, temperature and humidity. The particle size range of EDM (GRIMM Aerosol Techik GmbH & Co KG, Ainring, Germany) is 0.25–32 μm and works on the principle of light scattering at single particles with a diode laser. GRIMM-11D (GRIMM Aerosol Techik GmbH & Co KG, Ainring, Germany) measured the mass and number concentration of PM_{10}, PM_4, $PM_{2.5}$, PM_1 and total counts, considering the size distribution within a size range of 0.25–35 μm (Wu et al., 2022). GRIMM EDM 107 (GRIMM Aerosol Techik GmbH & Co KG, Ainring, Germany) aerosol spectrometer was used for measuring particle mass and number concentration in the 0.25–32 μm diameter range. The flow of the instrument was controlled by an internal pump and kept at 1.2 l/min. The Alphasense OPC-N3 (Alphasense, 2024), which provides aerosol number and mass concentrations in the size range between 0.35 and 40 μm, was used to monitor the spatial and temporal variation in $PM_{2.5}$ and PM_{10} concentrations. This low-cost sensor, which is widely used in research, measures the PM number concentration bypassing the sample air at 210 ml/min through a laser beam of 658 nm wavelength.

Several previous studies have used these instruments before for air pollutant measurements (Abhijith and Kumar, 2019; Rivas et al., 2017; Sharma and Kumar, 2020). Further, the datalogger sound level monitor measured an A-weighted sound pressure level (dB) between 30 and 110 dB with a 0.1 dB detection limit. The average A-weighted equivalent sound pressure level for every 15 min ($LAeq_{15\ min}$) is calculated using the Eq. (1) (Makarewicz and Gołebiewski, 2006) where L_i is each sound pressure level reading in dB and n is the total number of measurements: Similar time averages have been used in previous studies (Davies et al., 2009; Kumar et al., 2022).

$$LAeq = 10log\frac{1}{n}\sum\nolimits_{i=1}^{n} 10\hat{}\frac{Li}{10} \tag{1}$$

All instruments' data were averaged to 1 min for further analysis. On-field colocation was carried out during the monitoring period to verify the low-cost sensors' measurement. The on-field colocation mimicked the real-world conditions and provided more accurate correction factors for low-cost sensors. The colocation was carried out for a total of 6 h. EDM-180 was used as a reference instrument to calibrate OPCs. The verification was performed by computing the coefficient of determination (R^2), and the coefficient between the EDM-180 and all other portable aerosol monitors were higher than 0.78, 0.96 and 0.96 for PM_1, $PM_{2.5}$ and PM_{10}, respectively (SI Fig. S3). Linear regression models were used to reduce the difference in concentration between instruments. Regression coefficients are provided in the SI Table S2. The boxplots before and after applying regression coefficients are shown in SI Figs. S2 and S3, respectively.

2.4. Data collection and analysis

The monitoring campaigns collected high-resolution ambient air quality and noise data before (pre-installation) and after (post-installation). The monitoring campaigns collected high-resolution ambient air quality and noise data before (pre-installation) and after (post-installation) installing a GS at the car park and GG at the school gate. At both locations, the pre-and post-installation monitoring was carried out for five days each, starting at 08:00 h (local time) and finishing at 15:00 h. The starting and finishing times were decided based on when the students were in school (excluding after-school club hours) and exposed to air pollution. There are two categories of post-installation data for the GS location: post-GS1 denotes PM concentration immediately after installation, and post-GS2 shows PM concentration in the second phase of post-installation monitoring to consider the increased leaf density. For the GG the "pre-GG" refers to the period from 06 to 13 September 2023 and the "post-GG" refers to the period from 15 to 25 September 2023. For the GS, the "pre-GS" refers to the period from 06 to 12 June 2023, the "post-GS1" refers to the period from 21 to 23 June 2023, while the "post-GS2" refers to the period from 03 to 09 October 2023.

The leaf area index (LAI) of Ivy (*Hedera Helix*) was calculated following the method used by Weerakkody et al. (2017). Six 30 cm × 30 cm quadrants were randomly selected on the GS to determine the average number of leaves in a quadrant. The mean surface area of leaves was calculated from the individual surface areas of ten random leaves measured using ImageJ (Schneider et al., 2012). The LAI is calculated for post-GS1 and post-GS2 monitoring periods using the following equation:

$$LAI = \frac{Mean\ surface\ area\ of\ ivy\ leaf \times average\ number\ of\ leaves\ per\ quadrant}{Total\ area\ of\ the\ quadrant} \tag{2}$$

The effect of GS and GG is calculated by the difference in pre- and post-installation PM concentration behind the screen or gate normalised to the concentration in front. The normalisation was done to make the pre-installation and post-installation data comparable.

$$C_{AB}^{+} = \frac{C_{AB}}{C_{BB}} \tag{3}$$

C_{AB}^{+}= Baseline normalised concentration at SPs after the GI barrier.
C_{AB}= Baseline concentration at SPs after the GI barrier.
C_{BB}= Baseline concentration at SP before the GI barrier

$$C_{AB}^{++} = \frac{C'_{AB}}{C'_{BB}} \tag{4}$$

C_{AB}^{++}= Post-installation normalised concentration at SPs after the GI barrier.
C'_{AB}=Post-installation concentration at SPs after the GI barrier.
C'_{BB}=Post-installation concentration at SPs before the GI barrier.

% change in normalised PM concentration was calculated by the difference between baseline (pre-installation) normalised concentration (C_{SP}^{+}) at different SPs and post-installation normalised concentration at respective SPs (C_{SP}^{++}).

$$(\%\Delta PM) = \left(\frac{C_{SP}^{++} - C_{SP}^{+}}{C_{SP}^{+}}\right) \times 100 \tag{5}$$

C_{SP}^{++}= Post-installation normalised concentration at any sampling point.
C_{SP}^{+}=Baseline normalised concentration at any sampling point.

The instruments' data were cleaned and analysed using statistical software R (version v4.3.0) and the OpenAir package. On each monitoring day, the first 20 min of measurements were considered a warming-up period and were excluded from the analysis. The Met Office (Met office UK, 2024) provided the hourly meteorological parameters for the measurement site for the field measurement period. To investigate the effect of wind direction on PM reduction, the data was divided based on the wind flow direction with respect to the alignment of GS and GG. The dataset was divided into three wind direction sectors: 'parallel to the GS or GG' (P), 'towards the GS or GG' (wind flowing from the road towards the GS or GG) (T), and 'away from the GS or GG' (wind flowing from GS or GG towards the road) (A). The orientation of the GS and GG was parallel to the adjacent road. The description of different wind direction sectors and their angular division has been given in SI Table S3 for the GS and gate. The wind rose diagram in each monitoring scenario can be observed in SI Fig. S5.

3. Results and discussion

3.1. Variation in PM concentrations before the installation of the green screen (baseline scenario)

Fig. 3 shows the PM_{10}, $PM_{2.5}$ and PM_1 concentration variation in all SPs before and after installation of the GS (post-GS1 and post-GS2). Table S4 summarises the data variability (maximum and minimum), mean, median and standard deviation of PM concentration in each of the sampling locations (L1-L6) during school hours (08:00–15:00 h) for pre and post (GS1 and GS2) GS installation. The results showed that the average daily concentration varied from 18.32 ± 2.48 μg/m^3, 12.55 ± 0.70 μg/m^3 and 10.45 ± 0.45 μg/m^3 for PM_{10}, $PM_{2.5}$ and PM_1, respectively, considering all locations in baseline monitoring during school hours. The average concentration of PM_{10} and $PM_{2.5}$ was highest during the baseline scenario at sampling location 2, which was behind the proposed GS in the car parking area. The higher PM concentration right behind the GS proposed location could be explained by vehicle activity in the car park area, such as braking and accelerating, leading to higher PM concentration due to particle emission and dust resuspension. The cars coming for pick-up and drop-off contribute to higher PM concentration due to the idling of engines and has been identified as one of the major drivers of high PM concentration (Kumar et al., 2020). The availability of trees may also have influenced PM concentration just behind the GS by resuspension of accumulated particles (Chen et al.,

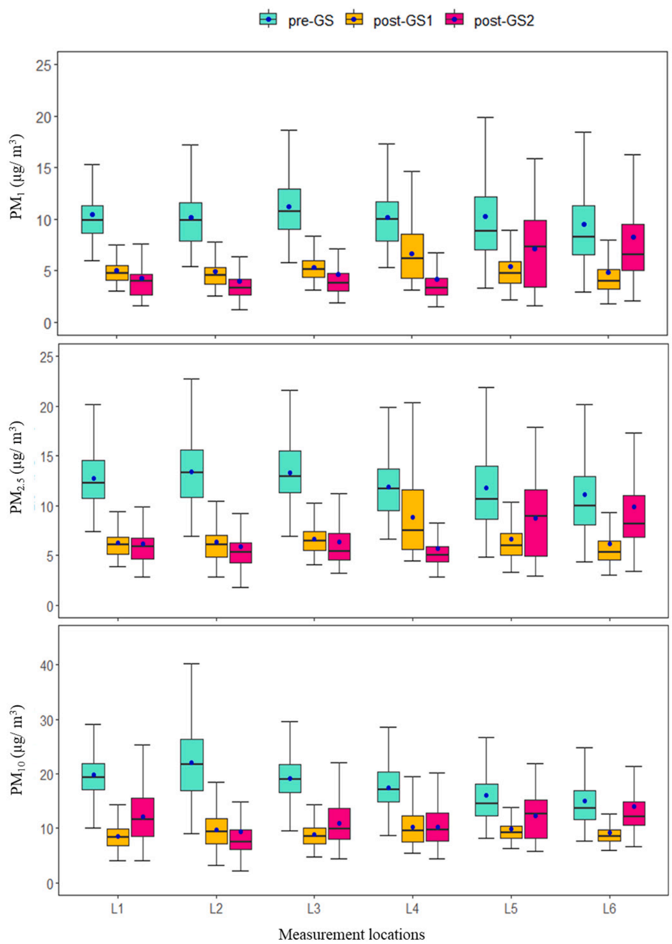

Fig. 3. Box plots showing concentrations of PM_{10}, $PM_{2.5}$ and PM_1 in front (L1) and behind the GS (L2-L6) during pre-installation (pre-GS) and post-installation (post-GS1 and post-GS2) monitoring.

2016). Moreover, since the baseline monitoring was performed during the summer season and no rainfall was observed during the period, the absence of rainfall may have caused the deposited particles to accumulate on the leaves' surface and increased the resuspension (Chen et al., 2016).

Playgrounds are usually associated with higher concentrations of PM_{10} due to the resuspension during the time of children's activities, especially when considering sandy playgrounds (Minguillón et al., 2015; Rivas et al., 2018; Osborne et al., 2021). The lower concentration of PM_{10} in our study near both playgrounds (at L3 and L6) can be attributed to the presence of paved playgrounds and, thus, lower resuspension of PM during children's activities. L4 and L5 were located on the rooftop, and no activity occurred in the area, leading to a lower baseline concentration of PM_{10} at these SPs than at L1-L3. There was no significant variation in $PM_{2.5}$ (12.55 ± 0.70 μg/ m^3) and PM_1 (10.45 ± 0.45 μg/ m^3) at all SPs during baseline monitoring.

The baseline PM concentration variation shows the effect of local activities around the SPs and its distance from the road. The concentration reduces with distance from the road for PM_{10}, $PM_{2.5}$ and PM_1 at all SPs except at L2 and L3 which were located in the car park area where vehicle emission was a prominent factor affecting PM concentration.

3.1.1. Overall PM reduction after the installation of the green screen (post-GS scenarios)

In order to understand the effect of the GS on the PM concentration, the percentage change in the normalised concentration was calculated before and after the GS installation (Eq. 3). As shown in Fig. 3, the highest reduction in normalised concentration (normalised to L1) was observed in PM_{10} concentration at SPs L2-L4, during the post-GS2 scenario as compared to the normalised base scenario concentration. The percentage change in normalised concentration of PM_{10} in post-GS2 with respect to base scenario (ΔPM10) was 31 % at L2, and for $\Delta PM_{2.5}$ and ΔPM_1 was 10 % and 6 %, respectively. The reduction in concentration (ΔPM_{10}) declined further to 6 % and 3 % at L3 and L4, respectively. No significant changes were observed in $\Delta PM_{2.5}$ and ΔPM_1 (<2 %) at L3 and L4. No effect of the GS was observed at L5 and L6, which were located further away (>35 m) from the GS, showing the negative change in normalised concentration (increase in concentration as compared to base scenario) for all PM fractions. The post-GS1 scenario showed no significant reduction in overall percentage change in normalised PM concentrations for all fractions at all SPs behind the GS. Increased concentrations were observed at SPs L3-L6, which could result from reduced particle dispersion due to the creation of a recirculation zone by a highly porous barrier (Steffens et al., 2012). The post-GS1 monitoring took place just after the installation of the GS at a time when the screen was not fully developed and grown, showing an LAI of 2.03 ± 0.04 m^{2}m^{-2}. On the other hand, during the post-GS2 monitoring, the GS had increased thickness and lower porosity, presenting a LAI of 2.14 ± 0.12 m^{2}m^{-2}. A lower LAI value could explain the non-significant reduction in concentration observed during the post-GS1, in contrast to the significant reduction observed during the post-GS2.

The higher PM reduction during the post-GS2 scenario suggests that the PM removal effect of the screen was improved by an increase in the LAI of the screen, as also observed in other studies (Abhijith and Kumar, 2020; Tomson et al., 2021a, 2021b; Wróblewska and Jeong, 2021). Our previous work (Abhijith and Kumar, 2019) observed a contrasting result of increased concentrations of all PM fractions even after increased leaf area density (LAD). This could be due to the lower height of the hedge (<1 m), which is insufficient to create a barrier effect for particles at breathing height. In the present study, the screen's height was >1.5 m, which may lead to a barrier effect at the breathing height behind the screen. Also, in agreement with previous studies, the percentage reduction in $PM_{2.5}$ and PM_1 was lower than that for PM_{10} at the three locations behind the GS (L2, L3 and L4), which indicates less impact of GI on fine particle removal (Brantley et al., 2014; Viippola et al., 2018; Abhijith and Kumar, 2019).

The PM reduction at some SPs behind the GS (post-GS2) suggests that the GS can provide an effective solution against incoming pollutants by altering the wind flow and dispersing the incoming PM. GS should be designed carefully before installation with respect to its height, thickness and location. A mature and well-grown GS with high LAI is more effective in reducing PM concentrations behind the screen.

3.1.2. Influence of wind direction on PM reduction by green screen (post-GS scenarios)

Table S7 provides concentration variation of PM_{10}, $PM_{2.5}$ and PM_1 at different SPs with respect to wind directions during GS monitoring. The wind conditions have been divided into three categories based on the direction of wind flow (A, P and T) as described in Section 2.5. Pre- and post-GS1 data have all the wind direction points, but the prevalent wind directions in post-GS2 monitoring were A and P, with no data point available for 'towards-the-screen' (T) wind direction.

During post-GS1 monitoring, the normalised concentrations of all PM fractions at each SP behind the screen increased compared to that during the pre-GS scenario when the wind direction was from the screen towards the road (A), except at L5 and L6. This finding is in line with the results reported by previous studies (Steffens et al., 2012; Tong et al., 2015), showing that the recirculation zone is created if wind passes through a porous vegetation barrier, which reduces the wind speed and dissipation of upwind turbulent eddies. This recirculation zone is responsible for limited particle dispersion and higher local concentration. When wind direction was from the road towards the screen (T), the post-GS1 monitoring showed a slight reduction in normalised PM_{10} at L2 and L3, as shown in Table S5 (4% and 3 %, respectively). However, it increased the normalised concentration of $PM_{2.5}$ and PM_1 (−2 % and −8 %, respectively) at L2 in the car park area. The maximum reduction in PM concentration was found during post-GS2 monitoring when the wind direction was 'parallel to screen' with ΔPM_1, $\Delta PM_{2.5}$ and ΔPM_{10} of 19 %, 18 % and 42 %, respectively, compared with pre-GS concentration in similar wind direction. The higher reduction of normalised PM concentration could be due to an increase in LAI in the post-GS2 monitoring period compared with the pre and post-GS1 period, as observed in our previous studies (Abhijith et al., 2017; Abhijith and Kumar, 2019). As the distance from the GS increases, no specific pattern of PM concentration variation was observed with respect to different wind directions, and the effects of local activities were more prominent than the GS's filtration effect.

The notable reduction of 42 % just behind the green screen in PM_{10} concentration, while the wind flows parallel to the screen, could be explained by the sweeping effects, as discussed in the literature (Abhijith et al., 2019). The reduction was higher for coarse particles (PM_{10}) than fine particles (PM_1, $PM_{2.5}$). The % change ~~of in~~ in PM concentration with respect to change in the wind direction suggests that air quality data should be collected before installation, and GI should be robustly maintained to keep it dense and healthy to achieve long-term benefits (Natural England, 2023).

3.2. Variation in PM concentration before installing green gate (baseline scenario)

Fig. 4 shows the PM_{10}, $PM_{2.5}$ and PM_1 concentration variation at different SPs in front and behind the GG during pre (pre-GG) and post-installation (post-GG) monitoring. Table S6 summarises the data variability (maximum and minimum), mean, median and standard deviation of PM concentration on each sampling location P1-P5 during school hours. The results showed that the average daily concentration varied from 22.67 ± 2.34 μg/m^3, 16.95 ± 2.62 μg/m^3 and 15.12 ± 2.66 μg/m^3 for PM_{10}, $PM_{2.5}$ and PM_1, respectively, considering all locations in baseline monitoring during school hours.

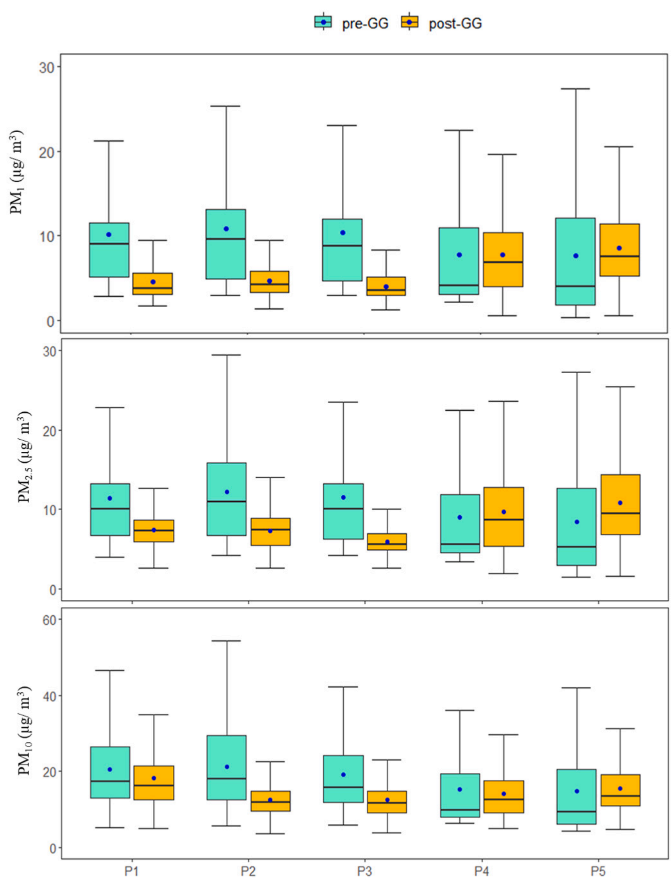

Fig. 4. Box plots show concentrations of PM_{10}, $PM_{2.5}$, and PM_1 at different sampling points (P1-P5) in front and behind the GG during pre-installation (pre-GG) and post-installation (post-GG) monitoring.

The average baseline concentrations of PM_{10}, $PM_{2.5}$ and PM_1 at P2 were not significantly different from respective concentrations at P1 (Table S6). A Similar pattern was observed at P3 with a slight reduction in average PM_{10} concentration compared to that at P1. The average PM_{10} concentration showed further reduction till P4 with no significant change in $PM_{2.5}$ and PM_1 concentration (compared with P1). At P5, the concentrations of all PM fractions (PM_{10}, $PM_{2.5}$ and PM_1) increased, which may be influenced by local activities in the nearby playing area and higher resuspended particles. Baseline monitoring data provided insights into PM variation with distance from the SP1 (near to the road) without a GG. The results suggest that PM_{10} concentration reduces with distance from the road, with little to no variation in $PM_{2.5}$ and PM_1 concentration. The local activities at SPs resulted in a higher local concentration of PM at the furthest SP (P5) from the road.

3.2.1. Overall PM reduction after installing green gate

To find the effect of GG installation, the percentage changes in the normalised PM concentrations at different SPs were calculated using Eq. (3). The reduction in PM concentration could be the result of enhanced dispersion, and absorption and deposition on leaves' surface and on the non-fabric base material.

Overall, the highest reduction in normalised concentration was found in PM_{10} (32 %) at P2. In contrast, at the same SP, the corresponding reductions in $PM_{2.5}$ and PM_1 were 7 % and 5 %, respectively. At P3, ΔPM_{10}, $\Delta PM_{2.5}$ and ΔPM_1 were 25 %, 19 % and 12 %, respectively. At P4, ΔPM_{10} was 2 %, whereas $\Delta PM_{2.5}$ and ΔPM_1 were negative, showing an increased normalised concentration compared to baseline monitoring. This could be due to resuspended particles and weakened momentum for pollutant transport by increasing distance from the GG (Morakinyo et al., 2016). At P5, the change in PM concentration showed no specific pattern related to concentrations at other SPs. This may be due to the prominent effect of local activities and higher distance from the GG. P4 and P5 were located at a distance of 36 m and 48 m from the GG, respectively and were in the playground area. The resuspended PM due to children's activities and higher distance from the GG resulted in a lower impact on PM reduction.

The PM variation at different SPs before and after the installation of GG indicates that GG can provide an effective solution against incoming traffic-generated particles on school premises. PM concentration is reduced with a distance of up to 23 m from the GG, with 32 %, 19 %, and 12 % maximum average reductions in PM_{10}, $PM_{2.5}$, and PM_1, respectively. The results also suggest that PM reduction at a certain location by GG depends upon its distance from the GG and the type of activities taking place. As such, these factors should be considered while assessing the impact of GI in air pollution reduction. Moreover, when planning and designing an appropriate GI solution in schools, it is essential to consider both the location of the GI and its distance from the primary areas where children spend their time. For example, adding GI near playgrounds can be beneficial to children, giving them high activity levels and increased breathing rates. Children of five-six years of age are at risk of breathing larger volumes of air per minute in light and moderate activity environments (Kawahara et al., 2012). In this case, minimising their exposure to air pollutants and other harmful aspects of the urban environment, such as noise or heat, could bring them a healthier environment.

3.2.2. Influence of wind direction on PM reduction by green gate

Table S8 provides concentration variation of PM_{10}, $PM_{2.5}$ and PM_1 at different SPs with respect to wind directions during GG monitoring. The categories of different wind directions have been described in Section 2.5. Pre- and post-GG data have data for all the wind directions (A, T, P) that were used to calculate the PM removal effect of the GG.

The effect of the GG under different wind directions is assessed using Eq. (3) with respect to corresponding PM concentrations at different SPs under the particular wind direction. During parallel wind direction, normalised PM_{10} concentration just behind the wall (P2) was reduced by 30 %, with 15 % and 13 % reduction in $PM_{2.5}$ and PM_1. A similar trend was observed in parallel wind direction at P3 with 23 %, 19 % and 16 % reduction in PM_{10}, $PM_{2.5}$ and PM_1 concentrations, respectively. The presence of the kitchen and common lunch hall near SPs (P2 and P3) may have also affected the particle dispersion pattern. At P4 and P5, no pattern was observed in PM concentration as these points were located in the playground and away from the GG to have any significant barrier effect on PM concentration. When the wind was flowing from the GG towards the road (A), ΔPM_{10} was found at 44 % (P2) and 28 % (P3), $\Delta PM_{2.5}$ at 7 % (P2) and 22 % (P3), and ΔPM_1 was found as 4 % (P3) and increased concentration of −2 % (P2). The negative ΔPM_1 at P2 could be due to the proximity of the kitchen near to P2. At P4 and P5, normalised concentration increases for PM_{10}, $PM_{2.5}$ and PM_1.

When the wind was flowing from the road to the GG (T), there was very little improvement achieved in $PM_{2.5}$ and PM_1 concentration (4 % and 7 %) just behind the green gate at P2, where PM_{10} concentration increased slightly by −5 %. The increase in PM_{10} just behind the green gate could be due to the formation of a behind-barrier wake zone for larger-size particles having low deposition velocity (Tong et al., 2016) The reduction in normalised concentration increases further with distance, with 25 %, 20 % and 12 % reduction in PM_1, $PM_{2.5}$ and PM_{10} concentration, respectively, at P3, as compared with normalised concentration in baseline scenarios when the wind was flowing from the road towards the GG. If all wind directions are considered together, the GG was effective in reducing PM within 24 m distance from the road depending upon the distance of the SPs from the GG and the influence of location and activities, with the highest reduction of up to 38 %, 23 % and 25 % in PM_{10}, $PM_{2.5}$ and PM_1 concentration, respectively.

3.3. Influence of GI on PM concentration decay

The effect of GS installation was only noticeable till L3 and reduced afterwards with distance from the GS. At SPs located beyond 25 m

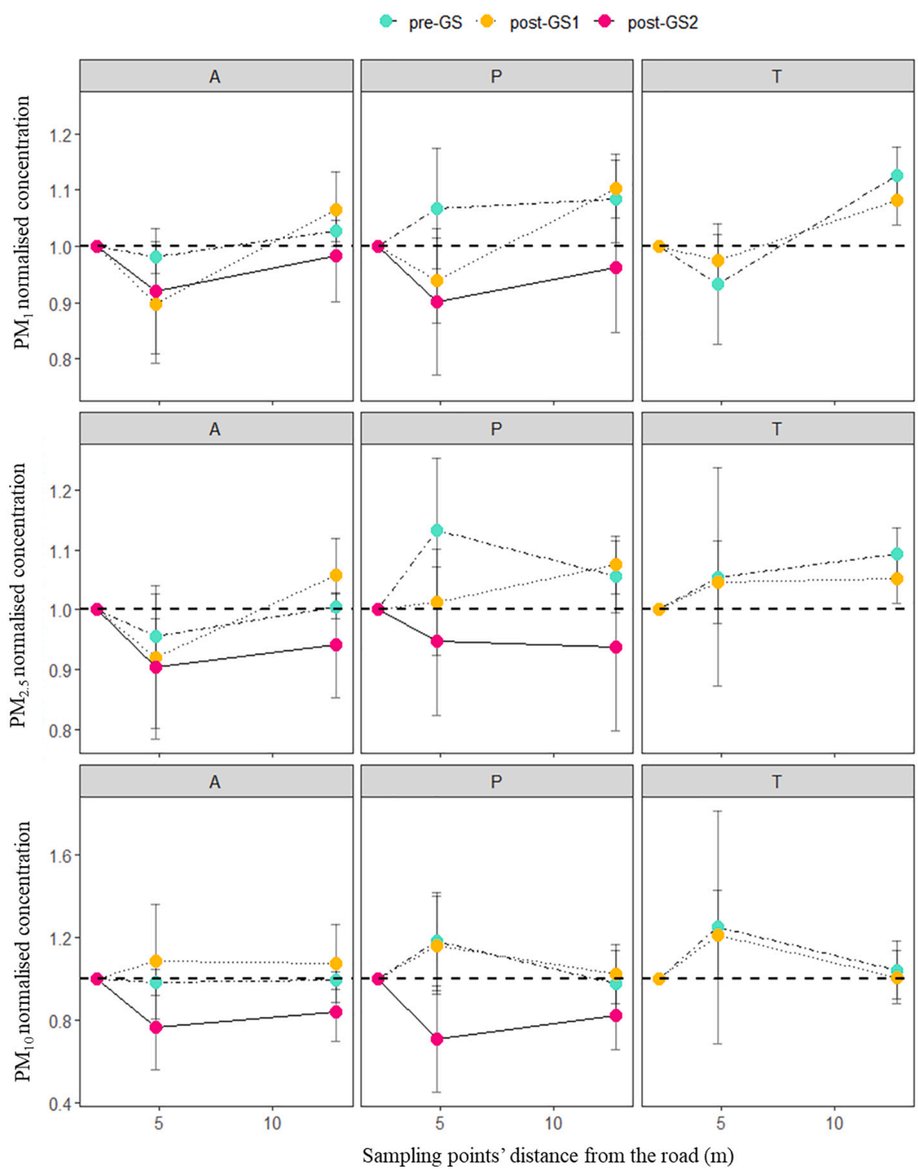

Fig. 5. Concentration variation with distance (concentration gradient) for PM_{10}, $PM_{2.5}$ and PM_1 in front and behind the GS during pre-installation (pre-GS) and post-installation (post-GS1 and post-GS2) monitoring.

distance from the GI, the effect of local activities dominated the PM construction over the filtration effect of GS at these SPs. Therefore, to show the impact of GI on PM decay gradient, only the SPs L1-L3 (GS) and P1-P3 (GG) are considered (Fig. 5 and Fig. 6). During the first phase of post-installation monitoring for GS (post GS1), PM concentration did not significantly improve after the GS installation because of the highly porous screen (not fully grown as discussed in Section 3.1.1). These findings agree with the previous study by Zheng et al. (2021) that found a similar decay pattern of PM. The study investigated the impact of dense and porous vegetation barriers. It concluded that dense vegetation has a stronger interception effect on particles, leading to less penetration and lower PM concentration. The second phase of post-installation of GS (post GS2) resulted in an overall reduction in PM_{10}, $PM_{2.5}$ and PM_1 normalised concentration from 3 to 31 %, 1–10 % and 1–6 %, respectively, depending upon the distance from the screen. The decay was more significant with distance in coarse-sized PM (PM_{10}) than in finer PM ($PM_{2.5}$ and PM_1). The increase in the GS's density resulted in a higher reduction in PM_{10} behind the screen than PM_1 and $PM_{2.5}$. The concentration reduction effect of the GS was not in proportion with the distance for $PM_{2.5}$ and $PM_{10,}$ with a sharp decline just after the screen, as also found in a study by Tong et al. (2016), which concluded that the PM concentration decay was non-linear and doubling the leaf area density (LAD) will not double the reduction of the PM concentration. The decay in PM concentration follows no specific reduction pattern with respect to wind direction. The highest reduction behind the GS was found in PM_{10} concentration parallel to the screen wind direction (42 %) just behind the screen. The decay in PM concentration decreases with a distance of 13 % at L3 and 6 % at L2 in a similar wind direction.

The geometry of the surrounding area behind the GG was not similar to that behind the GS. The kitchen emissions caused ΔPM_1 and $\Delta PM_{2.5}$ to be lower at P2 (just behind the GG), as discussed in Section 3.1. PM_{10}'s concentration decay was highest at P2 (32%) and reduced with horizontal distance. The reduction in normalised concentration ranges from 2 to 32 %, 7–19 % and 5–12 % for PM_{10}, $PM_{2.5}$ and $PM_{1,}$ respectively, depending upon the distance from the edge of the road. A continuous decay was found in PM_{10} till 36 m distance from the road (at

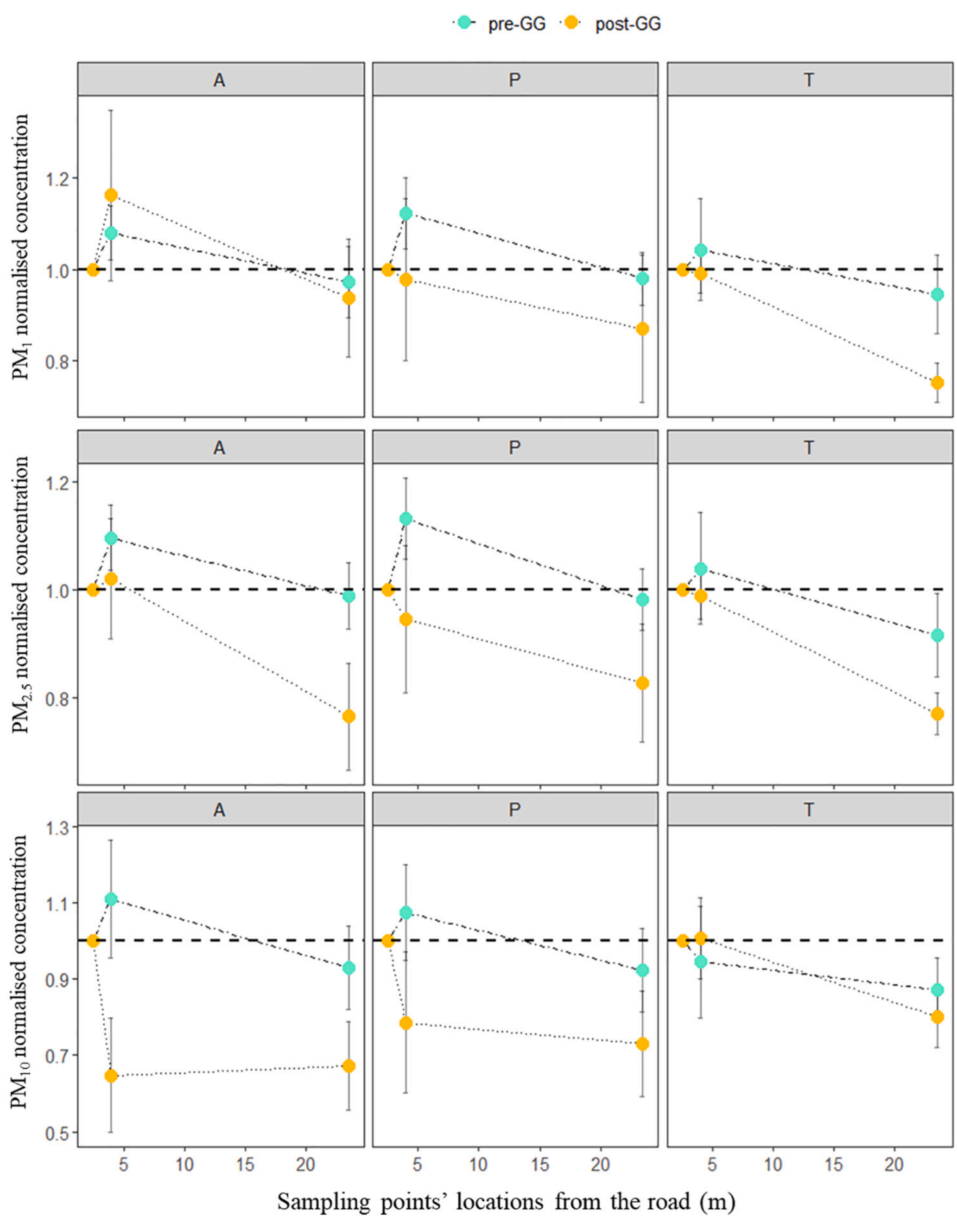

Fig. 6. Concentration variation with distance (concentration gradient) for PM_{10}, $PM_{2.5}$ and PM_1 in front and behind the GG during pre-installation (pre-GG) and post-installation (post-GS1 and post-GS2) monitoring.

P4), where the concentration became approximately similar to that at P1 (front of the GG). The local activities at SPs P4 and P5 (in the playground) were responsible for the sudden rise in the PM concentration, which shows no resemblance to the decay trend.

The reduction in PM concentration with horizontal distance depends upon the distance of the sampling point from the GI, local meteorology and activities (near the SP), PM size fraction and wind direction. The reducing effect is more substantial with larger-sized particles (PM_{10}) and when the wind direction is parallel to the GS. The thickness and the growth of leaves in terms of LAI also affected the PM decay, with higher decay in the post-GS2 scenario having increased LAI than the post-GS1 scenario, which emphasises the importance of regular maintenance and watering of GI for higher LAI (Battaglia et al.,1998) Similarly, for GG, the decay in PM with distance was more when the wind direction was parallel to the gate.

3.4. Long-term variations in PM behind the green screen

Fig. 7 shows the monthly average PM_{10}, $PM_{2.5}$ and PM_1 concentrations under three wind conditions (T, P, A) at monitoring point L2 from June to October and the PM concentration ratio. More prolonged monitoring allowed us to understand changes in the reduction in PM over the period and the impact of LAI due to the growth of GS and the influence of meteorology. PM_{10}, $PM_{2.5}$ and PM_1 concentrations were lowered abruptly after installing GS at the behind location L2 under all wind conditions. For instance, under '*T-towards the GS*'(T) wind condition PM_{10}, $PM_{2.5}$ and PM_1 reduced from $24 \pm 7 \mu g m^{-3}$, $14 \pm 5 \mu g m^{-3}$, and $12 \pm 5 \mu g m^{-3}$ (June, mean ± SD) to 10 ± 5 to $17 \pm 11 \mu g m^{-3}$, 7 ± 2 to $12 \pm 9 \mu g m^{-3}$ and 5 ± 2 to $11 \pm 7 \mu g m^{-3}$, respectively from July to October. '*A-away from the GS*'(A), wind flow conditions recorded a maximum decrease of less than half in PM concentration (Fig. 7). Inconsistent reduction in PM concentration during these months may be due to less developed GS in an early growth stage with lower values of LAI. This can be compared to the sudden decrease and fluctuation in pollutant concentrations during the leaf-growing period observed with a deciduous hedge (Ottosen and Kumar, 2020). The LAI of the installed GS of Ivy (*Hedera helix*) was 2.03 ± 0.04 $m^2 m^{-2}$ at installation (June). It increased to 2.14 ± 0.12 $m^2 m^{-2}$ at the end of the monitoring period

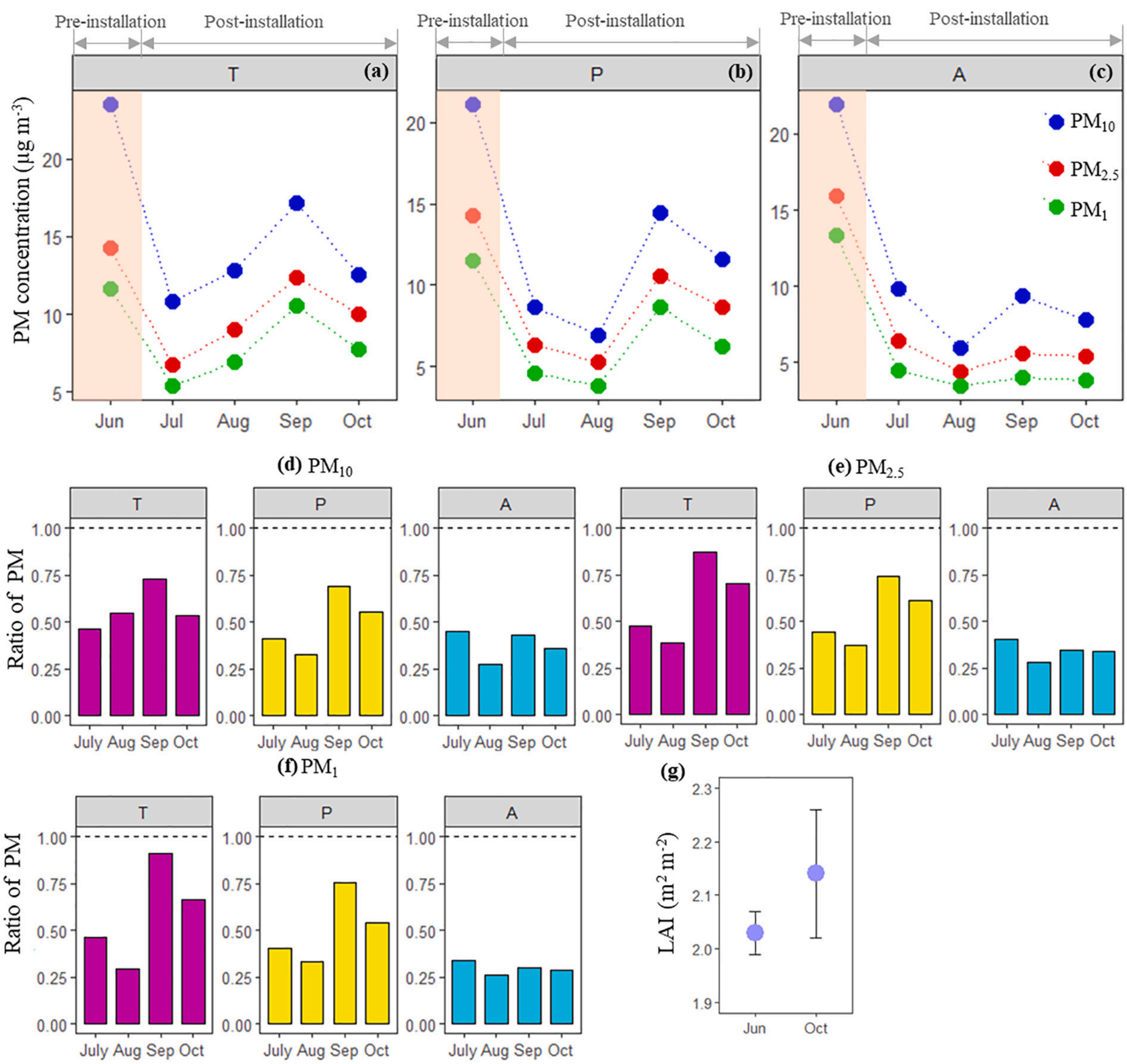

Fig. 7. Mean PM_{10}, $PM_{2.5}$ and PM_1 concentration variation from June to October at monitoring point L2 in the car park (a, b, c) under three wind conditions ('*Towards the GS*'[T], '*parallel to the GS*' [P], '*away from the GS*' [A]). The red-shaded area shows the preinstallation period (June). Post-installation of GS is from July to October. The pre and post-GS installation PM concentration ratio (monthly $PM_{post\text{-}installation}/PM_{pre\text{-}installation}$), (d) PM_{10}, and (e) $PM_{2.5}$, and e) PM_1 divided into three wind direction classifications (T, P, A).

(October) (Fig. 7g). This LAI was lower than the previously reported values of 3.2 ± 0.27 m^2m^{-2} (Tomson et al., 2024) and 2.69 ± 0.07 m^2m^{-2} (Weerakkody et al., 2017) measured on fully grown ivy GG. Therefore, the GS was in the growing stage during the monitoring campaign. Moreover, stress from wilting during August–September with limited rain and insufficient watering may also contribute to the variation in PM reduction and low rate of increase in LAI.

The change in PM is more clearly visualised when analysing the ratio of PM fractions before and after GS installation, as observed in Figs. 7 e-f. All relative PM ratios were below 1 in all wind conditions, ranging from 0.29 to 0.90, indicating a considerable decrease in PM concentration behind GS after installation. A similar variation in relative concentration change of about 0.48 to 0.65 was reported by Ottosen and Kumar (2020) when comparing hedges in front and behind along the same road. Under '*T-towards the GS*' wind condition, the highest drop in relative PM concentrations was for PM_1, about 0.29, followed by $PM_{2.5}$ and PM_{10}, showing about 0.38 and 0.55, respectively. This trend in the reduction of PM fractions is observed with Ivy GS at a school perimeter (Abhijith et al., 2022), hedges (Abhijith and Kumar, 2019; Ottosen and Kumar, 2020), tredge (Sheikh et al., 2023) and with GG (Weerakkody et al., 2017, 2018). Since GS is in its growth stage, a further increase in LAI is expected in the coming seasons, ensuring a higher decrease in PM concentration year-round when it reaches maturity.

3.5. Impact of GI on noise levels

Fig. 8 shows the mean and hourly variation of short-term noise levels as $L_{Aeq\text{-}15min}$ during school working hours before and after the installation of GG. The placement of GG showed a reduction of 2–5 dB(A) in noise levels. Average noise levels behind GG were 68.00 ± 4.70 dB(A) and 66.10 ± 4.72 dB(A) for pre- and post-installation periods. Contrastingly, the noise level in front of the GG remained almost equal for pre- and post-installation with values of 71.4 ± 3.7 dB(A) and 71.1 ± 4.0 dB(A), respectively (Fig. 8c). This means GG reduced the average noise level to 5 dB(A) compared to the noise level in front of GG. Moreover, the average noise level at the monitoring point behind GG decreased by 2 dB(A) compared with pre- and post-installation periods. The hourly variation of average noise levels post-GG displays this reduction clearly in Fig. 8a. The GG consisted of a thick cloth base with pouches attached to a wooden frame, and plants were inserted into the pouches, forming a uniform vegetation layer. This system may function similarly to noise barriers. Noise barriers reported an average reduction of 6–7 dB(A) from railway lines (Fiorini, 2022) and a reduction of 17–35 % behind barriers at a distance of 0-10 m from a road (Tezel-Oguz et al., 2023). In addition to measured noise reduction, the presence of GI can reduce the perception of traffic-related noise up to 10 dB(A) (Dzhambov and Dimitrova, 2015; Van Renterghem and Botteldooren, 2016; Van Renterghem, 2019; Bogdanov et al., 2022). This is an additional benefit of increasing GI on school premises.

In contrast, the installation of GS resulted in a fluctuating average noise level (LAeq-15 min) behind GS, as shown in Fig. 8. The average noise levels behind GS were 71.9 ± 6.3 dB(A) and 63.4 ± 3.8 dB(A) during post-GS1 and post-GS2 periods, respectively (Fig. 8d). The noise levels in front of the GS were 68.9 ± 7.6 dB(A) and 66.4 ± 2.0 dB(A) during the same periods. An increase of 3 dB(A) in average noise level was reported behind GS during the post-GS1 monitoring period, as presented in Figs. 8b and d. Conversely, average noise levels were lower than 3 dB(A) at the monitoring point in front of GS during the post-GS2 monitoring period, with a slight increase in LAI. Thus, the impact of the installation of GS on average sound levels was inconclusive. A GS with low LAI and thickness is not effective in reducing noise levels. Further assessment with mature dense (high LAI) GS is required to determine its efficacy of noise reduction potentials. This assessment of GS and GG indicated that installing these GI solutions has considerable potential for reducing noise levels on school premises.

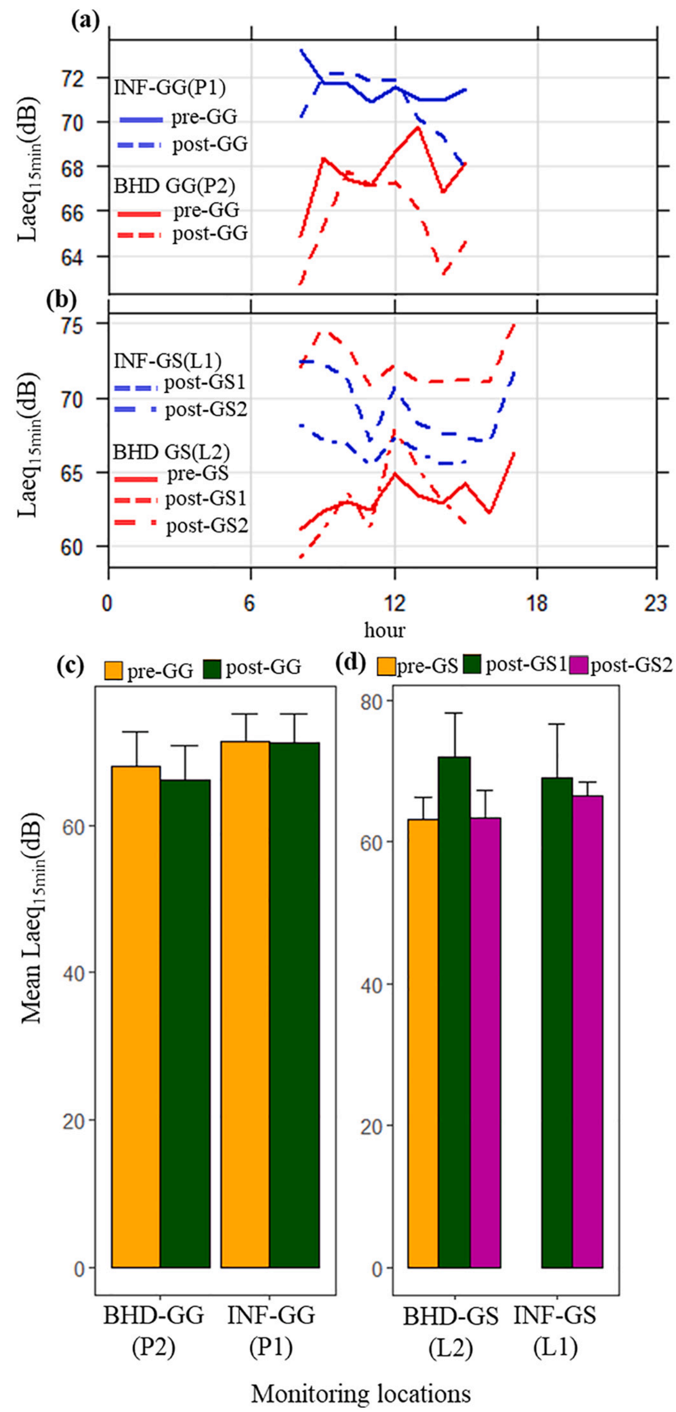

Fig. 8. Hourly average equivalent sound levels during pre and post-installation of GG (a) and GS (b) during school working hours. (c) Bar plots show average and std. deviation of equivalent sound levels in front and behind the GG at the gate during pre-installation (Pre-GG) and post-installation (post-GG) monitoring periods. (d) Bar plots show average and standard deviation of equivalent sound levels in front and behind the GS during pre-installation (pre-GS) and post-installation (post-GS1 and post-GS2) monitoring periods.

3.6. Perceived benefits of GI and engagement activities

Fig. 9 summarises the Likert scale assessment of participating parents' perception of air quality in the school, air and noise pollution reduction potentials GI and its other co-benefits before and after installation of GS and GG. The survey was used to understand parents' and guardians' concerns about air and noise pollution, their opinion on

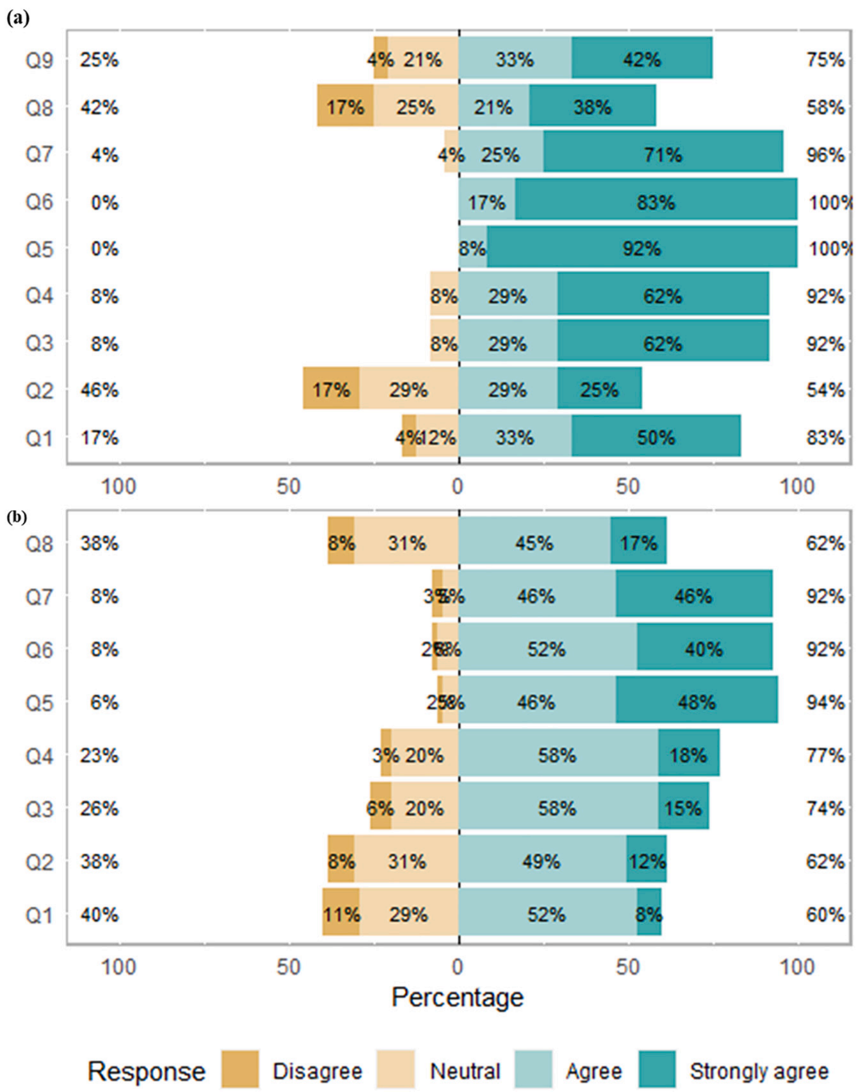

Fig. 9. Likert scale summary of responses from parents on perceived benefits of GI before (a) and after (b) installation of GS and GG. Questions\ statements from Q1 to Q8\Q9 of both surveys are given in the SI Table S10.

GI implementation and their knowledge of the efficacy of GI. In addition, it assessed the impact of co-building and installation of the GS and GG. Surveys can be used to understand stakeholders' perceptions of nature-based solutions, ensuring collaboration in planning and implementation (Mitincu et al., 2023; Bodin and Crona, 2009; Rozylowicz et al., 2019). The survey before the installation of the GI in the school received only 25 responses from the parents, whereas the after-installation survey produced 66 responses from 200 students. A significant increase in the number of responses showed increased involvement in overall project activities in school. Before GI introduction in school, 83 % and 54 % of participants were worried about students' exposure to air and noise pollution, respectively (Fig. 9a. Q1 and Q2). After the installation of GG and GS, participants' concerns about air pollution dropped to 60 %. Whereas for noise pollution, it slightly reduced to 62 % (Fig. 9b. Q1 and Q2). This indicates an improvement in awareness about the effectiveness of GI in improving air quality and relatively less impact on noise pollution. Considerable reduction in air pollution concentration and relatively less lowering in nose levels matched with perceived reduction in surveys. Most participating parents and guardians (~92 %) were optimistic about the efficacy of GG and GS in reducing exposure to air and noise pollution (Fig. 9a; Q3 and Q4). After the GI implementation, when questioned about whether students' involvement in constructing the green gate was an excellent educational opportunity to learn about plants and biodiversity, over 94 % of parents provided highly positive responses (Fig. 9b; Q5). Despite the significant increase in the responses, nearly two-thirds of participants (74 % and 77 %) stated that installing GG and GS curbed air and noise pollution in the school (Fig. 12b; Q3 and Q4). In both surveys, nearly all participants (<92 %) believed introducing multiple GI in school and student participation in the project activities benefited students' well-being, enhancing their knowledge of plants and biodiversity (Fig. 9a, b; Q5, Q6 and Q7). The level of satisfaction in contributing to the activities for improving air quality remained the same at around 60 % among participating parents in both surveys (Fig. 9a, b; Q8). This assessment of responses enabled us to determine participating parents' concerns and views of the work and understand the level of engagement, participation and satisfaction in the project activities. For example, we observed more than double the increase in response, and positive survey comments indicated significant improvement in engagement and satisfaction with the project. The involvement of parents as stakeholders and understanding their perceptions and concerns are fundamental for the success of projects implementing nature-based solutions (Ferreira et al., 2021). Parents perceived significant improvement in air pollution and lesser reduction in noise levels after the installation of GI, which resembled observations from the measurements.

Fig. 10 shows snapshots of various engagement activities, such as the

Fig. 10. (a) Students actively participate in the building of the GG. Each student chooses a plant and then waits for their turn to plant it in a pouch of their choice on the GG. (b) View of the finished GG from the outside. (c) and (d) students surveying plants, insects and other living organisms to roughly estimate biodiversity on the school premises.

co-building of GG and biodiversity surveys. These activities aimed to serve three social aspects of the successful implementation of GI in school: creating GI value for the stakeholder/community, engaging with the project, and nurturing working relationships (Onori et al., 2018). A 2022 study conducted by the Temple Group for Surrey County Council (SCC) revealed that 68 % of Surrey residents consider taking action on climate and the environment to be "extremely" or "very" important (SGF, 2022).

While assembling the GG, each student chose one plant and placed it in a desired pouch in the frame of GG, as presented in Fig. 10a. Thus, a personal connection to a specific plant on the GG is established. Moreover, students' participation in the building of GG and the survey of biodiversity as engagement and learning activities had the highest positive (>94 %) response from parents in the perception survey (Q5, Fig. 9). As a measure of success among school communities, they set up a new GoFundMe (GoFundMe, 2024) page to install additional GI on the school premises, continuing activities that had started in this project. In addition, students surveyed and counted plants, insects, and other living organisms to estimate the biodiversity on the school premises roughly using the iNaturalist app (Matheson, 2014) on iPads, as presented in

Figs. 10c and d. Students identified 33 and 34 species in the survey conducted at school premises in July and October 2023, respectively, before and after the installation of GG and GS. The survey and pupils' engagement indirectly increase the awareness of the benefits of GI, as well as continued collaboration and communication between the stakeholders, which reduces barriers to implementing nature-based interventions (Castellar et al., 2024). Engagement and awareness activities were essential for the uptake of the benefit of nature-based solutions (Bermúdez et al., 2022) and allowed collaboration with stakeholders at different levels (Frantzeskaki, 2019; Sarabi et al., 2019). These activities allowed this work to be a successful nature-based solution project, establishing collaboration and engagement of the community and stakeholders (Dushkova and Haase, 2020).

4. Summary and conclusions

The study demonstrated a successful co-designing and co-production of GI interventions in a school through a participatory research collaboration between GLL, Sandfield Primary School, ZCG, and parent and resident groups. The study showed the importance of collective efforts between the school, scientists, communities around the school, and public organisations in co-implementing GI to improve air quality in schools. This study investigated the effect of two different GI configurations (a GS, and a GG) on PM concentration in a primary school located in the centre of Guildford. We evaluated the impact of wind conditions on PM concentration in the presence of GI and their influence on horizontal PM reduction with the increase of distance. We assessed the parents' perception of the benefits of GI implementation in school and conducted engagement and participatory activities with students.

The key conclusions drawn from this study are as follows:

- Co-designing, co-production and co-implementation are essential for successful GI interventions in schools. This strategy facilitates the implementation of site-specific GI solutions while accommodating school-friendly considerations and delivers multiple benefits to the school community.
- The overall results (without considering the effect of wind direction) suggest that GI placed at the school boundary effectively reduces PM concentration in the area behind it. The highest reduction was found in PM_{10} in both GI configurations (GS and GG). The SP just behind the screen showed a 31 % improvement, and the corresponding SP behind the GG showed a 32 % improvement in PM_{10} concentration compared to the pre-installation phase.
- The reduction in finer PM was up to 10 %, 6 % (GS) and 19 %, 12 % (GG) behind the GI for $PM_{2.5}$ and PM_1, respectively, depending upon the location of the SP. Attenuation is found in PM concentration at different SPs at a distance from the GI, with higher reduction at SPs near the GI.
- The concentration reduction was not proportional to the distance from the GI. Still, a clear decay trend was found, with the highest reduction just behind the GS, and it decreased afterwards up to about 26 m from the screen. A higher reduction was observed when the screen had increased LAI after a short growth period in the second phase of GS monitoring. The results thus suggest that the screen's porosity is also important in affecting PM concentration.
- Wind direction affected GI's impact on PM reduction. When the wind direction was parallel to the GS, the highest reductions of 42 %, 18 %, and 19 % were observed in PM_{10}, $PM_{2.5}$, and PM_1 concentration compared to pre-installation monitoring for the same wind direction. The respective reductions in PM_{10}, $PM_{2.5}$, and PM_1 concentration were 30 %, 19 %, and 16 % at different SPs.
- Prolonged monitoring behind GS showed a sudden reduction in all PM after the installation of GI. The relative PM concentration (before and after implementation of GS) reported a reduction ranging from 0.29 to 0.90. The highest decrease in relative concentration levels was observed for PM_1, about 0.29, followed by $PM_{2.5}$ and PM_{10}, about 0.38 and 0.55, respectively, in the perpendicular winds coming from the road to GS.
- Installation of GG resulted in the reduction of 5 dB(A) in the average noise level behind the GG. Whereas the introduction of GS showed no influence on noise levels.
- Most of the parents (>74 %) perceived the installation of GI in school as decreasing air and noise pollution exposure, and they considered students' involvement in project activities to be highly beneficial for enhancing their knowledge of plants and biodiversity.
- In addition to co-creation and co-implementation, various engagement and awareness activities established multilevel collaboration and engagement of the community and stakeholders in both technical and social aspects, resulting in a successful and sustainable nature-based solution project. The 'social contagion' factor from the GI interventions was vital, demonstrated by several enquiries about further GI as a result of this project. At the same location (York Road) several organisations have enquired about installing GI, aware of the fact that further action to create green corridors provides more significant benefit than standalone installations. Interested parties include Waitrose and Surrey, and Sussex Police; however, the cost of implementation has proven to be an obstacle. The exception is Guildford Nursery, across the road from the Sandfield site, which has benefitted from a funding competition run by Zero Carbon Guildford, funded by a successful bid through the corporate match-funding site Action Funder.

The key recommendations drawn from this study are as follows:

- A collaborative approach focusing on co-designing and co-implementation results in the successful and sustainable installation of the most suitable GI intervention. A collaborative approach is essential for greater uptake of GI intervention by the stakeholders and community. The process allows us to understand the concerns of stakeholders, easily identify and implement GI interventions and ensure the engagement and involvement of stakeholders and the community. These elements are essential for a successful nature-based solutions project.
- After installing the green screen at the school boundary facing the road, PM_{10}, $PM_{2.5,}$ and PM_1 were reduced by 31 %, 10 %, and 6 % compared with the pre-installation concentration, respectively. GS could be a suitable GI intervention along school boundaries where heavy traffic roads are situated alongside them. The results of this study suggest that GSs can act as a filter for incoming particles, and their screening effect can reduce PM concentration in nearby areas. This finding highlights the importance of GS in improving the air quality of schools.
- Green gate is effective in reducing PM_{10}, $PM_{2.5}$ and PM_1 concentration by 32 %, 19 % and 12 % compared with pre-installation concentration, respectively. The GG concept presents an innovative solution to curb air and noise pollution without interfering with the gate's functions. The results suggest that GG is an effective intervention to curb the ingress of air pollutants that also helps to increase the aesthetic beauty of the school entrance while contributing to local biodiversity.
- Evergreen species and continuous maintenance are recommended for GI interventions. Evergreen species effectively reduce air pollution throughout the year due to lesser leaf area density variations than deciduous plants. A recurring maintenance plan is essential to ensure healthy vegetation and automated irrigation systems can lower maintenance for GI interventions. Long-term monitoring at the GS location indicated these observations, and the evergreen Ivy screen is expected to provide greater air pollution reduction throughout the year.
- Engagement and awareness activities are critical for the successful implementation of GI interventions and can create further engagement. Planning engagement and awareness activities alongside the

co-implementation will help improve knowledge of the interventions and continue collaboration and relationships with stakeholders and the community. The study reinforces the role of nature-based activities in engaging students across the educational spectrum, particularly those who may struggle with the standard curriculum. Providing an element designed around the students—a living wall for which the children were involved during planting – ensures engagement and activity across the student base.
- GI remains prohibitively expensive for a majority of organisations, and efforts need to be made to find innovative ways to remove cost barriers to ensure the uptake of GI at the scale necessary to provide adequate climate mitigation and adaptation strategies.

GI can yield numerous social and environmental benefits, such as improved air quality, noise reduction, and aesthetics. The study also highlighted the importance of community engagement in the planning and implementation of GI in schools, which could have practical implications for optimising GI planning in the future. The results indicate that the efficiency of GI installed in a school environment is affected by different factors such as the location of GI installation with respect to the source and the receptors (school children), the density of vegetation in terms of LAI and local characteristics of the place of GI installation such as availability of kitchen, parking area or the playgrounds. The complexity of the interdependence of GI's effectiveness on these factors emphasises the need for its careful design to optimise the benefits. To further increase the understanding, more focus is needed on designing an optimum GI configuration in a school environment, including the effect of the width of the barrier and the combination of different GI configurations on children's exposure.

CRediT authorship contribution statement

K.V. Abhijith: Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Nidhi Rawat:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Ana Paula Mendes Emygdio:** Writing – review & editing, Investigation. **Charlotte Le Den:** Writing – review & editing, Project administration. **Kate Collins:** Writing – review & editing, Investigation, Funding acquisition. **Paul Cartwright:** Writing – review & editing, Funding acquisition. **Kate Alger:** Writing – review & editing, Investigation, Funding acquisition. **Ben McCallen:** Writing – review & editing, Methodology, Funding acquisition. **Prashant Kumar:** Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.177959.

Data availability

Data will be made available on request.

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