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Towards a holistic understanding of the role of green infrastructure in improving urban air quality

By Karina Andrea Corada Pérez
Imperial College London
Centre for Environmental Policy

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STATEMENT OF ORIGINALITY

I declare that this thesis and the research to which it refers are the product of my own work, under the supervision of Dr Audrey de Nazelle and advised by Dr C. Matilda Collins and Dr Huw Woodward. This work and the material of this thesis have not been submitted for any degree at any other academic or professional institution.

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Against all odds, I am finishing an incredible four-year journey toward a PhD. These years of study left a transformative experience academically and personally. I have grown as an interdisciplinary environmental scientific woman. I have fallen and I have learned to get up to move forward. Today, I am grateful for the decisions made and for those who have accompanied me on this path.

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ABSTRACT

Air pollution has been identified as a major problem in modern societies, threatening urban population health. Pedestrians, in particular, are directly exposed to one of the main sources of air pollutants: road transport, which is concentrated in proximity to the road, worsening the air.

Green infrastructure (GI) has been promoted as a natural method for reducing exposure to local street air pollutants and providing additional Ecosystem Services with a range of environmental, social and economic benefits for citizens. The effectiveness of GI for improving air quality depends on the spatio-temporal context and the species-specific characteristics of the GI. Urban planting could maximise this benefit by a holistic understanding of the effects of GI in cities, balancing its benefits and constraints. However, little is currently known about the application of GI design and planning with regard to air pollution mitigation. Moreover, there is little agreement on the quantifiable effectiveness of GI in improving street air quality as its effectiveness is highly context dependent. Holistic guidance is therefore needed to inform practitioners of site- and species- specifics, trade-offs, and GI maintenance considerations for successful urban planting. This research reviews the academic literature addressing GI-related characteristics in streets, creating a holistic framework to help guide decision-makers on using GI solutions to improve air quality. Additionally, this research aims to understand how and which GI, along with other local characteristics, influence pedestrian air quality and how these characteristics are considered in real-world practice within the United Kingdom.

This research progresses through three stages: First, the mechanisms by which GI is considered to influence air quality were identified through literature reviews. A specific literature review was then conducted for each mechanism to extract the associated GI and spatial characteristics that affect the potential for GI to mitigate urban air pollution. In the second stage, this list of characteristics, together with other Ecosystem Services, was discussed in consultation with practitioners in the UK. A survey was conducted to explore and evaluate the recommendations and resources available for planning plantings, as well as the practitioners’ knowledge about the characteristics associated with mitigating air pollution. Supported by results from the survey and the literature reviews, the third stage evaluated (validated) an easy-to-use computational model for its potential use in improving planting decisions for air pollution mitigation.

Green infrastructure influences air quality by providing surfaces for pollutant deposition and absorption, effects on airflow and dispersion, and biogenic emissions. The relationship between the specific GI and the spatio-temporal context also influences air quality. Street structure, weather variables, and the type, shape and size of GI influence the dispersion of pollutants, with micro-and macro-morphological traits additionally influencing particulate deposition and gas absorption. In addition, maintaining GI lessens air quality deterioration by controlling biogenic emissions.

According to participants in the survey, aesthetics were the principal drivers of urban planting, followed by improving well-being and increasing biodiversity and air pollution mitigation as a lesser priority. Characteristics such as airflow manipulation, leaf surface traits, and biogenic emissions were the less important influences in planting decisions in the UK, despite the fact that these characteristics influence air quality. Perhaps, a lack of communication of current information and low confidence about which specific characteristics have a tangible effect on air quality reduces the incorporation of GI for air pollution mitigation purposes.

Uncertainties exist about the quantification of pollutants removed by GI. Field campaigns and computational models still need improvement to address the effectiveness of GI in real-world environments adequately and also to understand whether GI can exert a significant effect on pollutant levels under real-world conditions. This research showed that a promising and easy-to-use model used to evaluate the effectiveness of trees in removing particles was not an acceptable model to study the effect of GI on streets. The validation results showed a poor agreement between wind tunnel data and the model results. More effort is needed to develop better modelling tools that can quantify the actual effect of GI on improving street air quality.

This research contributes to the air pollution mitigation field, explicitly helping to inform decision-making for more health-promoting urban settings by optimising the expected benefits of GI through a holistic understanding of their impacts. Facilitating the communication of current evidence through a holistic guide that considers both the benefits and trade-offs of planting decisions for air quality improvement. Improving information on air pollution mitigation to feed the decision-making process might maximise the benefits of GI planting for air pollution mitigation in streets.

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LIST OF PUBLICATIONS RESULTING FROM THIS THESIS

Chapter III

Corada, K., Woodward, H., Alaraj, H., Collins, C. M., & de Nazelle, A. (2021). A systematic review of the leaf traits considered to contribute to removal of airborne particulate matter pollution in urban areas. Environ Pollution, 269, 116104. doi:10.1016/j.envpol.2020.116104

ABBREVIATIONS

APTI	Air Pollution Tolerance Index
BPM	Biogenic Particulate Matter
BVOC	Biogenic Volatile Organic Compounds
CFD	Computational Fluid Dynamic
COPD	Chronic Obstructive Pulmonary Disease
ES	Ecosystem Services
EDS	Ecosystem Disservices
GI	Green Infrastructure
GLV	Green Leaf Volatiles
GW	Green Wall
GR	Green Roof
H/W	Aspect ratio (λ_s)
LAD	Leaf Area Density
LAI	Leaf Area Index
PBAP	Primary Biogenic Aerosol Particles
PM	Particulate Matter
SEM	Scanning Electron Microscope
SIRM	Saturation Isothermal Remanent Magnetisation
UCL	Urban Canopy Layer
UFP	Ultrafine Particles
V_d	Deposition Velocity
WHO	World Health Organisation
WT	Wind Tunnel

Chapter 1. Introduction

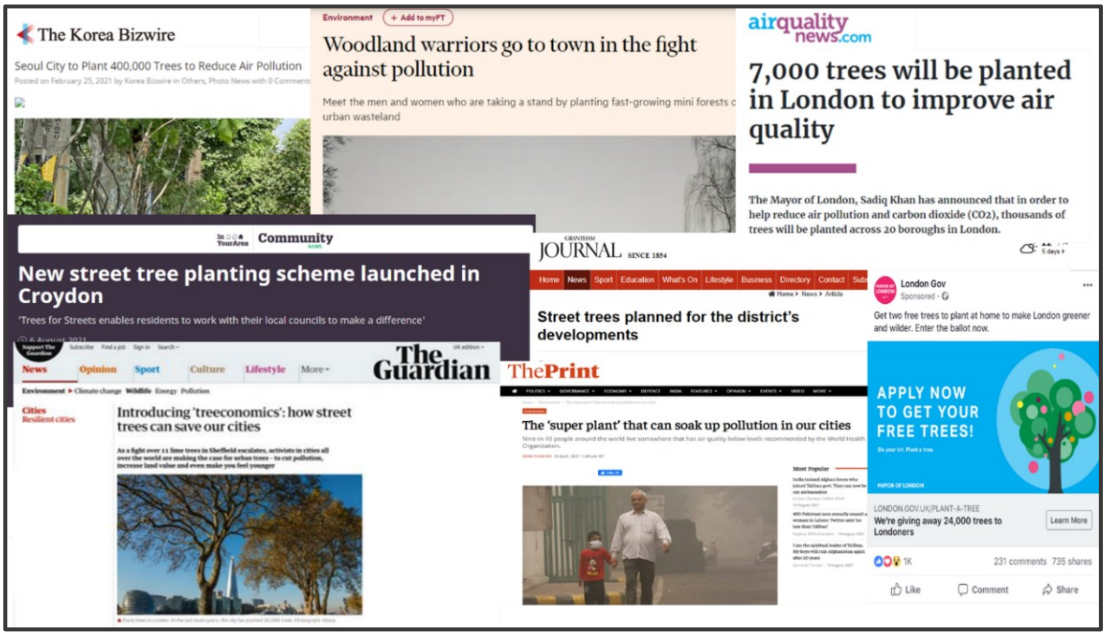
1 Green infrastructure as a mitigation strategy for air pollution in cities: The problem

Picture yourself by a busy road in a city centre with traffic congestion and people walking, crossing a street, or just waiting to cross. A distressing situation confronts you: grey is the principal colour, with cement overwhelming the city, while the glinting colours of cars cross the view. You may not see it, but all around you are tiny particles and gases which pass through your nose and mouth, entering your respiratory system when you breathe. These particles are so small that your physiology cannot prevent them from entering your lungs and, ultimately, your bloodstream, where they remain, causing both short- and long-term health problems.

The good life and prosperity promised by cities are threatened by environmental degradation as a result of several anthropogenic activities. For example, road transport is currently the largest source of urban particle emissions in the UK (DEFRA, 2020a), but this contribution to air pollution (e.g., particulate matter) varies from 5% to 61% in cities worldwide (Heydari et al., 2020). Cohort studies on traffic-related air pollution have shown a relationship between exposure to traffic emissions and the exacerbation of asthma, coronary heart diseases, impaired lung function, chronic obstructive pulmonary disease, lung cancer, cardiovascular diseases and reduced life expectancy (HEI, 2010; Doiron et al., 2019; Cohen et al., 2020; Lelieveld et al., 2020; Bettiol et al., 2021; Boogaard et al., 2022).

In 2020, actions taken by several countries to control the spread of coronavirus diseases (COVID-19), such as lockdowns, led to an improvement in air quality when the volume of road traffic decreased (DEFRA, 2020b; Jia et al., 2021a; Nigam et al., 2021). Several cities, however, experienced different patterns of air pollutant reduction (Adam et al., 2021). In general, cities with larger traffic volumes (e.g., Delhi) showed particulate matter (PM) reduction during the COVID lockdown that was attributable to reduced traffic-related air pollution (Kumar et al., 2020). Other pollutants, such as tropospheric ozone (O_3), for example, remained at a similar level, or even increased, compared to the pre-lockdown period (Adam et al., 2021; Brancher, 2021; Jia et al., 2021a). These differences are due to the formation, dispersion, distribution and concentration of air pollutants, which have diverse sources and are influenced by seasonal variations and weather parameters (Adam et al., 2021). Years after the first worldwide lockdown, restrictions started to lift, and air pollution took over the streets again.

Planting vegetation has been proposed and studied as a potential solution to reducing exposure to air pollutants in streets (Nowak 1994; Nowak et al., 2006; Islam et al., 2012; Gromke et al., 2016; Ghasemian et al., 2017; Abhijith & Kumar, 2020; Moradpour & Hosseini, 2020; Riondato et al., 2020). This interest extends beyond academia; it is evident in community groups, news articles and advertisements around the globe advocate for and motivate the planting of vegetation, especially trees, as an invaluable asset to improving air quality and reducing exposure to harmful pollutant levels locally (Figure 1).


The Korea Bizwire

Seoul City to Plant 400,000 Trees to Reduce Air Pollution

Posted on February 25, 2021 by Korea Bizwire in Others, Photo News with 0 Comments

Woodland warriors go to town in the fight against pollution

Meet the men and women who are taking a stand by planting fast-growing mini forests c urban wasteland

airqualitynews.com

7,000 trees will be planted in London to improve air quality

The Mayor of London, Sadiq Khan has announced that in order to help reduce air pollution and carbon dioxide (CO2), thousands of trees will be planted across 20 boroughs in London.

In Your Area Community News

New street tree planting scheme launched in Croydon

'Trees for Streets enables residents to work with their local councils to make a difference'

Grantham JOURNAL SINCE 1854

Street trees planned for the district's developments

London Gov

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Get two free trees to plant at home to make London greener and wilder. Enter the ballot now.

APPLY NOW TO GET YOUR FREE TREES!

Do your bit. Plant a tree.

LONDON.GOV.UK/PLANT-A-TREE

We're giving away 24,000 trees to Londoners

The Guardian

Introducing 'treeconomics': how street trees can save our cities

As a fight over 11 lime trees in Sheffield escalates, activists in cities all over the world are making the case for urban trees – to cut pollution, increase land value and even make you feel younger

ThePrint

The 'super plant' that can soak up pollution in our cities

Nine-in-10 people around the world live somewhere that has air quality below levels recommended by the World Health Organization.

Figure 1. A selection of online news articles related to planting street trees to improve air quality. Search date: between 2019-2021

Introducing Green Infrastructure (GI) has been viewed as a win-win solution, reducing ground-level exposure and offering multiple Ecosystem Services (ES) to citizens (Hewitt et al., 2020). In streetscapes, GI influences air quality and responds to other social needs (e.g., aesthetic, cultural), providing economic, health, and other environmental benefits without substantial cost (Reid et al., 2005).

Green infrastructure influences air quality through a range of mechanisms. It can capture air pollutants either through the direct deposition of particles on surfaces or by absorbing gases and ultrafine particles. The different shape types of GI can also influence the dispersion and transport of pollutants by altering airflow. Alongside these benefits, GI also presents some Ecosystem Disservices (EDS) to people. For example, the emission of pollen and Biogenic Volatile Organic Compounds (BVOC) decreased air quality. Green infrastructure can also bring about biological hazards such as diseases, facilitate animal attacks, and harbour poisonous organisms, potentially leading to increased maintenance costs (von Döhren & Haase, 2015; Speak et al., 2018).

Despite the drawbacks, GI has been used and positioned as a possible strategy for improving air quality locally. Although its effectiveness in countering air pollution has been questioned, several studies of street trees or vegetation barriers have shown a protective effect that helps reduce pedestrian exposure to air pollutants in streets (Al-Dabbous & Kumar, 2014; Brantley et al., 2014; Abhijith & Gokhale, 2015; Li et al., 2016; Tong et al., 2016; Rafael et al., 2018; Abhijith & Kumar, 2019; Ozdemir, 2019; Konczak et al., 2021). The conclusion is, however, not clear cut, with several studies showing that street trees potentially worsen street-level pollutant concentrations (Gromke & Ruck, 2007, 2008b; Buccolieri et al., 2009; Buccolieri et al., 2011; Salim et al., 2011b; Gromke & Ruck, 2012; Ng & Chau, 2012; Salmond et al., 2013; Lin et al., 2020) due to aerodynamic effects as the GI reduces ventilation in streets (Buccolieri et al., 2011; Wania et al., 2012; Vos et al., 2013; Morakinyo & Lam, 2016b). These contrasting findings are partly due to different methodologies and contexts as well as an incomplete understanding of the different GI mechanisms that influence air quality. This dichotomy can lead to the incorrect and ineffective implementation of GI in urban environments.

The scientific community in this field has investigated and discussed the need to understand how air quality is affected by GI in specific urban environments (Han et al., 2022). But, thus far, all the mechanisms by which GI influences air quality are typically not considered jointly since these underlying mechanisms are complicated (Janhäll, 2015). Modelling studies have shown the complexity of simulating GI in streets due to the high number of variables that should be considered (Tiwari et al., 2019). Most scientific studies, therefore, focus on one or two mechanisms with few included variables; this contributes to generating contradictory results. A consideration of both the air quality-related Ecosystem Services and Disservices may lead to better-informed decisions about species selection and placement, strengthening the positive aspects of the GI and minimising those that worsen air quality (Escobedo et al., 2011; Sicard et al., 2018).

While many researchers and practitioners are enthusiastic about using GI as an air pollution mitigation strategy (Dzierzanowski & Gawronski, 2011; McDonald et al., 2016; Jayasooriya et al., 2017; Mayor of London & Partnership members, 2020), others caution that approaches to this are simplistic and that GI should not be used primarily to solve air quality problems (Blanusa & Hunt, 2013; Hewitt et al., 2020; Tomson et al., 2021). Problems may arise if practitioners (e.g., urban planners and tree officers) unquestioningly use GI to “clean the air” without considering its species-specific characteristics and urban context. Practitioners’ guides, usually, provide: advice on the benefits of GI, lists of potential species for street planting, a planting guide from planning to managing the GI, pruning practices and favourable species to cope with climate change on the streets (Natural England, 2011; Trees

& Design Action Group, 2012; Barcham, 2021, n.d.). Yet only a few guides have started to include some leaf and tree characteristics which may improve air quality locally (Hirons & Sjöman, 2019; Forest Research, n.d.). Despite the considerable amount of information and the many guides for planting GI in cities available to practitioners, there is little evidence of how these guides are applied in urban design for air pollution mitigation. Developing a comprehensive framework that promotes the optimal use of GI for air pollution mitigation could ensure its successful integration into future urban planning strategies (Gallagher et al., 2015).

But *what is the full range of GI characteristics that can influence urban air quality? Can a comprehensive framework of GI characteristics influencing air quality be established with a view to helping practitioners make improved GI planting decisions? How is air pollution mitigation included in the design of urban green infrastructure in urban plantings?* This thesis intends to answer these questions, making a novel contribution to the literature concerning our understanding of how GI placed in streets can improve air quality and inform decision-making around promoting healthy urban environments.

2 Research aims and objectives

- ### Aim

To understand how green infrastructure and its characteristics influence air quality in the pedestrian zone, using two approaches: first, by exploring the GI characteristics published in the academic literature and then by evaluating how these characteristics are considered in the decision-making processes of urban planting practitioners in the United Kingdom.

- ### Objectives

1) Identify and describe the key mechanisms by why GI influences air quality in streets through a literature review.
2) Review the literature for evidence on the GI characteristics and context influencing air quality in streets.
3) Distribute a questionnaire to UK practitioners to evaluate their knowledge and practices regarding air pollution mitigation in relation to the use of GI in urban planting.
4) Develop a comprehensive framework to inform GI characteristics and management that could maximise air quality improvement.
5) Study (validate) an easy-to-use computational model for non-expert users to study the dispersion of pollutants at a microscale.

3 Thesis outline

Controlling emission intensity and blocking source-receptor pathways are two strategies for reducing human exposure to air pollution (Gallagher et al., 2015). The inclusion of GI (used inclusively through this document to cover any vegetation or green infrastructure) has been highlighted as a low-cost and easily applicable strategy for influencing source-receptor pathways (McDonald et al., 2016; Rafael et al., 2018). The great variety of forms and types of GI that can be included in a street provides various alternatives when there is limited available planting space (Figure 2). In **Chapter 2**, the different types of GI are described, and the benefits and drawbacks (ES and EDS) that these provide in urban areas are presented, providing the conceptual framework of this thesis.

Figure 2. Examples of Green Infrastructure on a street in Monaco.
Credit: Karina Corada

Among all the GI services that can be delivered to citizens, this research focuses on how GI positively or negatively influences air quality. Green infrastructure has the potential to affect local-scale air quality through four mechanisms: 1) wet and dry deposition (deposition), 2) absorption, 3) biogenic emissions, and 4) aerodynamic effects (dispersion) (Figure 3). **Chapter 3** is dedicated to the GI characteristics that may improve pollutant deposition, focusing on identifying which leaf traits might maximise airborne particle removal and the local context that contribute to variations in the accumulation of particles on leaves. **Chapter 4** identifies and discusses the GI characteristics and local context that affect absorption and biogenic emissions. **Chapter 5** identifies and discusses the effects of GI in streets, specifically associated with the dispersion of pollutants. Dispersion, unlike the previous mechanisms mentioned, is associated with the macro characteristics of the species (e.g., canopy) and GI management, which induces modification of the wind flow.

After reviewing the literature, a list of associated GI and local context characteristics, along with urban planting guidelines and other ES was compiled in a questionnaire, which was distributed to practitioners to understand how planting decisions are currently made. This questionnaire assesses whether air pollution is considered in urban planting and if related GI characteristics are incorporated in planting decisions. **Chapter 6** analyses the questionnaire results discussing how academic research contributes to the practical decisions of urban planting. The questionnaire responses indicate that respondents felt that access to an easy-to-use computational model could improve their planting decisions. Furthermore, highlighted as a need by questionnaire respondents and driven by the complexity of providing clear guidance to resolve locally specific dispersion context, in **Chapter 7**, this work explores the use of a potentially easy-to-use model for non-expert users to study the effect of GI on air quality. Finally, **Chapter 8** offers an overall discussion highlighting the main findings and contributions.

All supporting materials are presented as part of the Appendix.

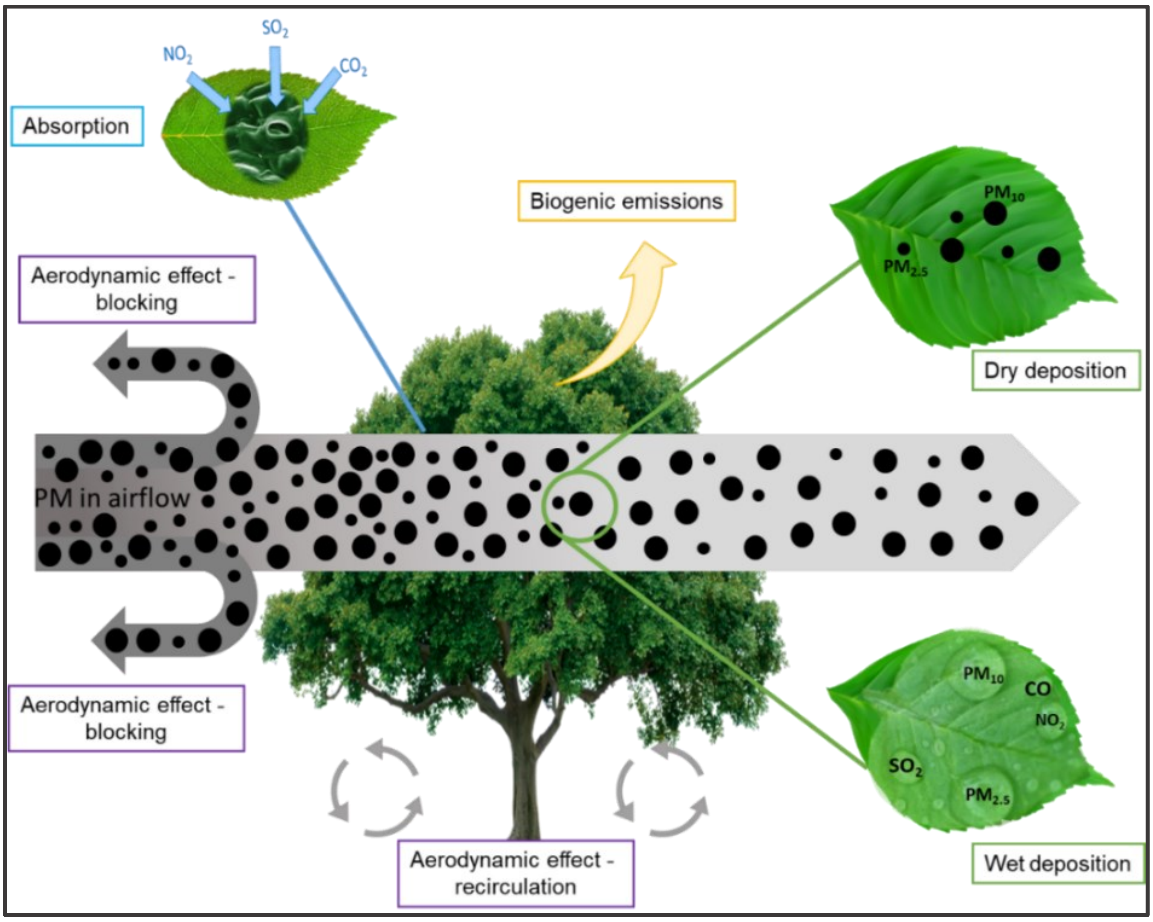


Figure 3. Schematic summary of the mechanisms by which Green Infrastructure influences air quality. Source: Own Elaboration

This research differs from other research in the field in the following ways:

- **The inclusion of different types of green infrastructure**. Most of the literature includes trees or hedges, but this research studies the effect of trees, hedges, shrubs, green walls, and green roofs on air quality.
- **The four mechanisms were studied jointly**. It focuses on holistic vegetation functions, integrating how GI absorbs, disperses, deposits, and emits natural gases and particles. Subsequent reviews focused on exploring the GI characteristics that influence each mechanism. Most of the literature so far has only focused on one or two mechanisms, with none combining the four mechanisms that influence air quality in streets. Additionally, the strength of evidence surrounding the influence of each GI characteristic was evaluated.
- **The practitioner perspective is included**. Practitioner knowledge has been sought to bridge the gap between academic research and practical decision-making, understanding the decision-making process of GI urban planting.
- **The consideration of computational modelling**. Most of the literature investigates GI using computational models which require high-level mathematics, physics, and computer science understanding. Thus, the ability of an easy-to-use model to simulate the effect of trees on air pollution at the microscale (street) is studied for non-expert users.

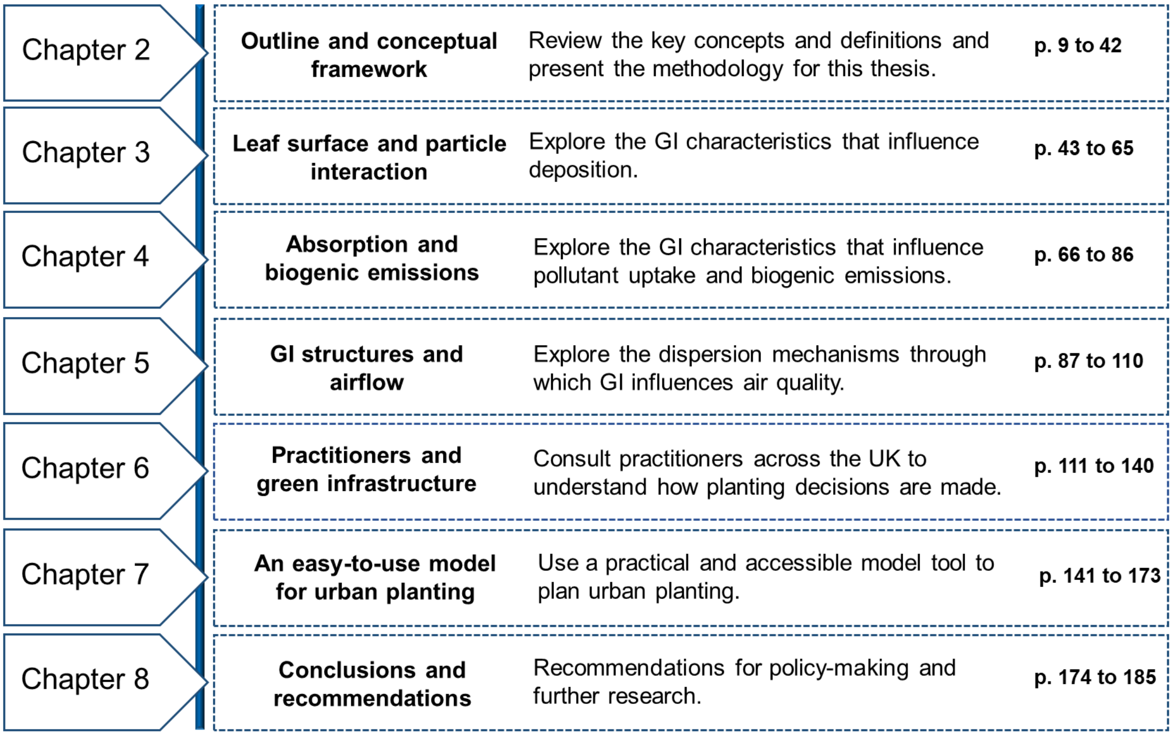
4 Scope of the study

Some Ecosystem Services and Disservices associated with air pollution were included in this research. Other Ecosystem Dis/Services provided by urban GI, such as food production, energy conservation, carbon sequestration and storage, heat island reduction, water filtration, stormwater runoff management and enhancement of human health and well-being, were mentioned in this work. However, they were not part of the main discussion in this research.

Only pollutants from traffic, such as particulate matter, nitrogen oxides, and volatile organic compounds, were studied in this research. Carbon dioxide is mentioned, but it was excluded from the discussion because its absorption by vegetation corresponds to another research field, carbon sequestration and storage.

One type of reaction in the atmosphere is the photochemical reaction of pollutants (i.e., sunlight reactions). This reaction is explained in the context of BVOC to generate tropospheric ozone (O_3).

A flow chart is presented to facilitate the reading and navigation of this thesis, highlighting the analytical steps of the research (Figure 4).



Chapter 2	**Outline and conceptual framework**	Review the key concepts and definitions and present the methodology for this thesis.	**p. 9 to 42**
Chapter 3	**Leaf surface and particle interaction**	Explore the GI characteristics that influence deposition.	**p. 43 to 65**
Chapter 4	**Absorption and biogenic emissions**	Explore the GI characteristics that influence pollutant uptake and biogenic emissions.	**p. 66 to 86**
Chapter 5	**GI structures and airflow**	Explore the dispersion mechanisms through which GI influences air quality.	**p. 87 to 110**
Chapter 6	**Practitioners and green infrastructure**	Consult practitioners across the UK to understand how planting decisions are made.	**p. 111 to 140**
Chapter 7	**An easy-to-use model for urban planting**	Use a practical and accessible model tool to plan urban planting.	**p. 141 to 173**
Chapter 8	**Conclusions and recommendations**	Recommendations for policy-making and further research.	**p. 174 to 185**

Figure 4. Flowchart for improved navigation through the thesis.

Chapter 2. Conceptual framework

This Chapter

- Presents the thesis framework.
- Introduces the keywords, definitions and concepts used in this research.
- Establishes the context of this research by showing what has been done in urban green infrastructure to improve air quality.
- Defines the mechanisms by which green infrastructure influences air quality.

1 A brief historical context of urban greenspace

Historically, green infrastructure (GI) has been a part of cities around the world; for example, the Hanging Gardens of Babylon were reputedly the most beautiful man-made gardens in the ancient world. Although no archaeological evidence has been found, ancient writers described this garden as '*This structure supports an extensive and deep mass of earth, in which are planted broad-leave trees of the sort that are commonly found in gardens, a wide variety of flowers of all species and, in brief, everything that is most agreeable to the eye and conductive to the enjoyment of pleasure (Philo of Byzantium, around 250 BC)*' (Finkel, 1988). But it was not until the 19th century that social movements promoted the creation of greenspaces around fast-growing cities, as massive urbanisation exacerbated the precarious social and working conditions of the Industrial Revolution.

In 1858 in New York City, the founder of American landscape architecture, Frederick Law Olmsted and his partner Calvert Vaux built Manhattan's Central Park and designed other urban greenspaces to remedy the detrimental effects of urban living. They believed that public parks or natural scenery in cities would promote rest, democratic values and improved social life (Eisenman, 2013; Austin, 2014). Back in Europe, the grid-like structure of Barcelona, Spain, was designed by the Catalan architect Ildefons Cerdà in 1860. His urban designs constituted a new form of urban planning inspired by nature and based on ventilated spaces. This grid structure maximised exposure to sunlight and provided green spaces at the centre of each block. Cerdà's designs responded to the unhealthy environment to which citizens were exposed (Pallares-Barbera et al., 2011; Santasusagna Riu et al., 2021). In the mid-19th century, Paris, France, was subject to a suffocating population density, and was devastated by cholera and other diseases. The architect Georges-Eugène Haussmann, inspired by London's parks and avenues, demolished medieval infrastructures to build wide tree-lined boulevards to enhance architectural beauty and improve sanitation (Laurian, 2012). In London, UK, the Annual Report of the Registrar General of Births, Deaths and Marriages in

1839 presented a higher mortality rate in the East End of the city due to massive overcrowding, unsanitary conditions and polluted air. This report prompted a petition to Queen Victoria urging the formation of a park to improve citizen' lifestyles. This was the first time that a green area was requested to diminish deaths and improve the lifespan of the population (Tower Hamlets Council, 2021). In the late 19th century, the garden movement and workers' colonies in London used social pressure to increase access to green spaces and help urban beautification, thus improving the lives of city dwellers from all social classes. Formal street tree planting was part of urban planning and quickly spread from London to other cities in the UK, where it was viewed as a symbol of good urbanisation (Goodwin, 2017). All these architects and designers were all part of the urban sanitarian movement, where they believed that they could promote health through better urban designs, in particular, through increasing green areas.

Although sanitary and working conditions have improved over the centuries, similar problems still exist in some cities: overcrowding, slums, traffic jams, high levels of noise, air pollution, and health problems. The concept of GI remains a powerful tool in urban planning to improve the quality of urban living in many dimensions. The multifunctional benefits that GI delivers to the population have entrenched its popularity among different actors, such as practitioners, academics, urban planners, stakeholders, and authorities (Matthews et al., 2015). This popularity continues to rise as GI is able to help tackle the impacts of climate change and other modern urban problems, such as urban air pollution (Dover, 2015).

The 21st century has become the urban century, defined by a massive increase in urban populations and the concomitant expansion and construction of cities to accommodate this. The proportion of people forming part of the urban population is unprecedented and continues to rise. In 2018, approximately 55% of the global population lived in cities, and it is now predicted that 68% of the world population will live in cities by 2050 (UN DESA, 2019b). Future population growth is critical to urban planning strategies, as this entails more emissions and, thus, exposes more people to air pollution (Hewitt et al., 2020). A greater understanding of the influence of GI on streets is vital to achieving its potential air quality benefits.

This thesis provides some insight into a comprehensive understanding of the effects of GI on streets to enhance air pollution mitigation. Green infrastructure has been studied broadly in different academic fields, but there is a lack of synthetic and holistic knowledge about the mechanisms by which GI influences air quality. GI **adsorbs (deposition)** and **absorbs (absorption)** pollutants, **emits biogenic gases and particles** and influences the **dispersion** of pollutants. The words in bold font identify four traditionally separate research fields with little or no interaction between them. This research unites these four mechanisms, but an overview of the key concepts is needed before an in-depth review of the mechanisms and GI characteristics that influence air quality. To provide this overview, this **Chapter** is divided into four parts. First, the thesis framework is illustrated. Second, the study area, its elements and problems are explained. Third, the definition, benefits, and drawbacks of GI in cities are discussed, and finally, the definition of each mechanism is given.

2 Thesis framework

A mixed-method approach was used in this research to provide a holistic understanding of GI in the context of improving air quality. This approach uses two or more quantitative and/or qualitative studies within a single project (Collins et al., 2006; Onwuegbuzie & Leech, 2015), drawing upon the strengths of these methods to provide an innovative approach to addressing contemporary phenomena and cross-disciplinary issues. Collins et al. (2006) propose 13 steps which help organise and determine the rationale and purpose of the approach (See Appendix A, Figure 1) (Collins et al., 2006).

This research used sequential literature reviews to investigate and understand how GI affects air quality (qualitative and quantitative methods). After that, a list of GI and local characteristics that may influence air quality was consulted with UK practitioners to understand how air pollution influences their decision-making processes in urban planting (qualitative and quantitative methods). Finally, a computational model was explored as a potential practitioner tool to improve GI design for air quality mitigation purposes (quantitative method) (Figure 5).

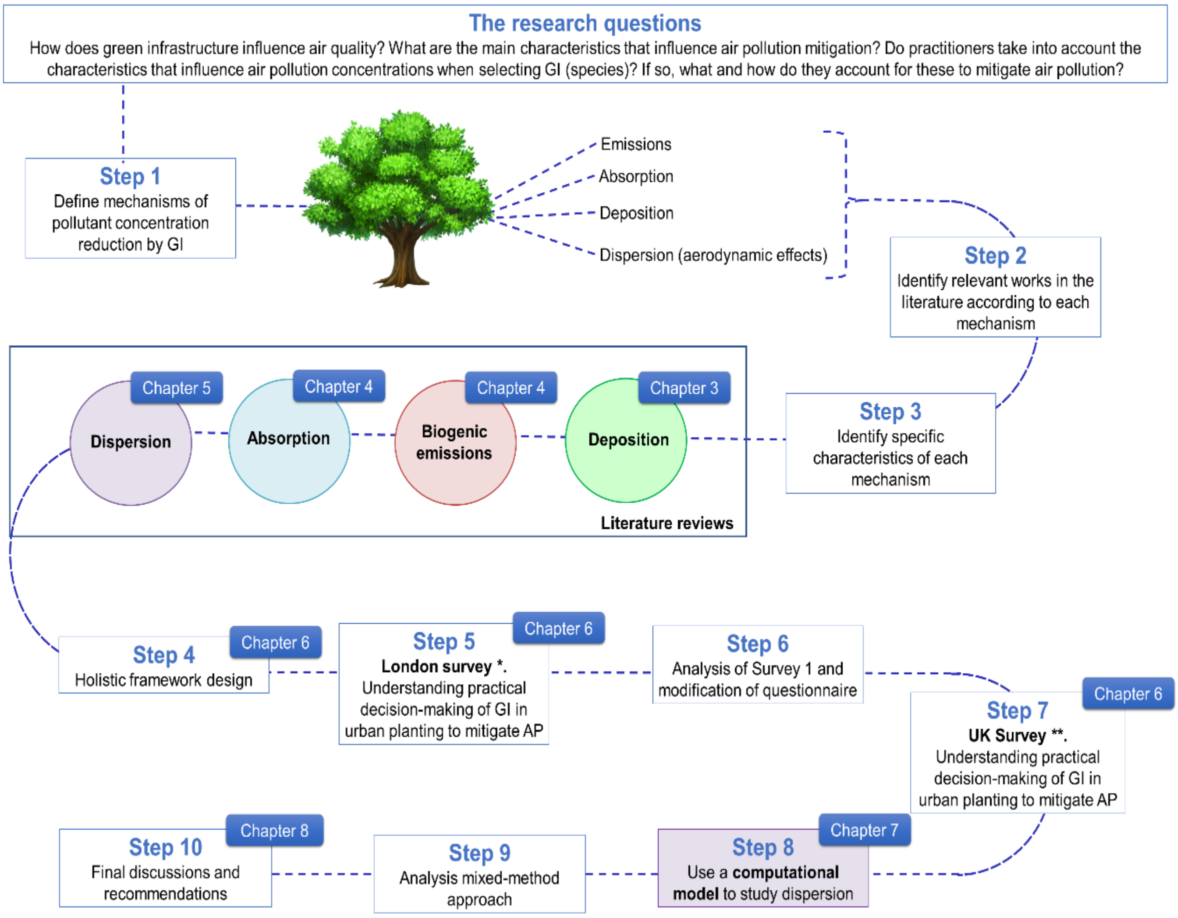


Figure 5. The sequence and methodology of this research.
GI is green infrastructure, AP is air pollution, London survey* and UK survey** identify two stages of the survey. First (Step 5), a questionnaire was distributed in London; after that, some modifications were made it (Step 6), and a final questionnaire (Step 7) was conducted in the UK.

The following sections explain the context of this research and define key concepts necessary to understand this research.

3 The urban area

According to the Department for Environment Food & Rural Affairs (DEFRA), urban area is defined as a "*continuously built-up urban area meaning complete (or at least highly predominant) building-up of the street front side by buildings with at least two floors or large detached buildings with at least two floors. […] Urban sites should measure air quality which is representative of a few km^2.*" (DEFRA, 2022).

This urban area concentrates more than half of the world's population. Projections indicate that the world's population will grow, reaching 8.5 billion in 2030, with urban areas as the main form of settlement (UN DESA, 2019a). This population agglomeration will require an expansion of cities accompanied, for example, by changes in transport modes and strategic urban GI planning (Lu et al., 2021; Ramyar et al., 2021).

3.1 The urban atmosphere

The lowest part of the Earth's atmosphere, which makes direct contact with the urban surface, is the Atmospheric Boundary Layer, where the Earth's surface strongly influences turbulence, temperature, moisture, thermal mixing and the addition of air pollutants. The layer is subdivided into different regions that vary according to the topography (Figure 6) (Oke et al., 2017d). The Urban Canopy Layer (UCL) is the region where this research is focused. It extends from the ground to the roofs of buildings and treetops (roughly 10 m) and is defined by urban elements, such as **street configurations**, **buildings**, **pollutant sources**, **green infrastructure, and human activity**. In the UCL, there can be intense wind shear and mixing at roof level, though deeper down within the street, the urban conditions are different. Different urban elements disrupt wind and radiation exchange, affecting thermal outdoor comfort and wind profiles (Oke et al., 2017a).

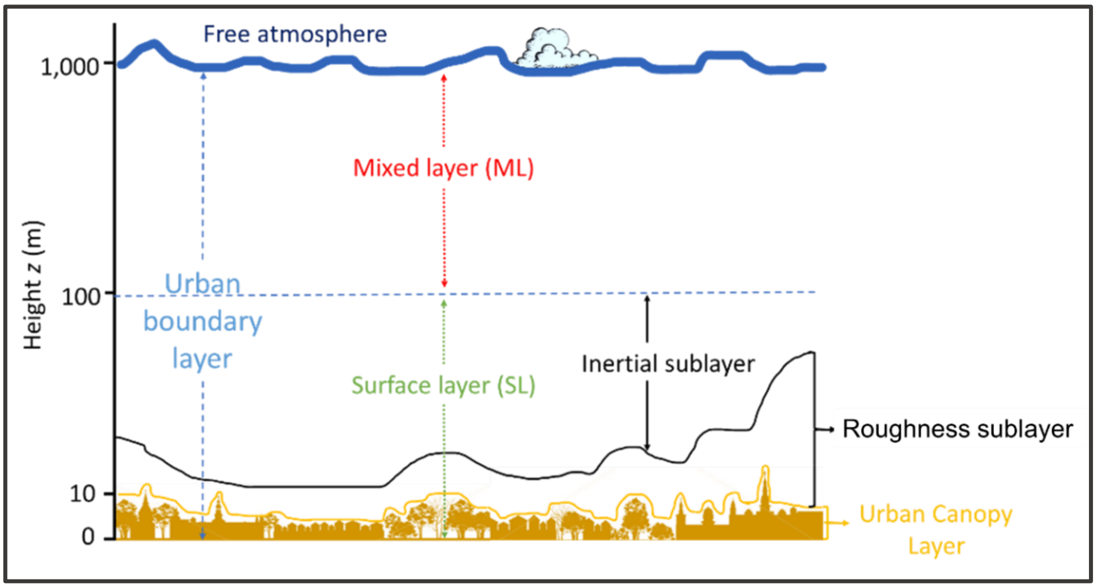


Figure 6. Schematic of the typical layering of the atmosphere over a city.
Source: Adapted from Oke et al. (2017b)

3.1.1 Air pollution: sources and type of pollutants

Human-made (anthropogenic) sources such as agriculture, power stations, industrial plants and transport emit primary pollutants, often associated with the combustion of fossil fuels, directly into the atmosphere. Road transport, for example, is a major mobile source of urban pollution (Harrison et al., 2021), emitting a range of gaseous and particulate pollutants directly from the exhaust pipe, along with non-exhaust particles from the mechanical wearing-down of tyres, brakes, clutches, the road surface and via road dust resuspension. The composition of road-derived pollutants varies from city to city and is dependent upon traffic volumes, vehicle fleet composition, fuel type, urban morphology, and the local climate (Pant

& Harrison, 2013; Kumar et al., 2014; Heydari et al., 2020). Despite these variations, the pollutants emitted and recirculated by vehicles are most concentrated in proximity to roads, impacting the health of pedestrians, cyclists, drivers, and residents in that zone.

Vehicles emit a large quantity of primary gaseous pollutants, such as nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbons and particulate matter (PM), which can also result from secondary formations. Important secondary pollutants are formed in the atmosphere through a chain of chemical reactions between air pollutants, such as NOx, CO, Volatile Organic Compounds (VOC), and methane (CH_4). For example, tropospheric ozone (O_3) (ground-level ozone) is formed by a photochemical reaction in the presence of NOx and VOC from anthropogenic and natural sources (e.g., trees). Ozone can irritate eyes, nose, and airways. Emerging evidence has shown that both short-term and long-term exposures to O_3 are associated with increased mortality due to respiratory and cardiovascular diseases (Zhang et al., 2019a).

Particulate matter (PM) is one of the greatest environmental risks in cities (WHO, 2021a). It consists of a complex mixture of organic and inorganic substances suspended in the air. Particles with a diameter of 10 microns or less ($\leq PM_{10}$) can penetrate the upper part of the respiratory system and lodge deep inside the lungs. However, fine particles 2.5 microns or less in diameter ($\leq PM_{2.5}$) and ultrafine particles or nanoparticles ($\leq PM_{0.1}$) are a greater threat to human health since they can penetrate lung tissues, travel in the bloodstream and lodge in organs, including the heart, thereby causing many severe health diseases (WHO, 2021b).

Nitrogen oxides ($NO_x = NO + NO_2$) come from vehicles, power stations and heating; they mainly enter the air by burning fuel. Exposure to high concentrations of NO_2 can irritate and inflame airways in the human respiratory system. Exposure to high concentrations of NO_2 may contribute to the development of asthma and increase susceptibility to respiratory infections. Even short-term exposure periods can aggravate respiratory diseases, particularly asthma, including increased airway resistance (e.g., pneumonitis), decreased lung function, and damage to lung tissue (Tiwary et al., 2019e).

3.1.2 Urban air pollution: The health problem in urban areas

Air pollution is one of the major problems of modern societies. It is defined as the presence of substances in the atmosphere that can cause adverse effects on the environment, ecosystem and human health (Tiwary et al., 2019a). According to the World Health Organization (WHO), outdoor polluted breathable air caused more than 4.2 million premature deaths in 2016, as well as other associated health problems, such as cardiovascular and respiratory diseases (WHO, 2021a).

Exposure to air pollution has been linked to a range of adverse health effects (Doiron et al., 2019). Acute symptoms include eye, nose and throat irritation, wheezing, coughing, headaches, aching lungs, bronchitis, and pneumonia. Chronic effects include chronic obstructive pulmonary disease (COPD), heart disease, asthma, leukaemia, lymphomas, and lung cancer (Kampa & Castanas, 2008; HEI, 2010). There is growing evidence of the health risks associated with exposure to fine and ultrafine particles that accelerate cognitive ageing and increase the risk of Alzheimer’s disease (Kilian & Kitazawa, 2018; Fu & Yung, 2020; He et al., 2021). All citizens can be affected by air pollution, but underlying health conditions, age, and the extent of exposure to pollutants make some people more susceptible than others (Cohen et al., 2020; Lelieveld et al., 2020). The latest studies on the effect of traffic-related air pollution on human health continue providing epidemiological evidence between long-term exposure to air pollution and adverse health outcomes (Boogaard et al., 2022). Health outcomes, such as circulatory, ischemic heart disease and lung cancer mortality, asthma onset in children and adults, and acute lower respiratory infections in children are associated with traffic-related pollutants (Boogaard et al., 2022).

The harmful health effects of air pollutants have led most regions of the world to develop air pollution standards (or guidelines) to regulate their presence in the air. Accumulating evidence on the low-level effects and widespread impact of air pollution has recently led the WHO to revise their guidance towards much lower levels for most pollutants than previously advised (WHO, 2021b) (See Air Quality Standards in Appendix A, Table 1).

In light of the large number of people exposed daily to traffic pollutants, it deserves greater attention to find strategic and effective measures to protect people from air pollution.

3.2 An urban sub-unit: The street canyon

Harmful air pollutants in urban areas are of particular concern within street canyons because pollution sources come from multiple locations in outdoor spaces. For example, emissions could come from buildings, vehicles, chimneys, and GI. In addition, airflow follows complex patterns due to urban elements (e.g., buildings, trees) in the UCL (Oke et al., 2017c).

A street canyon is formed by buildings continuously lined up on both sides (Oke et al., 2017a). These streets become pollution hotspots due to increased traffic levels and reduced natural ventilation (Ahmad et al., 2005). A two-dimensional cross-section describes street canyons, referred to by the dimensionless ratio H/W, where H is the height of the buildings adjacent to the street and W is the canyon width. The ratio (H/W) is known as the canyon aspect ratio (λ_s) and has a significant effect on the dispersion of pollution (Oke et al., 2017b). The value of λ_s is used to classify streets into *regular* ($H/W \sim 1$ or $0.5 < H/W < 2$), *deep*

(H/W ≥ 2), and *shallow/avenue* (H/W ≤ 0.5) (Vardoulakis et al., 2003). If the street only has buildings along one side, it is classified as an open road (Figure 7).

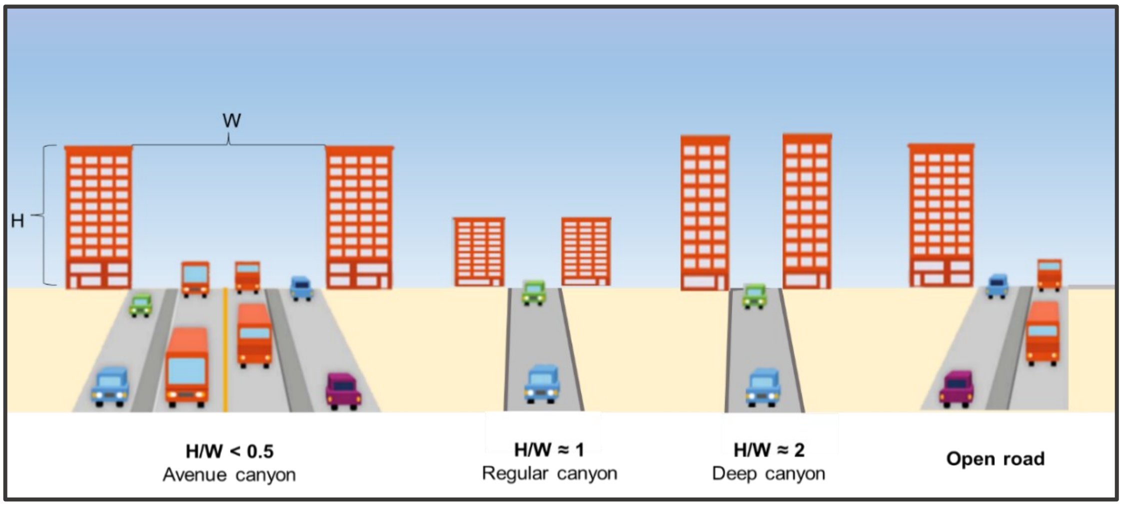


Figure 7. Schematic representation of typical streets in urban environments. Height (H) to width (W) ratio of a street canyon. Source: Own elaboration

In this outdoor space, pedestrians are exposed to high concentrations of ultrafine particles (0.02 - 1 μm) in the street canyons in a short time. A field campaign was carried out on a busy street in central London, UK, to assess pedestrian exposure while walking through the busy urban area. The field campaign determined that the average pedestrian exposure along the road was 37.7 μgm^{-3} when walking through the busy road (WHO air quality guideline 2021 for PM$_{2.5}$ is 15 μgm^{-3} 24h mean) (Kaur et al., 2005). Knowledge of exposure to air pollutants along streets can be valuable in managing air quality, assessing health threats, and how to manage GI to reduce pedestrian exposure on streets.

3.2.1 Airflow patterns in street canyons

The aspect ratio and wind direction influence the airflow patterns in an urban area. The wind flow topology within a street canyon - and consequently the pollutant dispersion - is primarily governed by the angle of the wind flow (wind direction) and by urban elements such as GI located within the street (Gromke & Ruck, 2012).

The most common street ratio studied in GI studies is H/W=1 in a perpendicular wind flow (Gromke & Ruck, 2007, 2008b; Balczó et al., 2009; Salim et al., 2011a; Jeanjean et al., 2015; Stabile et al., 2015; Moradpour et al., 2017; Marucci & Carpentieri, 2019). In these conditions, there are two fundamental vortex structures: a canyon vortex in the middle part of the street (cross-canyon vortex) and corner eddies at intersections or the ends of the street (Figure 8) (Gromke & Ruck, 2008b; Oke et al., 2017b). The canyon vortex is created when the airflow from the right, for example, enters the street canyon flowing down from the windward wall. At ground level, the airflow is directed against the atmospheric wind direction towards the leeward wall. In front of the leeward wall, the airflow moves upward and is partially entrained into the atmospheric cross flow above roof level, however, at ground level, the airflow carries traffic emissions, accumulating air pollutants (Figure 8A) (Gromke & Ruck, 2008b; Oke et al., 2017b).

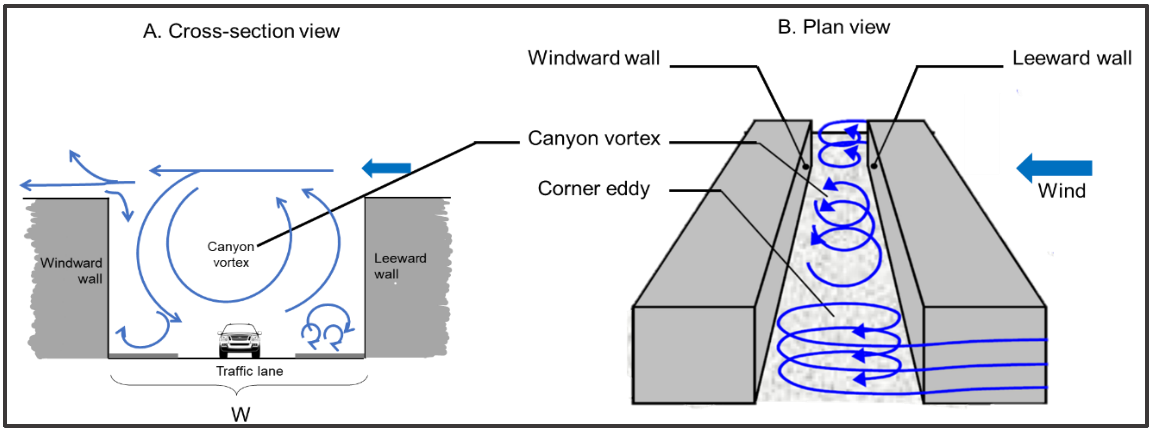


Figure 8. Flow field and fundamental vortex structures in a regular street canyon. Adapted from Gromke and Ruck (2008b) and Vardoulakis et al. (2003)

Other vortexes and airflow patterns are formed with street canyons under parallel and oblique wind conditions (Figure 9). Parallel wind aligns with the canyon with a possible uplift along its walls, so there is generally good ventilation in the street (Figure 9D) (Ahmad et al., 2005; Gromke & Ruck, 2012; Amorim et al., 2013). In comparison, oblique wind creates a helical flow (spiral vortex), also known as a corkscrew flow regime (Figure 9C) (Ahmad et al., 2005; Buccolieri et al., 2011; Gromke & Ruck, 2012).

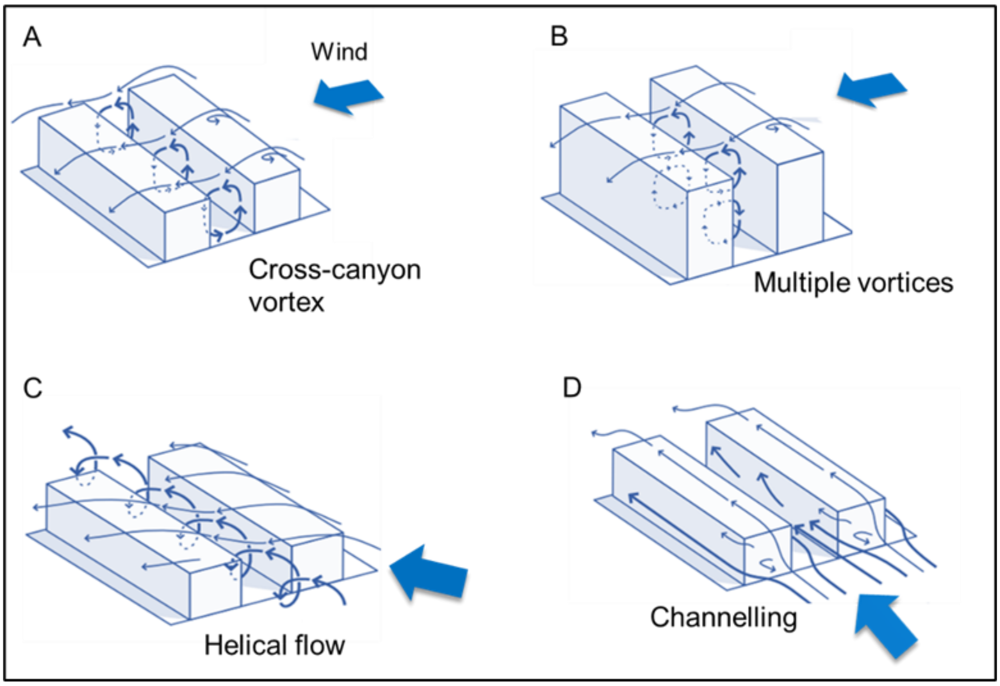


Figure 9. Typical flow patterns in a street canyon.
a) perpendicular wind, b) multiple vortexes in a deep canyon, c) oblique wind direction, and d) parallel wind direction. The blue arrow indicates the wind direction. Source: Adapted from Oke et al. (2017b)

There is a large body of research on street ventilation and air quality; some of the principal findings are:

- In most *regular* street canyons, pollutant concentrations are higher on the leeward side of the street than on the windward side when winds are perpendicular to the street (Ries & Eichhorn, 2001; Balczó et al., 2009; Salim et al., 2011a; Gromke & Ruck, 2012; Moonen et al., 2013). This may also depend on traffic volume and speed.
- When wind is parallel to the street, the channelisation increases the dispersion of pollutants inside the street canyon, consequently improving the air quality inside the street canyon (Wania et al., 2012).
- Pollutant concentrations decrease with height relative to the ground level (depending on roughness length[1], temperature, wind direction and atmospheric stability) (Wu et al., 2002; Wu et al., 2014).
- Pollutant concentrations decrease as the distance from the road (source) increases (Wu et al., 2002).
- Street canyon depth and length, aspect ratio, building configuration, roof shape, and street elements impact street ventilation and dispersion, dilution and the accumulation of pollutants (Voordeckers et al., 2021).

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[1] This represents the theoretical height at which the mean wind speed becomes zero. Roughness length (z_0) is a physical measure of the roughness of a surface to airflow.

3.3 An urban element: Green infrastructure

3.3.1 Multiple definitions of green infrastructure

Green space or greenspace, urban green area, green infrastructure, public greenspace, urban green spaces, urban vegetation, urban forest; urban parks, urban habitat, greenery, green belt, green environments, green network, urban ecosystem, landscape, urban trees, and *vegetated area* are some of the terms that, with little distinction, describe vegetation in cities in scientific articles, government webpages and authorities' reports. Although some researchers have argued that a definition of GI is not required because the term is commonly understood, there are variations in meaning and use according to discipline, geographical region and profession (Mell, 2008; Matsler et al., 2021) (Box 1). So far, definitional ambiguity has not created substantial problems, perhaps because most professionals agree about the broad benefits that GI provides in cities (Wright, 2011), although not all GI offers the same benefits. A proper definition for specific research can avoid ambiguity and unintended consequences (Taylor & Hochuli, 2017; Matsler et al., 2021).

Throughout this thesis, **Green Infrastructure (GI)** is defined as:

All-natural or semi-natural vegetation designed and **strategically** planned in urban areas. This includes rows, groups or stand-alone elements. This includes, for example, green walls, shrubs, hedges, and trees that deliver multiple Ecosystem Services with particular emphasis – in this research – on improving air quality.

A different definition is provided for **green areas/spaces**:

"Any vegetated areas of land or water within or adjoining an urban area, for example, urban forests, gardens or parks" (Forest Research, 2010, 2021).

Box 1. Diverse definitions of green infrastructure and other related terms

WHO → *"Urban green space: all urban land covered by vegetation of any kind. This covers vegetation on private and public grounds, irrespective of size and function, and also includes small water bodies such as ponds, lakes or streams ("blue spaces"). It is a component of green infrastructure"* (WHO, 2017).

FAO → "*Urban forests: networks or systems comprising all woodlands, groups of trees, and individual trees located in urban and peri-urban areas; they include, therefore, forests, street trees, trees in parks and gardens, and trees in derelict corners. Urban forests are the backbone of the green infrastructure, bridging rural and urban areas and ameliorating a city's environmental footprint"* (FAO, 2021).

European Commission → "*GI: a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services. It incorporates green spaces (or blue if aquatic ecosystems are concerned) and other physical features in terrestrial (including coastal) and marine areas. On land, GI is present in rural and urban settings"* (European Commission, n.d.).

House of Parliament, UK → "*Urban GI: a network of green spaces, water, and other natural features within urban areas. A green infrastructure approach uses natural processes to deliver multiple functions, such as reducing the risk of flooding and cooling high urban temperatures"* (House of Parlament, 2013).

Mayor of London → "*GI: a network of parks, green spaces, gardens, woodlands, rivers and wetlands, as well as urban greening, features such as street trees and green roofs, that is planned, designed and managed to promote healthier living, providing spaces for physical activity and relaxation, cool the city and absorb stormwater to lessen the impacts of climate change, filter pollutants to improve air and water quality, make streets clean, comfortable and more attractive to encourage walking and cycling, store carbon in soils and woodlands, create better quality and better-connected habitats to improve biodiversity and ecological resilience*" (Mayor of London, 2021).

EPA → "*Open space / green space: any open piece of land that is undeveloped (has no buildings or other built structures) and is accessible to the public, can include: green space (land that is partly or entirely covered with grass, trees, shrubs, or other vegetation, e.g., parks, community gardens, cemeteries, schoolyards, playgrounds, public seating areas, public plazas, vacant lots. Open space provides recreational areas for residents and helps to enhance the beauty and environmental quality of neighbourhoods"* (EPA, 2017).

EPA → "*GI: range of measures that use plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evapotranspiration stormwater and reduce flows to sewer systems or to surface waters"* (EPA, 2021).

Carne (1994) → "*Urban vegetation: the total assemblage of plants (including urban forests) within and on the perimeter of cities and towns"* (Carne, 1994).

Matthews et al. (2015)→ "*GI: an interconnected network of multifunctional greenspaces strategically planned and managed to provide a range of ecological, social, and economic benefits"* (Matthews et al., 2015).

3.3.2 Typologies and components of Green Infrastructure

There are many types and classifications of green elements in cities (Figure 10). In this thesis, two general GI typology distinctions are applied: 1) stand-alone elements such as street trees, hedges, shrubs, green walls, and green roofs, and 2) green spaces such as gardens, parks, and urban forests.

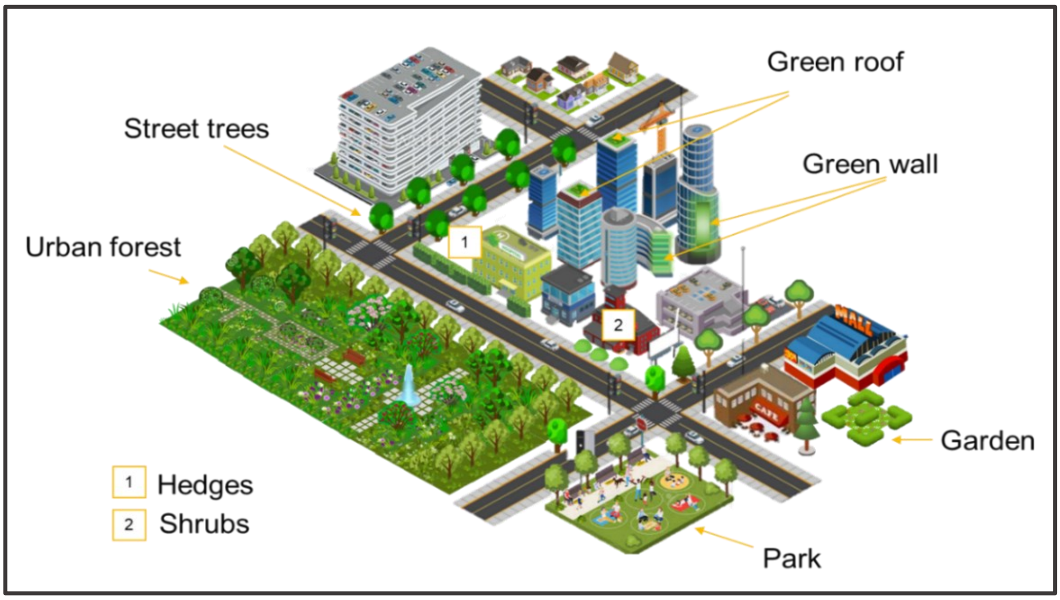

Figure 10. Types of green infrastructure in a built environment.
Source: Own elaboration

3.3.2.1 Stand-alone elements

Stand-alone elements are those GI types placed individually or as a distinct group (e.g., street trees or bushes) in built environments and specifically located along streets, for example, on sidewalks. These are usually in direct contact with urban stressors, such as traffic and mechanical damage by transport or people.

Street trees

Street trees are woody perennial plants, either evergreen or deciduous, with a trunk, branches, and foliage generally above human head height and located adjacent to or on a public road surrounded by paved ground (Figure 11) (Bolund & Hunhammar, 1999; Dandy, 2010).

Figure 11. Examples of deciduous and evergreen street trees from European cities.
Credit: Karina Corada

A crown is the agglomeration of leaves, stems and reproductive structures of the plant. A canopy is one or more crowns that grow in a particular area (Hirons & Thomas, 2018). Leaf area density (LAD) is commonly used to describe foliage characteristics and the vertical and horizontal crown structure. It is the total one-sided leaf area per unit volume (m^2 m^{-3}) (Figure 12).

Figure 12. Leaf area density profile of different types of vegetation (A), sparsely foliated tree (B), densely foliated tree (C) and common hedge (D).
Source: Adapted from Wannia (2007)

Another measure describing foliage is the Leaf Area Index (LAI), which is the leaf area per unit of ground area (dimensionless, m^2 m^{-2}) (Kenney, 2000) (Figure 13). Both parameters are useful measures for planning, management, and decision-making as they represent the foliage form and size in urban environments (Kenney, 2000).

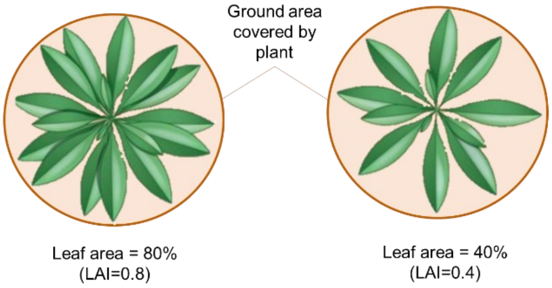

Figure 13. Leaf Area Index representation.
Source: Adapted from © Pearson Education, Inc., 2013

Street shrubs and hedges

A street shrub is a small, multi-stemmed tree, generally less than 3m in height. A hedge or hedgerow is a line of small tree or shrub species planted closely and trained together to provide dense foliage from ground level to a specified height (usually less than 4m) (Ottosen & Kumar, 2020) (Figure 14). Both can be located next to the sidewalks or within roadways.

Figure 14. Examples of shrubs (A) and a hedge (B).
Credit: Karina Corada

Green walls

A green wall, vertical greening system, living wall or green façade is a vertical vegetation structure in which different plants cover a wall or support material (Dover, 2015). Different types exist, the most simple of which is direct greening, where plants are encouraged to climb or colonise naturally either directly on a wall (Figure 15C) or indirectly from a wall using a support structure (Figure 15D) (Ottelé, 2011).

Figure 15. Green walls around London, UK.
(A) a building outside Covent Garden underground station, (B) The Athenaeum Hotel & Residences (Piccadilly), (C) a private house in Chiswick, and (D) a temporary green wall on a construction site in Leicester Square. Credit: Karina Corada

Green walls can be divided into two categories: green façade and living walls. Green façades are made up of climbing plants growing directly to the wall or with supporting structures. Living walls are used modular systems or panels, often comprised of plastic containers, where an irrigation system is provided as a growing medium of vegetation (Burhan & Karaca, 2013). Although different green walls exist (See Appendix A, Table 2 for types of green walls), scientific studies tend not to distinguish between different types, so that all the vegetation growing vertically on walls or other structures are referred as green walls. For this thesis, no distinction is needed, so green walls encompass all types of vegetation that grow from the ground or are pocket-planted on walls and buildings.

Green roofs

A green roof is a roof with a growing medium and vegetation; they are also known as eco-roofs, roof gardens and living roofs (Berardi et al., 2014; Besir & Cuce, 2018). There are three general categories (Dover, 2015; Besir & Cuce, 2018) (Figure 16):

- Intensive green roofs are complex designs. The growing medium is deep, with deeper substrates to support trees, small trees, and shrubs.
- Semi-intensive green roofs have intermediate depths of growing medium to retain water and grow a small range of plants (e.g., shrubs).
- Extensive green roofs are less weighty with shallower substrates and generally drought-tolerant plantings with low maintenance requirements.

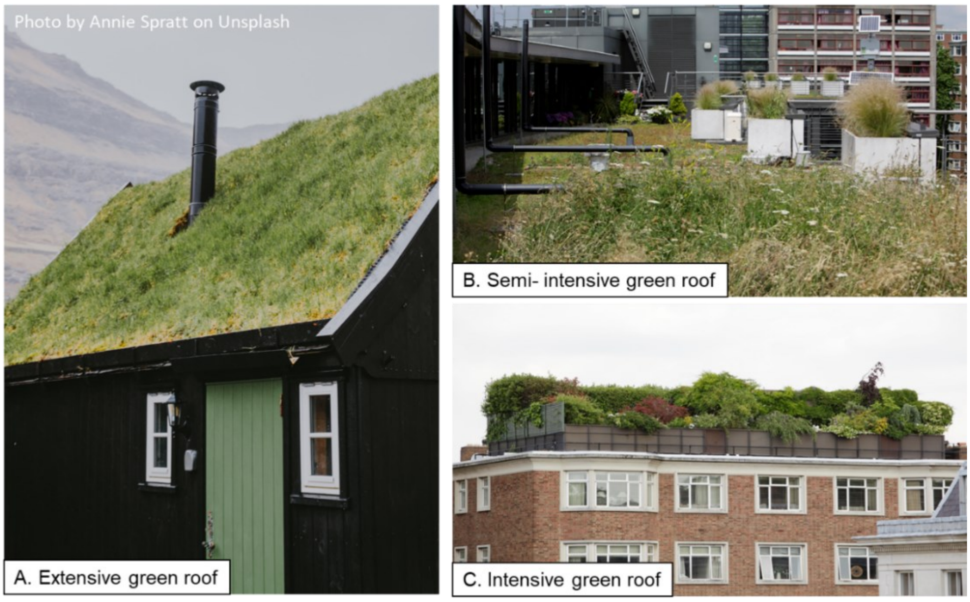

Figure 16. Examples of extensive, semi-intensive and intensive green roofs.
Source: Photo (A), credit: Annie Spratt on Unsplash. Photo (B) and (C), credit Imperial College London. Experimental green-roof Eastside, Imperial College London

3.3.2.2 Green spaces

Green spaces are open and accessible natural or seminatural spaces that provide opportunities for physical activity, play, rest, socialising and relaxation, including parks, gardens, cemeteries, green corridors, urban forests and playgrounds (Sinnett et al., 2015; Taylor & Hochuli, 2017) (Figure 17).

Figure 17. Types of green spaces in England.
(A) Burford cemetery, (B) Guildford Castle Garden, (C) Primrose Hill, London and (D) Ravenscourt Park, Chiswick, London. Credit: Karina Corada

In this research, street trees, shrubs, hedges, green walls, and green roofs are studied at the pedestrian level (Figure 18). Although green roofs are far away from the pedestrian level, literature does identify some influence on street-level airflow. In addition, some relevant information from green spaces is also considered.

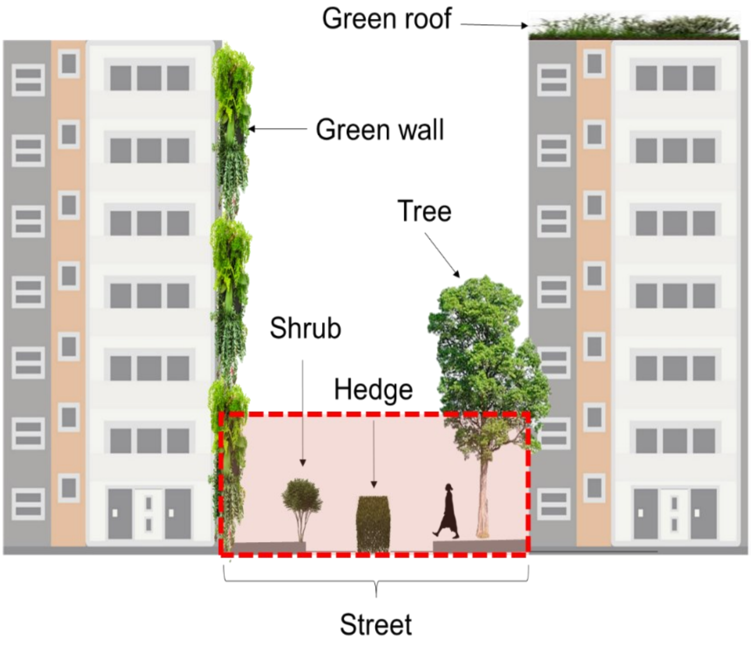

Figure 18. Representation of a street with examples of commonly studied green infrastructure. The dotted red circle indicates the 'pedestrian zone' boundaries of this research. Source: Own elaboration

4 Ecosystem Services of urban green infrastructure

Green infrastructure can be a nature-based solution for both climate mitigation and adaptation measure by reducing heat stress (Norton et al., 2015; Aram et al., 2019), reducing noise (Van Renterghem & Botteldooren, 2016; Zhao et al., 2021), improving urban biodiversity (Threlfall et al., 2017; Chen et al., 2021b), enhancing physical and mental well-being (de Vries et al., 2013; Lachowycz & Jones, 2014; Sandifer et al., 2015; Mygind et al., 2019), and improving air quality (Abhijith et al., 2017). Because of this multifunctionality, there is currently much enthusiasm within the academic, private, and political sectors about fostering a greater understanding of the concept of GI and its benefits. These benefits are commonly known as Ecosystem Services (ES), a term popularised by the Millennium Ecosystem Assessment (MEA)[2] which defines ES as "*the benefits that people obtain from ecosystems*" (MEA, 2003). These benefits are generally grouped under four types (MEA, 2003; Davies et al., 2017):

- **Supporting services** are those necessary to produce other ecosystem services that tend to be indirect or occur over a long period, such as nutrient and water cycling and soil formation.
- **Regulating services** are those benefits obtained from the regulation of ecosystem processes, for example, climate regulation, water treatment, biological control, pollination, air quality mitigation, and carbon sequestration.
- **Provisioning services** are the products obtained from ecosystems, such as food, medicines, and building materials.
- **Cultural services** are related to the societal appreciation of nature, including heritage, spiritual, social, educational, recreational, and aesthetic benefits derived from the ecosystem.

Social, economic, and environmental benefits are delivered daily by GI to humans at no additional cost (Figure 19). The key benefits of GI in cities are the promotion of comfortable urban green areas with aesthetic values, improved air quality, increased carbon storage, increased attraction of investment, reduced excessive heat and flash flooding, and improved physical and mental health (Dover, 2015).

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[2] Millenium Ecosystem Assessment (MEA) is a multinational expert group that aims to assess the consequences of ecosystem change for human well-being (MEA, 2003; Reid et al., 2005).

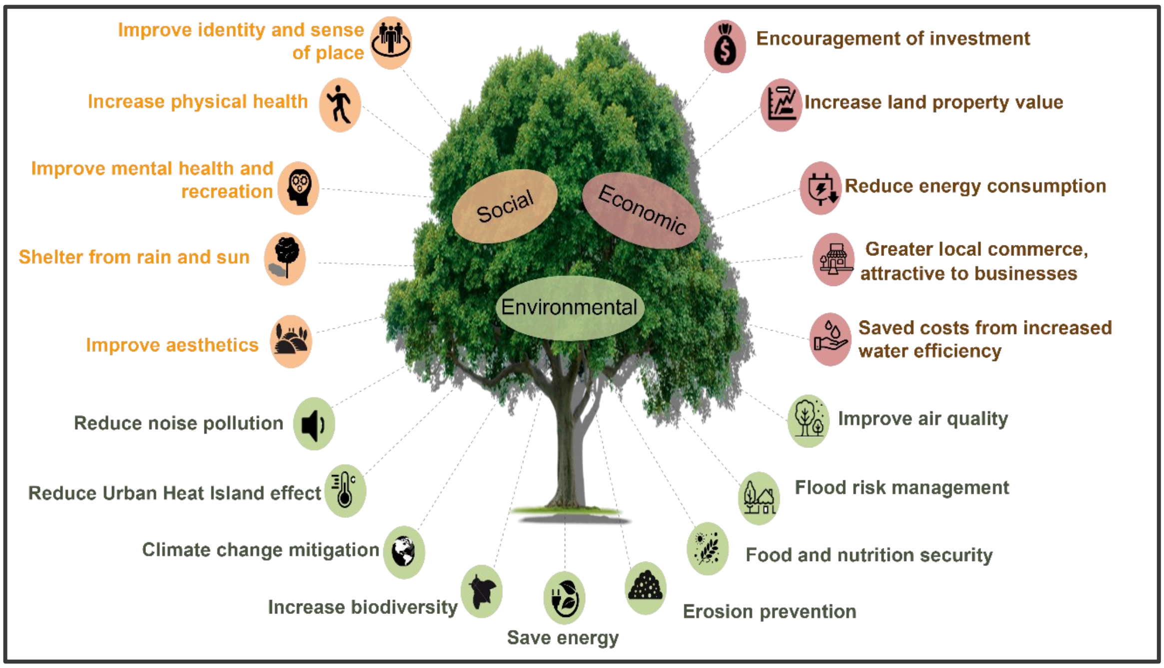

Figure 19. Benefits of Green Infrastructure in cities.
Source: Own elaboration

4.1 Benefits of green infrastructure

While the direct influence of GI on human health remains uncertain (Nieuwenhuijsen, 2021), many potential benefits to green space exposure have been reported:

- **Improved mental health and social capital:** People who live in greener areas perceived their health as being better, experiencing less acute health-related complaints, and having better mental health than people living in areas with less green space (de Vries et al., 2013). Those partaking in green outdoor activities and with exposure to nature reported greater self-esteem, self-efficacy, positive engagement, improved social skills and behaviours, improved cognitive performance, better mood and attitude, vitality, energy, pleasure, and delight. Being in a green environment might also decrease loneliness, frustration, worry, confusion, depression, tension, and tiredness (Maas et al., 2009; Sandifer et al., 2015; Mygind et al., 2019).
- **Improved physical health:** Recreational walking, increased physical activity and a reduction in sedentary lifestyles are associated with access to and use of green spaces. People who live in the greenest areas engage in 13% to 18% more days of physical activity than people who live in areas lacking greenspace Associations between greenspace and physical health have been reported in terms of positive effects on cardiovascular health, neurocognitive development and general well-being, and preventing obesity, sleep apnoea, osteoarthritis, hypertension, strokes, cancer, diabetes, and heart disease (Younger et al., 2008; Lee et al., 2012).

Vegetation naturally releases antimicrobial allelochemical organic volatile compounds (phytoncides) like α-pinene and d-limonene, which play an important role in increasing cell activity. These compounds enhance the activity of human natural killer cells, which protect against cancer and stimulate the endocrine and immune systems. Phytoncide exposure significantly decreases concentrations of adrenaline and noradrenaline, suggesting lower levels of stress (Li et al., 2009).

Besides human health benefits, GI provides environmental benefits and plays an important role in adapting cities to climate change (IPCC, 2022). This has led cities such as London, Copenhagen, Vancouver and New York to increase GI cover through tree planting schemes in an effort to enhance the 'green matrix' across streets in order to increase comfortable living (Campbell et al., 2014; City of Copenhagen, 2015; City of Vancouver, 2015; Mayor of London & Partnership members, 2020). The Mayor of London, for example, aims to increase tree canopy cover in the city by 10% by 2050 to protect, manage and expand the capital's urban forest (Mayor of London & Partnership members, 2020). Green Infrastructure thus contributes to making cities socio-economically and environmentally more sustainable through a variety of effects:

- **Multifunctionality*:*** This is defined as "*the potential for GI to have a range of functions, to deliver a broad range of ES. Multifunctionality can apply to individual sites and routes, but it is when the sites and links are taken together that we achieve a fully multifunctional GI network*" (Natural England, 2011).
- **Flexibility and adaptability:** The different typologies and fully flexible sizing of GI provide various functions and uses. For instance, GI can be added to building façades or roofs, thus providing multiple opportunities for increasing GI in urban areas where space is scarce or limited (Medl et al., 2017).
- **Resilience to climate change:** GI can reduce the Urban Heat Island (UHI) effect as well as people's exposure to heat at a street level. Vegetation absorbs solar radiation, cooling the street between 0.03°C and 3°C (Francis & Jensen, 2017). Indeed, 10 hectares of green space can reduce air temperature by 1°C (Coutts & Hahn, 2015). Green infrastructure can also mitigate risks from climate change, decreasing the risk of flooding through water storage and retention areas, increasing the thermal performance of buildings, and reducing atmospheric concentrations of carbon through storage and sequestration (Jones & Somper, 2014; Burgess, 2015).

4.2 Drawbacks (disservices) of green infrastructure

Green infrastructure is not ubiquitously beneficial, and there are also drawbacks or Ecosystem Disservices (EDS) to the presence of vegetation. For instance, the fallen leaves of deciduous species can cause blocked drains and gutters, presenting safety concerns in streets in autumn (Figure 20A) (Goodwin, 2017). Species with flowers and fruits may also become a messy and slippery problem for pedestrians when these are deposited on the ground (Hirons & Sjöman, 2019). Additionally, trees with solid root systems can damage urban infrastructure, lifting pavements and sometimes even creating instability in buildings (Figure 20B).

The adequate and appropriate selection and location of species is key to achieving the desired benefit. For instance, where high temperatures are a significant issue, landscape designs should consider positioning trees near buildings to mitigate increasing energy use (Vaz Monteiro et al., 2019; Feng et al., 2021). This is because dense crowns attenuate variations in temperature, reducing heat loss from the ground and offering shade in the summertime. However, this positive ES could bring EDS in air quality if there is no understanding of why a GI is being planted. As will be examined in **Chapters 4** and **5**. For example, dense crowns could deteriorate air quality in narrow street canyons accumulating pollutants due to wind reduction (Abhijith et al., 2017). In addition, many species release copious pollen and BVOC, which can cause respiratory problems such as asthma and an exacerbation of allergies, especially from these dense crowns (Cariñanos et al., 2017).

Figure 20. Fallen leaves can become a problem for walking and wastewater systems (A), and tree root growth can cause uneven and broken pavements (B).
Credit: Karina Corada

4.3 Green infrastructure: The promise of air pollution mitigation in cities

In collaboration with the C40 Cities Climate Leadership Group[3], the Nature Conservancy Organization lunched in 2016 a report called Planting Healthy Air. The report identified tree planting as a highly cost-effective strategy for reducing PM compare to other strategies to reduce PM (e.g., electrostatic precipitators in factories or power plants) (McDonald et al., 2016). However, an annual global investment of \$100 million in trees (including planting and maintenance) would provide 8 million people with a large (>10 $\mu g\ m^{-3}$) reduction of $PM_{2.5}$, 47 million people a reduction of > 5 $\mu g\ m^{-3}$, and 68 million people a reduction of 1 $\mu g\ m^{-3}$ (medium impact scenario), and an additional reduction in temperatures on hot days (McDonald et al., 2016). Costs would depend on the city and its emission profile, but GI is a modest strategy that can reduce health diseases and offer a unique attractiveness since it also provides other benefits, such as carbon sequestration, aesthetic beauty, stormwater mitigation, cultural and social enhancement. Nevertheless, the report did not mention or evaluate the negative cots of biogenic emissions or other EDS provided by GI (McDonald et al., 2016).

Despite the promotion of GI as a potential urban planning solution for improving air quality by both researchers (Pugh et al., 2012a; Bottalico et al., 2016; Tomson et al., 2021) and local authorities (Dublin City Council, 2016; Camden Council, 2020; Mayor of London & Partnership members, 2020; Ayuntamiento de Madrid, 2021; Brussels, 2021; White Rose Forest, 2021), the real influence of GI on air quality in streets is modest and underpinned by weak empirical evidence. Attempts have been made to estimate the value or percentage of air pollutants removed by different GI through field and computational studies, but estimates vary widely (Table 1). For example, regarding the mass of pollutants removed from the air, Nowak (1994) calculated that the 50.8 million trees in Chicago, USA removed 6,145 tonnes of air pollution annually (Nowak 1994). A Chinese study found that urban trees in Guangzhou can remove 344 tonnes of air pollution per year (Jim & Chen, 2008). In London, trees were estimated to remove 2,241 tonnes of air pollution (0.014 tonnes $ha^{-1}\ yr^{-1}$) (Rogers et al., 2015).

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[3] C40 cities is a global network of the world's leading cities to carry out urgent actions towards alleviating the climate crisis.

Table 1. Field and modelling studies estimated the effect of green infrastructure on air quality.

Pollutant	Type of GI	Effect on air quality (pollutant concentration reductions)	Research method	Reference
PM_{10}	Hedges	34%	Field investigation	Tiwary et al. (2008)
TSP	Greenbelts	65%.	Field investigation	Islam et al. (2012)
PM_{10}	Greenbelts	7-15%	Field investigation	Chen et al. (2015)
Tracer gas (SF_6)*	Hedges	46 - 61%	Wind tunnel experiment	Gromke et al. (2016)
PM_{10}	Trees	57%	Field investigation (mapping trees)	Ortolani and Vitale (2016)
Tracer gas (ethane)*	Tree	10%	Computational model	Ghasemian et al. (2017)
BC	Hedges	63%	Field investigation	Abhijith and Kumar (2019)
PM_{10},	Trees	9%	Computational model	Moradpour and Hosseini (2020)
CO	Trees	8%	Computational model	
NOx	Trees	8%	Computational model	
$PM_{2.5}$	Trees	2.5%	Software (i-Tree)	Velasquez et al. (2021)
TSP	Hedges	13.52% (Max 20.04%)**	Field investigation	Chen et al. (2021a)
PM_{10}	Hedges	13.65% (Max 23.39%)**	Field investigation	

TSP = total suspended particles / BC = black carbon
* Tracer gas simulated the traffic emissions. / ** 24 hedge species were studied. The percentage presented is an average. In parentheses are the percentage of the species with maximum removal.

Differences in the amount of estimated pollutant concentration reductions between the modelling and experimental studies may be attributed to differences in the GI characteristics considered in each study. Furthermore, the differences between the field experiments may be due to the variety of research methods that were carried out, as will be examined in **Chapter 3**.

5 Mechanisms by which green infrastructure can influence air quality

Green infrastructure could improve air quality through a combination of mechanisms and in different ways. GI **intercepts (deposition)** particulate matter (PM_{10}, $PM_{2.5}$ and PM_1), **absorbs** gases and UFP and affects **dilution and dispersion** of pollutants. Locally, GI planting enhances or reduces airflow (**dispersion**); this redistributes pollution but does not necessarily remove it.

Green infrastructure such as shrubs/hedges also act as a barrier if located on the sidewalk near traffic pollutants, blocking pollutants and extending the distance between pollutant sources and pedestrians (Hewitt et al., 2020). Immediately behind the barrier concentrations are reduced (sidewalk), while concentrations are increased on the side of the barrier facing frontal traffic (Abhijith & Kumar, 2019).

Planting GI also results in some negative impacts to the air quality. Some species are important sources of **biogenic emissions,** such as Biogenic Volatile Organic Compounds (BVOC) and pollen emissions (Cariñanos et al., 2017; Speak et al., 2018; Cariñanos et al., 2020).

5.1 Deposition

Deposition is the transport of particulates from the atmosphere onto a surface. There are two types of deposition: dry and wet deposition; the difference is that the first occurs in the absence of precipitation or water (Sienfeld & Pandis, 2016a).

The amount of pollutants removed by GI (vegetation) depends on different surface characteristics and weather parameters (details are provided in **Chapter 3**). Surface characteristics can influence the amount of pollutants in the following ways (Burgess, 2015):

- Short–term capture, where the pollutant is re-suspended and goes back into the atmosphere.
- Longer-term capture, where the pollutant is incorporated into the structure, for example, through a waxy layer (sequestration).
- Pollutant is transferred to a different medium. For example, where precipitation (liquid) washes off the particles from a leaf (solid medium).

5.1.1 Dry deposition

Dry deposition describes how particles from the free atmosphere are deposited on a surface, for example, a leaf (Figure 21).

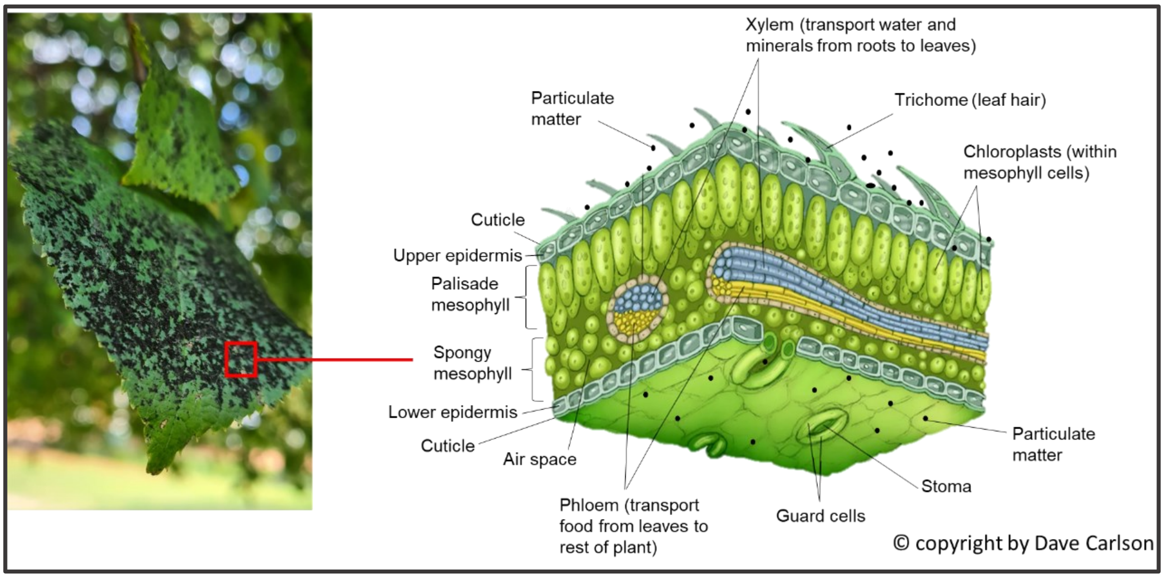

Figure 21. Illustration of a microscopic section of a typical leaf.
The image on the left shows a real leaf with dust on it. The image on the right is a general representation of a cross-section of a leaf. Image reproduced with permission of the rights holder ©DaveCarlson/CarlsonStockArt.com

Particle size determines how particles will be deposited. Generally, particles smaller than 100 µm are deposited on vegetative surfaces through different size-dependent processes (Smith & Jones, 2000; Smith et al., 2010):

- **Brownian motion** is the random movement of particles as a result of collisions with each other and surfaces. The smallest particles (>0.05 µm up to < 0.1 µm) are most responsive to this process since submicron particles behave similarly to gases and are efficiently transported across the quasi-laminar layer.
- **Inertial impaction** is when a particle impacts with obstructions and may adhere to the surface. The efficiency of this process increases with the particle size while decreasing with the obstacle's size.
- **Interception** is when a particle passes around an obstacle, “touches” it and is captured. This process is less efficient than impaction because viscosity near the surface slows the velocity of particles, while (leaf) microstructures enhance velocity on the surface.
- **Sedimentation** refers to the deposition of large particles (> 10 µm up to 1 mm) by gravity.
- **Rebound** affects particles of 5 µm and above. The particle's kinetic energy causes it to rebound from the surface it hits, though this depends on the nature of the surface adhesion.

The rate of particles deposited, or flux (F), is a function of deposition velocity (V_d) and the ambient pollutant concentration (C) (1):

$$F = C \times V_d \qquad (1)$$

Where F (g m^{-2} s^{-1}) is the pollutant flux, C is the pollutant concentration (g m^{-3}), and V_d is deposition velocity (m s^{-1}).

Deposition velocity represents the speed of pollutant removal and is inverse to the sum of resistances (2) (Figure 22). Vegetation (GI) presents three resistances: i) the aerodynamic resistance of pollutants to atmospheric transport (R_a), resistance above the canopy, ii) the resistance to diffusion across the surface boundary layer (a quasi-laminar flow layer) (R_b), and iii) surface resistance or canopy resistance (R_c), the sum of the deposition on the different surfaces such as soil, cuticle, stomata and the internal organs of the plant (Fowler et al., 2009; Tiwary et al., 2019b).

$$V_d = \frac{1}{R_t} = \frac{1}{R_a + R_b + R_c} \qquad (2)$$

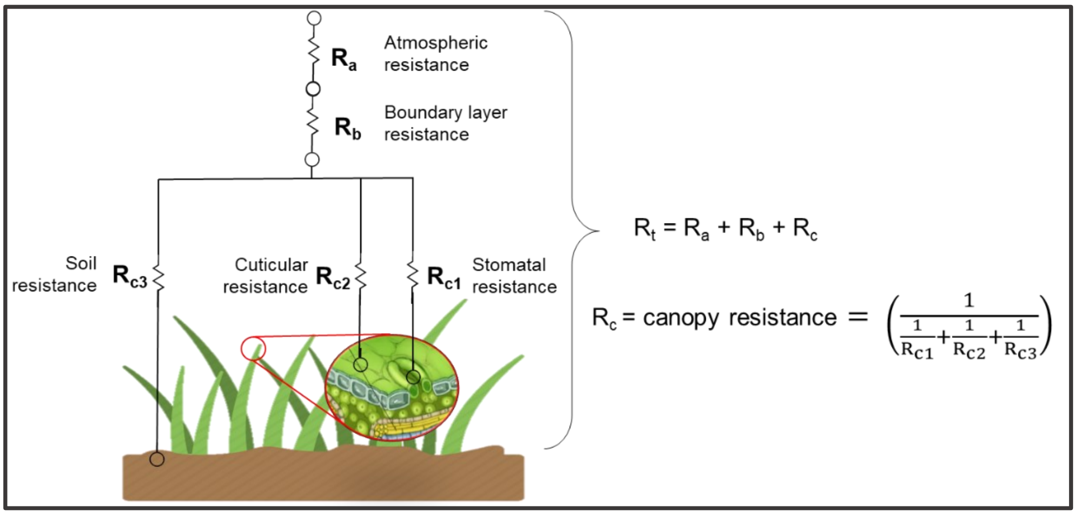

Figure 22. Representation of the resistances involved in deposition velocity. Adapted from Fowler et al. (2009)

The aerodynamic resistance (R_a) is low and tends to be zero for particles with a diameter less than 10 µm (Janhäll, 2015). Generally, R_a and R_b decrease with increasing wind speed and vegetative height, thus, less resistance (higher deposition rates) is expected over a forest than over grass (Seinfeld & Pandis, 2016). These resistances reflect the deposition process and have been used to calculate the amount of deposited particles in computational models (Nowak et al., 2006; Bruse, 2007).

Deposition velocity is the main parameter for estimating pollution removal or flux by trees (or other GI). Deposition velocities vary according to wind speed, particle size and the type of species (Beckett et al., 2000; Freer-Smith et al., 2005) (Table 2). In the literature, different deposition velocities are found. For example, deposition velocities for PM_{10} on vegetation vary from ~0.01 to ~10 cm $s^{-1,}$ and although a deposition velocity of 30 cm s^{-1} has been measured (Freer-Smith et al., 2005; Litschke & Kuttler, 2008), an intermediate value of 0.64 cm s^{-1} is widely and commonly used in modelling studies independent of the species or particle size being studied (Pugh et al., 2012a; Jeanjean et al., 2017).

Indirect and direct methods for quantifying V_d have also increased the range of values for V_d, as well as the uncertainty of what this value represents (Table 2). The most common method for determining deposition velocity is a wind tunnel using NaCl (sodium chloride) as a tracer representing $PM_{2.5}$. Generally, a wind tunnel with a hexagonal working section of 4m long is fitted with baffles to produce laminar flow (Beckett et al., 2000; Freer-Smith et al., 2004). The amount of NaCl deposited by each leaf during the exposure is then calculated using the gravimetric method (See section 5.1.2), the flow is known as well as the total leaf area, and then the deposition velocity is calculated (Freer-Smith et al., 2004). However, the studies using NaCl as a tracer actually use particles diameter ranging from 0.8 to 1.2 µm (PM_1) instead of particles representing $PM_{2.5}$ (Beckett et al., 2000; Freer-Smith et al., 2004).

These smaller particles are less frequently fixed on leaves (Xu et al., 2022); as a result, the measured v_d is typically less than larger particles (Yin et al., 2019). Diamond powder could be a good option as a tracer. According to Yin et al. (2019), diamond powder is mainly composed of particles with diameters of 1.8–2.5 µm, representing much better PM$_{2.5}$ (Yin et al., 2019). However, this tracer could increase the value of the research.

An indirect method is to use dust monitors. The monitors calculate mean air pollutant concentrations (C) in the site. The rate of particles deposited, or flux (F), is calculated from the concentrations of the different size fractions of particles present on the leaves and measured by gravimetric method, and using equation (1) (see above), the deposition velocity is calculated (Freer-Smith et al., 2005). Here a better representation of particle sizes exists, but the wind speed is unknown. In addition, the reliability of the result (V_d) will depend on the sampling period and the ability of the dust monitor to measure different particle sizes.

Table 2. Summary of average deposition velocities (cm s^{-1}) by wind speed from the literature.

Species	**Particle size**	**Wind speed (m s^{-1})**						
		1	**2**	**3**	**6**	**9**	**10**	**No inform**
Pinus nigra [a]	PM$_{2.5}$	0.13		1.15			28.05	
Cupressocyparis x leylandii [a]	PM$_{2.5}$	0.08		0.76			12.2	
Acer campestre [a]	PM$_{2.5}$	0.03		0.08			0.57	
Sorbus intermedia [a]	PM$_{2.5}$	0.04		0.39			2.11	
Populus deltoides [a]	PM$_{2.5}$	0.03		0.12			1.18	
Quercus petraea [b]	PM$_{2.5}$			0.831	1.757	3.134		
Alnus glutinosa [b]	PM$_{2.5}$			0.125	0.173	0.798		
Fraxinus excelsior [b]	PM$_{2.5}$			0.178	0.383	0.725		
Acer pseudoplatanus [b]	PM$_{2.5}$			0.042	0.197	0.344		
Pseudotsuga menziesii [b]	PM$_{2.5}$			1.269	1.604	6.04		
Eucalyptus globulus [b]	PM$_{2.5}$			0.018	0.029	0.082		
Ficus nitida [b]	PM$_{2.5}$			0.041	0.098	0.234		
Pine [c]	PM$_{10}$							2.79
	PM$_{2.5}$							1.75
	PM$_{1}$							36.24
Cypress [c]	PM$_{10}$							3.43
	PM$_{2.5}$							4.58
	PM$_{1}$							33.72
Poplar [c]	PM$_{10}$							0.57
	PM$_{2.5}$							0.81
	PM$_{1}$							25.43
Green wall (100% coverage) [d]	NO$_2$							0.3
	PM$_{10}$							**0.64**
Green roof [d]	NO$_2$							0.3
	PM$_{10}$							**0.64**
Sophora japonica [e]	PM$_{2.5}$		0.435					
Cinnamomum camphora [e]	PM$_{2.5}$		0.239					
Ginkgo biloba [e]	PM$_{2.5}$		0.263					
Ligustrum lucidum [e]	PM$_{2.5}$		0.317					
Pinus parviflora [e]	PM$_{2.5}$		2.853					
Salix babylonica [e]	PM$_{2.5}$		0.277					

[a] Beckett et al. (2000). Method Wind tunnel (tracer NaCl), [b] Freer-Smith et al. (2004). Method Wind tunnel (tracer NaCl), [c] Freer-Smith et al. (2005). Deposition velocity measured in Sussex field site, [d] Pugh et al. (2012a). Method model technique, [e] Yin et al. (2019). Method smog chamber (tracer diamond powder).

5.1.2 Quantifying particle deposition

Individual leaf

Direct and indirect methods such as gravimetric, saturation isothermal remanent magnetisation (SIRM) and microscopy imaging techniques have been used to quantify particle deposition on leaves. In the gravimetric method, leaves are washed with distilled water, and deposited particles are passed through preweighed filters with different pore sizes corresponding to different particle sizes (Dzierzanowski et al., 2011; Popek et al., 2013; Paull et al., 2020). Subsequently, the filters and the particles contained therein are weighed for particle quantification. Additionally, chloroform is used to dissolve particles retained in leaf waxes (Popek et al., 2013; Przybysz et al., 2014; Sgrigna et al., 2015). This method is both time-efficient and cost-effective, however, particles containing nonpolar molecules (e.g., CO, CCl_4, CH_4) can potentially dissolve, altering the total amount of deposited particles. In addition, this method cannot identify leaf micromorphological structures that retain particles (Corada et al., 2021). In the magnetisation method, SIRM, the leaf is exposed to strong magnetising fields at a constant temperature where a magnetometer quantifying the ferro(i)magnetic PM fraction. This method requires controlled laboratory conditions for temperature and the magnetic field to classify magnetic particles. The microscopy technique uses a Scanning Electron Microscope (SEM), which captures magnified images of deposited particles which are counted via image processing software (Burkhardt & Pariyar, 2014; Shi et al., 2017; Weerakkody et al., 2019). The SEM is expensive, and the technique requires an expert user to measure particle size distribution and provide insights on leaf micromorphology. This technique, however, quantifies deposited particles on a small fraction of the total leaf surface area so that a large number of images must be taken to provide conclusive results (Ottelé et al., 2010).

Green areas

Software is used to assess the capacity for GI to remove PM on a large scale (e.g., parks or trees in a city). The i-Tree software tool is commonly used for this purpose (Rogers et al., 2015; Jayasooriya et al., 2017; Riondato et al., 2020). This American software uses local data to provide tree analysis about pollution removal, carbon sequestration, building energy, tree planting inputs, and other management information (https://www.itreetools.org/tools/i-tree-eco). The software uses deposition velocity and resistances to predict the total pollution removal (Nowak & Crane, 1998; Nowak et al., 2006). Due to the growing demand to quantify the benefits of trees in urban areas, this software has been adapted for worldwide use, for example, in Canada, Australia, Mexico, Chile, the United Kingdom and the rest of Europe (Escobedo et al., 2008; de la Concha et al., 2015; Foster & Duinker, 2017; Gardner et al., 2017; Riondato et al., 2020).

5.1.3 Wet deposition

Wet deposition (also known as washout, wet removal, rainout, and scavenging) is a mechanism by which pollutants (gases and particles) are scavenged by hydro-surfaces such as mist, fog, rain, snow, and droplet water (Sienfeld & Pandis, 2016b). This deposition occurs in a short period and is episodic (e.g., how long the rain lasts) (Barrie & Schemenauer, 1986). The effect of wet deposition on pollutant removal is minor compared to dry deposition (Tallis et al., 2015). However, geographical location and the type of pollutants influence the effectiveness of the mechanism. In Scotland, for example, rainout represents around 38% of total annual deposition (Dore et al., 1992).

5.2 Absorption

Vegetation absorbs gases through natural metabolic processes, sequestering them in their tissues or metabolising them for biochemical functioning (Bell & Treshow, 2002; Fowler et al., 2009). Leaves are specialised structures through which photosynthesis and plant respiration occur. Plants take up CO_2 and release oxygen (O_2) through the stoma (minute openings) that is surrounded by guard cells which control its opening and thus the gas exchange (Figure 21) (Cieslik et al., 2009). Stomata are found in both the upper and lower surface (epidermis) of leaves. In leaf trees, stomata are between 17 and 50µm in length and have a density of between 100 and 600 mm^{-2}. The size and density of stomata vary widely across different species and geographical locations. For example, generally, angiosperm species[4] have relatively few or no stomata on their upper surface, but some angiosperm species (e.g., willow and poplar) have stomata on upper and lower surfaces (Hirons & Thomas, 2018).

The sequestration of CO_2 by trees has been studied widely; however, vegetation also acts as a natural sink for other urban pollutants, such as O_3, NO_2, SO_2, fine and ultrafine particles, and peroxyacetyl nitrate (PAN) (Omasa et al., 2002). Some plants are sensitive to particulate air pollutants and incur specific damage to leaves, flowers, and fruits (Gupta & Kulshrestha, 2016), resulting in acute and chronic injuries that lead to the inhibition of photosynthetic activities and thus reduce absorption (Gheorghe & Ion, 2011; Rai, 2016).

5.2.1 Quantifying gas absorption

Sap-flow measurement is a common technique for measuring gas absorption through inserting flow sensors into xylem tissue[5]. The flow sensor measures the transpiration rate associated with the stomatal opening and, thus, with gas absorption (Wang et al., 2012).

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[4] Species that reproduce through flowers. Their seeds are enclosed within fruit.

[5] Xylem tissue transports water and minerals from the roots to the rest of the plant, including stems and leaves.

Another technique is the introduction of stable isotopes (e.g., ^{15}N, ^{13}C) into sap flux which can reveal the amount of a gas taken up by a GI (Gong et al., 2021).

5.3 Biogenic emissions

The biosphere is a source of primary biogenic aerosol particles (PBAP), which comprise plant and insect debris, pollen, spores (a reproduction cell formed by some plants and fungi), bacteria and viruses. Vegetation (or GI) is the main emitter of biogenic emissions, such as pollen and gases. Plants emit biogenic volatile organic compounds (BVOC), which oxidise the atmosphere and produce organic material called secondary biogenic aerosols.

5.3.1 Biogenic Volatile Organic Compounds

Flowers, fruits, and leaves emit BVOC, a mix of compounds classified according to the chemical structure of a large set of hydrocarbons (C-H) (See Appendix A, Table 3). Most BVOC emitted by plants belong to the chemical class of isoprenoids[6] or terpenes[7], being isoprene (C_5H_8), the most abundant compound emitted by vegetation (Calfapietra et al., 2013). Other compounds, such as monoterpenes, sesquiterpenes, and homoterpenes, are also constituents of BVOC.

The compound and amount of BVOC released depend on the type of species (Table 3), physiological parameters, and environmental conditions (Calfapietra et al., 2013; Chen et al., 2020).

Table 3. Estimates global BVOC fluxes into the atmosphere with a major group of BVOC emitting plants.

BVOC	Chemical examples	Total annual global from 1980 to 2010 (Tg / year) (1)	Emitting plants
Isoprene	2-methyl-1,3-butadiene	594	Populus, Salix, Platanus, Cocos, Elaeis, Casuarina, Picea and Eucalyptus
Monoterpene	β-pinene, α-pinene, limonene	144	Lycopersicon, Quercus, Cistus, Malus, Pinus and Trichostema
Other reactive BVOCs	Acetaldehyde, 2-methyl-3-buten-2-ol	41	Grassland, Vitis, Brassica, Secale and Betula
Other less reactive BVOCs	Methanol, ethanol, formic acid, acetic acid and acetone	193	Grassland Vitis, Brassica, Secale and Betula

(1) The emission data set was calculated using the MEGANv2.1 model (Sindelarova et al., 2014).

Biogenic VOCs are responsible for a range of fragrances or odours, for example, piney odour. Fragrance plays a role in the communication between animals and plants, attracting pollinators, facilitating interactions between other plants, and protecting against predation (Kesselmeier & Staudt, 1999; Owen et al., 2003; Yuan et al., 2009; Holopainen &

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[6] A class of organic compounds composed of two or more units of hydrocarbons (H and C).

[7] A class of organic aromatic compounds composed of isoprene and oxygen.

Gershenzon, 2010). The latter is the most important function of BVOC: to protect the plant against biotic and abiotic stress (Calfapietra et al., 2013; Loreto et al., 2014).

Adding BVOC, especially isoprene, to the urban environment can change the ratio between anthropogenic VOC and nitrogen oxides ($NO_x = NO + NO_2$), triggering photochemical reactions and thus contributing to tropospheric O_3 and secondary particle formation (Calfapietra et al., 2013) (Figure 23).

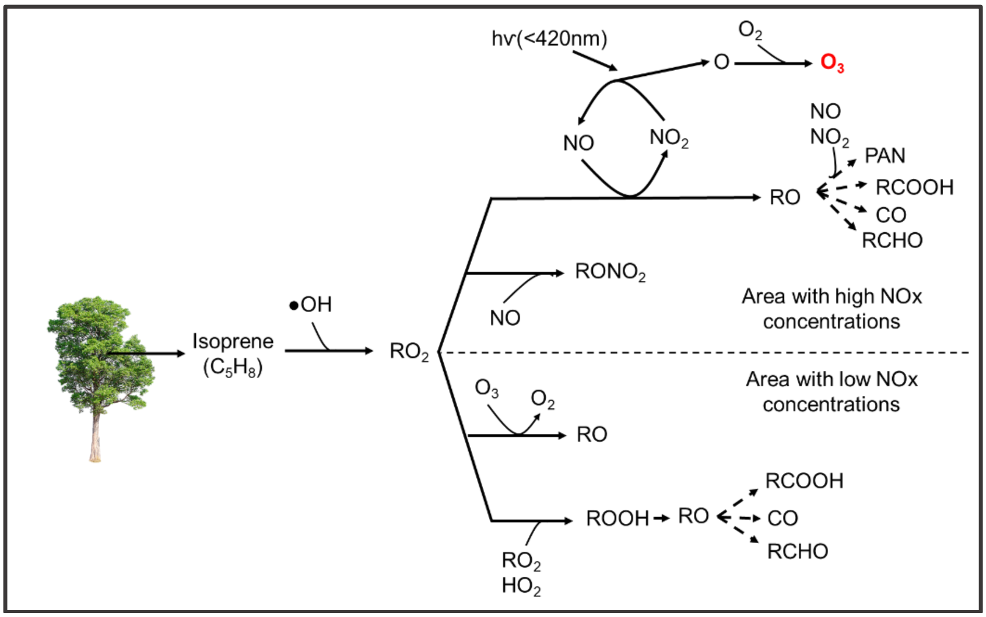

Figure 23. Reaction scheme illustrating potential products arising from the reaction of isoprene. In areas with a high level of NOx concentration, harmful products are formed, such as PAN (peroxyacetyl nitrates) and O_3 (tropospheric ozone). Source: Adapted from Harley et al. (1999)

5.3.1.1 Quantifying BVOC

The dynamic branch enclosure method is a standard in situ technique for measuring individual emissions of BVOC. Selected branches are enclosed in a chamber or in transparent Nalofan bags with absorbed tubes inside (Prendez et al., 2013; Aydin et al., 2014; Baraldi et al., 2018). Temperature, humidity, and Photosynthetically Active Radiation (PAR) in the chamber or bag are monitored, measured, and registered. The absorbed tubes are filled with Tenax (absorbed material for VOCs) and connected to a pump to assist the absorption of gases. A gas chromatograph quantifies BVOC absorbed in the Tenax tube (Prendez et al., 2013).

5.3.2 Biogenic Particulate Matter: Pollen

Pollen grains are the largest biogenic aerosol with a dominant range of 30-50 μm (Tiwary et al., 2019c). Pollen is a fine powder produced by trees, flowers, grasses, and weeds that contains the male gametes for reproduction. Pollination requires a vector to move pollen from the male anther of a flower to the female stigma. These vectors, called pollinators, could be wind or insects. Entomophilous species are those pollinated by insects, while those species pollinated by wind are called anemophilous.

Pollen is produced by cone-bearing (gymnosperms) and flowering plants (angiosperms), and it might contribute 4 - 11% of the total anthropogenic $PM_{2.5}$ mass and 12 - 22% of organic carbon in fine PM (Womiloju et al., 2003).

The production of large amounts of monospecific pollen (from one species) that air currents cannot always disperse concentrates the pollen grains, increasing allergies (Cariñanos & Casares-Porcel, 2011). Pollen is an additional particle that can enter into the airways. For most people sensitive to pollen, the amount released by urban vegetation causes allergic rhinitis (hay fever) and exacerbates chronic obstructive pulmonary diseases (Sedghy et al., 2018).

5.3.2.1 Quantifying pollen

Volumetric/pollen traps are standard devices for measuring pollen and spores (Buters et al., 2008). In addition, maps with spatial geographic information on vegetation and land use plus meteorological information have been used to determine allergenic pollen production in some cities (McInnes et al., 2017; Bogawski et al., 2019).

5.4 Dispersion

Dispersion, aerodynamic effect, or aerodynamic dispersion are used interchangeably to refer to the transport, diversion, and dilution of air pollutants (Bell & Treshow, 2002; Camuffo, 2014; Janhäll, 2015; Tiwari & Kumar, 2020). Dispersion describes airflow around obstacles and around or inside vegetation (GI) (Janhäll, 2015).

5.4.1 Quantifying pollutant dispersion

The effect of GI in dispersion has been studied using computational models, software, and wind tunnel experiments. Usually, the typical scenario is a street canyon with trees under different wind directions and speeds. The most frequently used methods for evaluating the effect of GI on pollutant dispersion are:

- **Dispersion models**

Dispersion models use mathematical equations to characterise the atmospheric processes (radiation, turbulence) that disperse a pollutant emitted by a source, providing specific meteorological parameters as well as the geometry and strength of the source (Tiwary et al., 2019d). Two dispersion models have been used to study the effect of trees on dispersion, the Eulerian and Lagrangian models. The Eulerian approach measures the properties of the atmosphere as it passes a fixed point and is used to predict particle transport and the number/type of particles collected by trees (Guo & Maghirang, 2012). The Lagrangian model tracks the trajectory of particles by solving motion equations (Han et al., 2011).

- **Computational fluid dynamics (CFD)**

These are sophisticated computational simulations structured around numerical algorithms applied to tackling fluid flow problems. Such CFD models include equations that involve fluid flow, heat transfer, and associated phenomena such as chemical reactions (Versteeg & Malalasekera, 2007). Reynolds-averaged Navier–Stokes (RANS) or Large Eddy Simulation (LES) equations that are used to predict particle dispersion and deposition. The RANS equation describes the 3D flow through mass, momentum, and energy conservation. It has been used to study the flow and dispersion of pollutants in urban environments (Karim & Nolan, 2011; Baik et al., 2012; Amorim et al., 2013; Moradpour et al., 2017). The LES is a turbulence model used to evaluate the impact of trees and urban geometry on pollutant dispersion (Salim et al., 2011a; Duan & Ngan, 2017; Wang et al., 2018).

- **CiTTyCAT**

The Cambridge Tropospheric Trajectory model of Chemistry and Transport (CiTTyCAT) is used to quantify the effect of trees on urban air quality (Donovan et al., 2005). This model investigates ozone production and transport based on temperature, humidity, pressure and surface pressure (Pugh et al., 2012b).

- **ENVI-met**

ENVI-met is a computational model designed to simulate plant-air-surface interactions in cities on a microscale (Bruse, 2007). This is a CFD model based on fundamental laws of fluid and thermodynamics, using the Eulerian approach to calculate mass, energy and momentum. A further description of the model is provided in **Chapter 7**.

- **GI4RAQ Platform**

The Green Infrastructure for Roadside Air Quality (GI4RAQ) is an online prototype offered to practitioners to simulate street vegetation barriers (e.g., hedges). The prototype focuses exclusively on the impacts of vegetation on pollution close to its source (Pearce et al., 2021).

Users draw a cross-section of the study street and fill in specific wind conditions, traffic emissions (NO_2 and $PM_{2.5}$), background concentrations, and barrier types (dimensions and seasonality). Once all user-specified parameters are set up, a report is displayed to the user (https://www.gi4raq.ac.uk).

- **Wind tunnel experiment**

A scale and idealised representation of a street with and without trees is physically modelled. Although scaling and representing vegetation is challenging (Gromke, 2011), this technique has been used to validate several CFD model studies on street tree dispersion impact (Hagler et al., 2011; Moonen et al., 2013; Jeanjean et al., 2015; Morakinyo & Lam, 2016b). This experimental representation can use fake vegetative structures with different porous materials in a lattice cage to simulate trees (Gromke & Ruck, 2008b), or it can use natural (real) tree branches located around scaled buildings (Ji & Zhao, 2018) to study the effect of GI in the dispersion of pollutants.

6 Conclusions

Green infrastructure positively impacts **air quality by capturing and absorbing** gases and particles; however, GI also influences the **dispersion of pollutants** and contributes **biogenic particles to the air,** which may have detrimental effects on health and the environment when improper species selections are made.

This chapter has presented the framework of this thesis, particularly the keywords and concepts necessary for understanding the impact of GI on air quality. There are multiple definitions of GI, but in this research, GI is understood as natural and **semi-natural elements strategically planned in a city to deliver ecosystem services**, such as reducing air pollutants exposure. Green walls, green roofs, shrubs, hedges, and trees are the common GI planted in cities and closed **streets,** and all can influence air quality.

Four mechanisms influence air quality and reduce the onward transportation and exposure of pollutants: **deposition, absorption, biogenic emissions, and dispersion**. Although attempts have been made to understand how GI influences air quality**, there remains a gap in the research around comprehensively understanding how GI characteristics influence air quality improvement in streets.** A holistic understanding of these characteristics can help practitioners (e.g., tree officers) make informed decisions to improve air quality.

For each mechanism described above, the following three chapters describe the specific GI characteristics and other spatio-temporal contexts, such as streets and weather parameters, which can influence street air quality.

Chapter 3. The impact of green infrastructure on air quality management from the perspective of deposition

This Chapter

- Identifies Green Infrastructure characteristics such as leaf traits that promote an effective particulate matter deposition.
- Evaluates the effectiveness of the identified leaf traits for capturing particulate matter.
- Discusses the uncertainties behind promoted leaf traits for efficiently particulate matter deposition.

1 Introduction

Several authors have concluded that the deposition of particles on surfaces is an effective method of air quality amelioration (Tiwary et al., 2009; Baldauf, 2017; Barwise & Kumar, 2020; Diener & Mudu, 2021). Due to physical processes, particles can be deposited on any surface, such as walls, pavements, or leaves. Leaves, however, offer more porosity and a more extensive deposition area than other materials. The problem is that deposited particles can be resuspended, washed, or blown off of the leaves, returning into the air, so that the air quality amelioration is only temporal in some species.

Considerable attention has been paid to understanding particulate matter (PM) deposition on green infrastructure (GI) in the last couple of years (Janhäll, 2015; Abhijith & Kumar, 2020; Xing & Brimblecombe, 2020a; Ysebaert et al., 2021; Dang et al., 2022). Leaf traits and spatio-temporal context may play a fundamental role in this understanding (Nowak et al., 2006; Grote et al., 2016; Chaudhary & Rathore, 2018). Particulate matter deposition on leaves depends on species-specific micromorphological leaf traits such as roughness and wax content, but there is little empirical evidence of leaf traits which effectively capture pollutants. Furthermore, up until now, planting strategies that seek to improve air quality in urban areas have not considered information related to leaf traits to maximise PM deposition, holding the common belief that the same amount of particles is deposited across all plant species.

No studies have provided a holistic review of the main leaf traits that influence PM deposition. A better understanding of the most influential leaf traits for the deposition mechanism is needed to help identify species that could be most efficient at capturing PM (Nowak et al., 2006; Grote et al., 2016; Chaudhary & Rathore, 2018).

This Chapter seeks to identify, through systematic literature reviews, the main leaf traits and spatio-temporal context associated with enhanced capture of PM by GI.

2 Method

2.1 Literature review

Three systematic literature reviews were conducted to identify the principal leaf traits that influence PM capture by GI. The first review was linked to street trees (ST), the second to green walls (GW), and the third to green roofs (GR). The review used the PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Moher et al., 2009). Each literature review had four phases: identification, screening, eligibility, and inclusion.

Phase 1: Identification and search strategy

Research articles published between 1980 and 2021 in English journals were searched in scientific databases such as ScienceDirect, Scopus, Web of Science and Google Scholar. A combination of search terms and synonyms were specified using Boolean search methods to identify candidate articles (Table 4).

Table 4. Search terms and synonyms used in the literature review. Source: Corada et al. (2021)

Search terms		
"leaves characteristics" OR "morphological " OR “traits” AND "leaves" OR "leaf" AND "deposition" AND "particulate matter" OR “PM” OR “air pollution” AND "urban areas" OR "city" OR "cities" OR "street" AND “air quality”		
Synonyms		
Street tree	**Green wall**	**Green roof**
"Urban trees" OR "trees” OR “Urban vegetation” OR “Urban” OR “vegetation”	"green walls" OR "living walls" OR "active green walls" OR “façade” AND NOT "thermal effects" OR "heat island" NOT "energy" NOT "indoor"	"green roof" OR "living roof" AND NOT "thermal" NOT "water retention” NOT "runoff"

Phase 2: Screening

Initial inclusion/exclusion was based on the significance of the title and abstract. If the initial screening identified admissibility of the article, then this was reviewed in detail to determine whether it would be included (inclusion phase). Duplicate, non-peer-reviewed journal papers, reports, and articles not related to the eligibility criteria were removed.

Phase 3: Eligibility

Articles were considered eligible if they: 1) were published in a peer-reviewed English-language journal; 2) included field data information; 3) studied at least one plant species in real conditions planted in streets (urban areas); 4) evaluated leaf traits and other factors of interest (e.g., weather and location, referred to throughout this Chapter as “spatio-temporal context”) through field measurements; and 5) included tables, figures or text summarising statistics of PM concentration deposited on leaves. Articles that did not mention the species studied or did not present PM concentrations on the leaves were excluded, as well as modelling studies.

Phase 4: Inclusion

Articles meeting the eligibility criteria were included. Some, though not all, of the articles, included additional information that the authors considered relevant or contributory to capture PM. These characteristics were noted, and this information was analysed separately. Selected articles were included in a simple Excel™ database, and information relating to publication year, keywords, citation counts, species, leaf traits, PM concentration on leaf and any spatio-temporal context were extracted for analysis.

2.2 Data analysis

The information from the selected articles was categorised and tabulated into six sections:

- **General information** included 1) sampling location; 2) sampling detail, such as sample height, the criteria for species selection, sampling date, background PM concentrations (if measured) and leaf area index (LAI); and 3) the PM measurement method. Results are shown in Section 3.1.
- **Green infrastructure characteristics** included botanical information about each studied plant species, such as 1) the common and scientific name of the species, 2) taxonomic rank (family rank), 3) morphological characteristics, and foliage. If the article included botanical information (e.g., phytomorphology[8], micromorphological characteristics), the information was extracted, but further botanical research was conducted if the article did not include it. Results are shown in Section 3.2.
- **Leaf trait information** summarised the morphological features of leaves and determined the contribution of leaf traits to capturing PM. Results are shown in Section 3.2.
- **Particulate matter concentration** contained the summary data of PM deposition recorded on the leaves of each studied species in each selected article. Due to variations in the methods used to estimate PM deposition between studies, it was impossible to compare PM concentrations across the selected articles. Some studies presented the PM deposited on leaves in concentration units per leaf (µg/m^2 or mg/cm^2) on the upper side of the leaf (abaxial) or the underside of the leaf (adaxial), while other studies presented the PM deposited as a total number of particles deposited on the leaf (number/mm^2). The temporal variability across studies hinders comparative analysis. Results are shown in Section 3.3.
- **Spatial and temporal context information** included additional information about how the context influences particle deposition. Results are shown in Section 3.4.

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[8] The study of the physical form and external parts of a plant.

The number of times the leaf trait was cited as effective or not across the reviewed studies was used to estimate the effectiveness of the leaf trait for PM deposition. The species noted within a study and the highest and lowest PM concentrations on their leaf surfaces were tabulated and classified dichotomously into high, medium, and low effectiveness according to the relative ability to remove PM in each study.

3 Results

3.1 General information

From an initial scoping of 428 potentially relevant and informative articles, 69 were finally selected for inclusion as data in the review. Street trees initially consisted of a significant number of studies (256); after analysing them, the final number of street tree articles was reduced to 62 articles. Green wall studies presented a large number of articles in the initial screening (132), but the selected articles were narrowed down to six articles following the filtration processes, while on green roofs, limited information was available, and only one article was selected. The systematic filtration and selection process for the identified literature is found in Appendix B, Figure 1.

3.1.1 Source geography

The selected articles came mostly from Asian countries (n = 35), including China (n = 30), with the largest number of studies carried out, and from European countries (n = 25), such as the United Kingdom (n =9), Poland (n = 5), and Belgium (n = 4) among others (See Appendix B, Figure 2 for geographical distribution).

3.1.2 Study designs

From now on, the term "selected study(ies)" is incorporated since the data extracted from each selected article will be compared.

A great variety of aims, sites, sampling strategies, sampling methods, and background measured concentrations were found across the selected studies.

- **Study aims.** Studies aimed to assess the foliar PM retention ability of plant species according to different conditions such as GI location, traffic flow, height, species, seasons, rainfall, leaf surface vs leaf waxes, and adaxial vs abaxial leaf side.
- **Site selection.** The most common study sites were next to heavy traffic roads and heavily polluted sites. The distance between the sample and the immediate pollution source (e.g., road) varied substantially. For example, one study only used street trees located 2m from the road edge (Leonard et al., 2016); others considered at intermediate distances from 10 to 25m (Sgrigna et al., 2015; Sgrigna et al., 2016; Liu et al., 2018); and others were located far away from the road between 30 to 90m (Mori et al., 2015) or 500m away

(Popek et al., 2015). One study was conducted in a garden, thus avoiding GI exposures to external sources such as traffic and industry emissions (Muhammad et al., 2019). Five studies used real leaves from a busy road to study PM deposition through a wind tunnel experiment.

- **Sampling strategies (leaf sampling).** The most prevalent species planted on the site was one of the most commonly used criteria for selecting the species of study. All studies sampled different numbers of leaves under real conditions. Leaves without signs of damage, disease or pests were randomly hand-picked and cut off with scissors. The leaves were sealed in pre-labelled sample bags or containers for transport from the collection point to a laboratory where the PM accumulated on the leaves was measured. Sampling height was primarily determined by pedestrian level. The most common height ranged between 1.5 and 2.0m; the maximum height was 12m, and the minimum was 0.01m for herbaceous species. The number of leaves collected, and the total leaf area calculated for each species varied among the selected studies. Twenty-nine studies did not clearly state either the number of leaves, nor the total leaf area, while 20 studies indicated only the number of leaves selected per species (2 - 50 leaves), and 13 studies only the total leaf area (100 - 500 cm^2) sampled.
- **Temporal considerations and number of species studied.** The duration of data collection and the number of plant species varied between studies. The most encompassing study collected and analysed of 47 different urban trees and shrubs in Poland and Norway over two years (Saebo et al., 2012). A study in Belgium sampled 96 different urban plant species in a garden experiment during June and September (Muhammad et al., 2019). Seven common trees present at 10 sampling sites in Gandhinagar city of Gujarat, India, were sampled across three seasons (summer, monsoon and winter) (Chaudhary & Rathore, 2018). In Beijing, leaf samples from three different common broadleaf species were collected on a single spring day (Lin et al., 2017). The effects of seasonal variation and preceding weather conditions were potentially influential on outcome measures (Nguyen et al., 2014), but were inconsistently recorded across the selected studies.
- **Sampling methods to measure particulate matter on a leaf.** Different methods were used to measure PM concentration, or the number of particles deposited on a leaf (See **Chapter 2**, Section 5.1.2.). The most common method was the gravimetric method (n=37), followed by Scanning Electron Microscope (SEM) (n=14) and Saturation Isothermal Remanent Magnetisation (SIRM) (n=8). Other methods were also used: dust detectors and samplers, a particle counter, and optical and atomic force microscopy. The gravimetric method was widely used to quantify PM on the leaves of street trees (59% of

studies), whereas measuring PM on the leaves of green walls and green roofs was most frequently estimated through SEM and SIRM, respectively.

- **Background concentrations.** Green infrastructure in highly polluted sample sites may present more PM deposited on leaves due to high background concentrations independent of the characteristics of their leaves. Thirteen studies only included ambient PM concentrations (PM_{10} or $PM_{2.5}$) from the nearest monitoring site from the leaf sampling. Two studies used fixed monitoring sites located 2 to 4 km away from the site sampling to obtain background concentrations. Five studies described traffic flows at the leaf sample site, and five other studies provided qualitative estimates of the PM ambient concentration (e.g., "*PM_{10} concentration exceeded daily limit on more than 70 days in 2012*"). The remainder (n=40) merely described the sites, which were usually in polluted areas or close to busy roads or motorways. In wind tunnel experiments, leaves were exposed to NaCl powder with a particle size ranging from 0.05 μm to 15 μm in a tunnel with a dimension which ranges from 50 cm to 6m long.

3.2 Green Infrastructure characteristics

Particulate matter deposition varied within and between taxonomic classifications with no clear pattern. Though features such as leaf traits are largely conserved within families and genera, some families, for example, *Platanaceae* and *Pinaceae,* contained species recorded as having both higher and lower deposition levels. Conclusions at this level are made increasingly difficult by an uneven representation of species within families and the variation in method. For example, Popek et al. (2013) and Chen X. et al. (2015) both used the gravimetric method, but one collected *Ginkgo biloba* leaves for three years and the other for six months, respectively. The first author concluded that the species had a high accumulation of fine PM in the wax, while the second concluded a low accumulation capacity for all PM fractions (Popek et al., 2013; Chen X. et al., 2015). Appendix B, Table 2 presents the level of effectiveness of PM deposition as a function of plant species.

Among the 69 selected studies, 390 species were studied in this research. Trees were more frequently studied than other GI (shrubs or vines). The most studied (citied) species were: *Sophora japonica, Pinus tabuliformis, Ginkgo biloba, Hedera helix,* ***Populus tomentosa****,* the **Platanaceae family**[9] *(Platanus acerifolia, hispanica,* and *orientalis),* ***Quercus ilex****, Tilia cordata,* ***Prunus cerasifera****,* ***Ailanthus altissima*** and ***Salix matsudana****.* The species in bold are recognised as tolerant species to air pollution (Hillier Nurseries & RHS, 2019).

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[9] The three species are often known by the common name London Plane.

3.2.1 Leaf traits information and particulate matter removal efficiency

The selected studies used different methods to identify the leaf traits of sampled species. Studies that used the SEM method captured the leaf traits in high-resolution images along with the amount of PM deposited on the leaf. Studies which used the gravimetric or the SIRM method could quantify the total amount of PM deposited on the sampled leaves, though leaf traits were not always identified. Relevant traits, such as trichomes and leaf roughness, were obtained from other sources.

Each study identified the leaf traits of some, or all, of the species sampled and justified why some species, based on their possession of certain leaf traits, accumulated more PM than others. Among the selected studies, there was no consensus as to which leaf traits are most effective in capturing PM, however, some leaf traits were commonly discussed. The most cited leaf traits for maximising PM deposition were micromorphological features, such as leaf wax cover, followed by trichomes and leaf roughness (Table 5).

Table 5. Common leaf traits cited as contributing to capturing particulate matter. Adapted from Corada et al. (2021)

Leaf trait	Definition	Number of studies		
		Street tree	Green wall	Green roof
Wax cover / Epicuticular wax	Layers of wax covering the surface of the leaf	24	2	1
Trichomes (leaf hairs)	Tiny outgrowths (hair) from the plant epidermis	23	3	1
Roughness	The leaf surface is irregular with some ridges	22	NR	NR
Leaf Wrinkles/ Ridges / Furrows/ Grooves	The leaf has grooves or channels usually running longitudinally	18	2	2
Leaf size	Size of the leaf	13	2	1
Leaf shape	Shape of the leaf	12	1	NR
Conifers / Pine species	Type of evergreen tree	12	NR	NR
Leaf wettability	Leaf wettability, indicating the affinity for water on a leaf surface	10	NR	NR
Stomata distribution / Stomatal density	The number of stomata per unit area of the leaf (Stoma: surface pores which allow gas exchange)	9	1	NR
Secretion	Release resins, gums, volatile compounds, and nectar from plant cells (secretory tissues)	5	NR	NR
Adaxial surface	Upper surface of a leaf	5	3	NR

*NR = Not Reported

The relative ability (quantitatively determined) of traits vs controls and the wider agreement between studies/authors enabled the classification of most cited leaf traits, which were classified (higher, medium, and low) according to the relative ability to capture PM (Table 6). Across the studies, however, there was frequently inconsistency when discussing the relative ability of specific traits to capture PM. For instance, some authors proposed that epicuticular wax is the best trait for trapping PM, especially ultrafine PM (Popek et al., 2013; Wang et al., 2015b; Popek et al., 2017; He et al., 2020a; He et al., 2020b), whereas others indicated that leaf hairs and rough surface were able to maximise deposition (Beckett et al., 2000; Mitchell et al., 2010; Saebo et al., 2012; Nguyen et al., 2014; Chen L., 2017; Popek et al., 2017; Shao et al., 2019).

Table 6. Leaf traits identified in the literature review and their PM capture classification (higher and medium effectiveness).
Source: Corada et al. (2021)

Trait	Specific trait	Most captured PM fraction		
		Large	Fine	Ultra-fine
Higher effectiveness				
Leaf size	Small	✓	✓	
Leaf shape	Acicular (needle)		✓	
	Lanceolate	✓	✓	
	Oblique - cordate	✓		
	Obovate	✓	✓	
Trichomes	Hair	✓	✓	✓
	Epicuticular trichomes	✓	✓	✓
	High density	✓	✓	✓
Roughness	Ridges, especially on adaxial side	✓	✓	✓
	Furrows, especially wide and shallow	✓	✓	
	Wrinkles and shallow furrows / Wrinkles and hollows	✓		
	Folds	✓		
	Deep / dense grooves	✓	✓	
	Cause of roughness not defined	✓		✓
Wax cover/ Epicuticular wax	High wettability			✓
Stomata distribution Stomatal density	Large		✓	
	High density			✓
	Existing	✓	✓	✓
	Cells arranged vertically and circular	✓	✓	
Stickiness/secretion	Glands and secretion			✓
	Honey dew	✓		
Adaxial and abaxial surfaces	Surface and side of the leaf	✓	✓	
Medium effectiveness				
Trichomes (Pubescence)	Short woolly hairs	✓	✓	
	hairy when young, then becomes glabrous OR sparsely pubescent	✓	✓	✓
	Abaxially pubescent when young and adaxially glabrous	✓	✓	✓
	Pubescent on both sides OR pubescent along veins on abaxial side	✓	✓	✓
	Fine short hairs	✓	✓	✓
	Sparse hairs or glabrous (adaxial) / dense hairs (abaxial)	✓	✓	✓
Low effectiveness				
Hair	Glabrous (hairless)	Not applicable		
Stomata distribution	Low density	Not applicable		
	Sunken stoma	Not applicable		
Surface	Shiny, glossy, smooth	Not applicable		
Leaf size	Large	Not applicable		
Leaf shape	Linear	Not applicable		
	Palmate	Not applicable		
	Narrowly elliptic, elliptic, obovate-elliptic to elliptic-ovate, oblong, ovate	Not applicable		
	Broadly ovate or broader	Not applicable		
Wax	Low wettability	Not applicable		
	Structure e tubular form	Not applicable		

The selected studies generally demonstrate that small leaves with rough, hairy, and sticky surfaces with a thin wax layer and large and dense stomata are more efficient in accumulating PM than large, smooth, and hairless leaves. In addition, needle leaf shape is considered the most efficient in capturing PM, followed by lanceolate, obovate, and oblique-cordate shaped leaves (Mitchell et al., 2010; Kardel et al., 2011; Saebo et al., 2012; Leonard et al., 2016), but more evidence is needed to conclude the effectiveness of those leaf shapes. See Appendix B, Figure 3 for types of leaf shapes.

Each of the leaf traits that have shown greater effectiveness are described below.

Leaf shape, leaf size and plant type

Broader plant traits, such as whether they are deciduous or evergreen and plant life-form (e.g., tree, shrub, herb, and grass) may have more convincing explanatory power than taxonomy *per se* (Corada et al., 2021). Tree type is very relevant to removal capacity; evergreen species are the most frequently cited species for high PM capture capacity in comparison to deciduous leaves (Przybysz et al., 2014). Evergreen conifers (e.g., pines), in particular, are generally more effective particulate sinks than deciduous broadleaved trees (Xu et al., 2018). Furthermore, the unique microstructure of evergreen conifers with needle leaves is considered to be more effective in PM accumulation due to its thicker epicuticular wax layer, mucus oils, complex foliage structure, grooved ridge protuberance, and potential for accumulating pollutants throughout the year and with different traffic pressures (Beckett et al., 2000; Dzierzanowski et al., 2011; Nguyen et al., 2014; Weerakkody et al., 2018; Xu et al., 2018; Jia et al., 2021b).

Other leaf shapes have also been classified as being the most effective, for instance, ovate and lanceolate (Table 7) (Saebo et al., 2012; Popek et al., 2013; Przybysz et al., 2014; Leonard et al., 2016). Palmate leaf shapes were largely identified as having lower PM capture capacity (Saebo et al., 2012; Chen X. et al., 2015; Mo et al., 2015; Weerakkody et al., 2017). The patterns suggested by this literature should be viewed with caution, as there was not enough evidence regarding other leaf shapes and the results varied according to the method used (Corada et al., 2021).

Small leaf size is associated with a more complex canopy, and therefore there are more leaves where PM can be deposited (Räsänen et al., 2013; Mori et al., 2015; Yan et al., 2016a). Smaller leaves, however, tend to move in the wind, fluttering in modest winds, and thus resuspend accumulated PM (Leonard et al., 2016). Further research is required to provide evidence on the effectiveness of small leaves.

Table 7. Some plant species, relative efficacity associated leaf traits and study details. Highlighted rows show species with highly effective PM capture. Studies with a similar study design and the same method for quantifying particles on a leaf were selected

Species	**Efficacy capturing PM (1)**	**Habit (2)**	**Foliage (3)**	**Leaf shape**	**Measure**	**Reference**
Westringia fruticosa	Highly effective	S	E	Lanceolate	G	Leonard et al., 2016
Persoonia levis	Less effective	T	E	Obovate		
Acer platanoides	Less effective for PM$_{2.5}$, PM$_{10}$ & TSP	T	D	Star-shaped	G	Sæbø et al., 2012
Betula pendula	Highly effective for PM$_1$	T	D	Ovate		
	Highly effective for TSP					
Cornus alba	Less effective for PM$_{10}$ & TSP	S	D	Ovate		
Fagus sylvatica	Less effective for PM$_1$	T	D	Elliptic; oval		
Pinus mugo	Highly effective for PM$_{10}$	S	E	Needle		
Robinia pseudoacacia	Less effective for PM$_1$ & PM$_{2.5}$	T	D	Elliptic; oval		
Stephanandra incisa	Highly effective for PM$_1$ & TSP	S	D	Ovate		
Catalpa bignonioides Walter	Less effective removal over three years	T	D	Cordate	G	Popek et al., 2013
Quercus rubra	Less effective during 2007	T	D	Obovate		
Sorbaria sorbifolia	Highly effective during 2007 & 2008	S	D	Lanceolate		
Syringa meyeri	Highly effective during 2009	S	D	Ovate		
Viburnum lantana	Less effective during the three years	S	D	Ovate		
Taxus baccata	Less effective in early spring	T	E	Linear	G	Przybysz A. et al., 2014
Taxus baccata	Less effective in late winter	T	E	Linear		
Hedera helix	Less effective in late spring	S	E	Rhomboid		
	Less effective retention in waxes in early and late spring					
Hedera helix	Less effective in waxes over late winter	S	E	Rhomboid		
Pinus sylvestris	Highly effective on leaf and in waxes	T	E	Needle		
Fraxinus chinensis	Less effective	T	D	Elliptic	S	Lin et al., 2017
Salix matsudana	Highly effective	T	D	Lanceolate		
Ulmus pumila	Highly effective for PM$_{2.5}$ & PM$_{10}$ on adaxial side	T	D	Lanceolate	S	Wang Lei et al., 2015
	Highly effective for PM$_1$ & PM$_{10}$ on abaxial side					
Ginkgo biloba	Less effective on both leaf surfaces	T	D	Fan-shaped		
Pinus sylvestris	Highly effective	T	E	Needle	W	Räsänen et al., 2013
Betula pendula	Less effective	T	D	Rhomboid		
Magnolia grandiflora	Less effective for PM$_{2.5}$	T	D	Elliptic	W	Xie C. et al., 2018
Buxus sinica	Less effective for PM$_{10}$	T	D	Obovate		
Cedrus deodara	Highly effective	T	E	Needle		

(1) Different particle sizes, PM= particulate matter, PM$_{10}$ = particle diameter 10µm, PM$_{2.5}$ = particles diameter 2.5µm, PM$_1$ = particle diameter 1µm, TSP = Total Suspended Particles

(2) T = tree / S = Shrub; [3] D = Deciduous / E = Evergreen

(3) G = gravimetric, S = SEM, W= Wind Tunnel

Trichomes

Trichomes are species-specific microscopic hairs characterised by different sizes, densities, and locations throughout the leaf. Species with dense hairs on their surface capture and retain PM more efficiently than glabrous (hairless) leaf surfaces (Saebo et al., 2012; Chen L., 2017; Zhang et al., 2017; Liu et al., 2018). See Baraldi et al. (2019) for different scanning electron micrographs of trichomes (Baraldi et al., 2019).

Roughness

Leaf roughness or textured leaves facilitate PM deposition and retention. Leaves with wrinkled, ridged or furrowed leaf surfaces capture more particulates, particularly coarse PM fractions (PM_{10}), than smooth and unwrinkled leaves (Blanusa et al., 2015; Leonard et al., 2016; Chaudhary & Rathore, 2018). Roughness provides more surface deposition for particles, and although surface roughness is directly proportional to the trapping ability of the leaves, the amount of PM accumulated on leaves depends on density, and the grooves' depth, and the width of furrows and ridges (Speak et al., 2012; Liu et al., 2018; He et al., 2020a).

Wax cover / Epicuticular wax

Epicuticular wax is the coating of a wax layer, covering the outer surface of the majority of plants. Its most important functions are reflecting solar radiation from UV to visible light, protecting against uncontrolled water loss, and influencing on surface wettability and particle adhesion (Koch & Barthlott, 2006). Plant waxes are a complex mixture of hydrophobic chemical components forming a complex three-dimensional crystalline microstructure such as platelets, rods, and tubules. See Baraldi et al. (2019) for different scanning electron micrographs of waxes (Baraldi et al., 2019).

Epicuticular wax has been identified as an efficient trait for capturing PM, especially fine and ultrafine particles, which can be buried in the waxy layer, permanently fixed in the leaf without returning to the air until the leaf falls (Song et al., 2015). These wax structures affect the interfacial area where PM is deposited and accumulated. Hence, PM accumulation on leaves might depend on the adhesive force between the leaf surface (chemical constitution) and PM fraction (Wang et al., 2015b; He et al., 2020b). In terms of the total of particles deposited on a leaf, there are more particles on the surface (around 60%) than in wax (around 40%) (Popek et al., 2017).

Leaf wettability

The affinity of the leaf surface to water is called leaf wettability which is determined by measuring the drop contact angle (DCA, θ) (Marien et al., 2019; Muhammad et al., 2019). Water droplets on hydrophilic leaves spread out (small DCA, $\theta < 90°$), thus PM is easily deposited on the surface (Räsänen et al., 2013; Xu et al., 2019a; He et al., 2020a). For example, for *Tilia cordata* and *Acer campestre*, both hydrophilic species, deposited PM was almost double compared to *Platanus hispanica* (hydrophobic) (Dzierzanowski et al., 2011; Popek et al., 2013). Moreover, hydrosoluble air pollutants (e.g., SO_2 or NO_2) can be dissolved on the wet leaf surface, removing them from the air. Species belonging to the *Fabaceae* and *Caprifoliaceae* family have non-wettable leaf surfaces ($\theta > 130°$), resulting in a low particle accumulation on leaves (Muhammad et al., 2019).

Stomata distribution/ stomatal density

Leaves with high stomatal density[10] efficiently accumulate fine and ultra-fine PM fractions. Stomatal density was found to positively impact PM deposition on both adaxial and abaxial surfaces (Weerakkody et al., 2018). Various selected studies demonstrated particles deposited among the stoma, even, in some cases, with ultrafine particles were absorbed by the stoma (Räsänen et al., 2013; Song et al., 2015; Wang et al., 2015b; Chen L., 2017; Zhang et al., 2017). Therefore, a higher number of stomata per leaf area (mm^{-2}) has a greater impact on accumulating PM.

Stickiness/secretion

Secretion or honeydew has a significant ability to retain PM (Barima et al., 2014). Kardel et al. (2011) studied the effect of aphids, which are small insects that often excrete a sticky waste product called honeydew. This honeydew produces a sticky surface where PM can be trapped. Notably, however, this effect did not override the effect of trichomes and should be researched in considerable detail (Kardel et al., 2011). Nevertheless, this secretion can affect pedestrians on public sidewalks, since it causes slippery surfaces.

Adaxial and abaxial surfaces

Particles can be deposited on both sides of the leaf, adaxial (upper surface) and abaxial (lower surface); however, more particles were found on the adaxial surface (Weerakkody et al., 2017; Weerakkody et al., 2018; Abhijith & Kumar, 2020).

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[10] Stomatal density (stomata/mm^2) is a function of the number of stomata per unit area of a leaf plus the size of the epidermal cells.

Fine ($PM_{2.5}$) and coarse ($PM_{10-2.5}$) particles tend to accumulate mainly on the adaxial leaf surface, while large PM (>PM_{10}) are accumulated on the abaxial leaf surface (Mo et al., 2015). This difference could be explained by the orientation of the adaxial leaf surfaces, which are usually directly exposed to environmental conditions (e.g., wind), as well as the distribution of the trichomes on each side of the leaf surface (Xu et al., 2018; Muhammad et al., 2019).

3.3 Uncertainties surrounding estimates of leaf trait efficacy

The variety of methods (data collection, species, leaf number, leaf age, sampling site, sampling, time, and laboratory procedure) and a lack of information on airborne background concentrations used across the selected studies make it difficult to comparatively quantify deposition of PM on leaves. In addition, a variety of different plant and planting types, across and within studies, might contextually influence PM accumulation on leaves. This variability prevented a meta-analysis of this wide-ranging data. Despite this, the removal efficiencies of leaf traits and the maximum and minimum PM concentrations deposited on leaves per method were evaluated across the selected studies (Table 8). It is, however, necessary to caution that comparisons within or between measurement methods are not definitive, given the variation in design and conditions present across selected studies.

Table 8. The total mass of particulate matter accumulation as a function of noted leaf trait across different method.
(I caution the reader in interpreting these results, as a substantial variety of study designs and conditions are summarised). Source: Corada et al. (2021)

Leaf traits	**Type**	**Total mass of PM accumulated on leaves found across the selected studies (1)**								
		Gravimetric ($\mu g/m^2$)			**SEM (N/mm^2)**			**SIRM (Mean leaf SIRM x10^{-6} A)**		
		Min	**Max**	**N° of species studied**	**Min**	**Max**	**N° of species studied**	**Min**	**Max**	**N° of species studied**
Leaf surface	Trichomes	13	119	10	5.0E+4	2.45E+6	9	17	99	2
	Lack of trichomes	0.01	10	7	NR	NR	0	8	38	1
	Wax cover	26	57	5	1.1E+4	1.2E+7	3	40	40	1
	Lack of wax cover	12	16	3	NR	NR	0	NR	NR	0
	Roughness or wrinkle leaf	38	110	6	4.2E+5	1.95E+8	5	15	66	3
	Smooth leaf	7.5	32	5	4.7E+6	6.6E+7	2	NR	NR	0
Leaf shape	Cordate	7.5	55	9	3.0E+6	3.0E+6	1	28	76*	2
	Elliptic	9.2	58	8	2.5E+6	2.7E+7	2	NR	NR	0
	Linear	27	110	5	4.2E+5	6.1E+5	2	20	27	2
	Obovate	9.5	48	18	NR	NR	0	NR	NR	0
	Ovate	6.3	177	65	1.7E+3	2.0E+8	8	40	40	1
	Palmate	8	52	8	NR	NR	0	NR	NR	0
	Lanceolate	9.7	232	18	5.7E+5	1.2E+7	4	15	66	3
	Needle	52	154	5	5.5E+7	6.6E+7	2	17	17	1
Foliage (3)	Evergreen	52		33	3.0E+7		12	26		8
	Deciduous	71		108	2.0E+7		7	56*		3

NR = Not reported. / * Leaf reported with trichomes.

(1) The most common methods were selected. The minimum (min) and maximum (max) values of the total PM deposited on leaves is given. Details about the PM capture by different size fraction of PM is shown in Appendix B, Table 2. The unit of SEM is particles per unit leaf area (N/mm^2). The unit for SIRM is Mean leaf SIRM normalized by leaf area (x10^{-6} A).

3.4 The spatial and temporal context

The context of GI planting can potentially promote PM deposition. These external characteristics were mentioned by the authors of selected studies as extra variables that influenced PM deposition, evidencing the importance of the spatial context for particle deposition.

Location of green infrastructure

The amount of pollutants deposited rises with increasing ambient air pollution concentration (Popek et al., 2015; Abhijith & Kumar, 2020; He et al., 2020b). Leaves were noted to accumulate higher concentrations of PM when located close to the pollution source. Plantings close to heavy road traffic have a higher particulate deposition than those further away or in lower-traffic areas (Sternberg et al., 2010; Saebo et al., 2012; Barima et al., 2014; Weber et al., 2014; Sgrigna et al., 2015; Chaudhary & Rathore, 2018). This deposition depends on the type of GI, because trees can also accumulate a significant amount of PM 50m away from a busy road (Sgrigna et al., 2015). Nevertheless, differences in PM leaf depositions were also related to background pollution levels in the sampling sites (Barima et al., 2014).

Weather parameters

Deposition is strongly influenced by local weather parameters such as precipitation, wind speed, and, to a lesser extent, temperature.

○ Rainfall/wash off

Precipitation has an important role in deposition as wet deposition (Matzka & Maher, 1999). Rain droplets both capture (encapsulate) and wash particles from leaf surfaces, thus acting as a leaf cleaner (Matzka & Maher, 1999; Corada et al., 2021). Rain washes off between 28% to 70% of accumulated PM on a leaf, with the percentage depending on the leaf traits and the intensity of the rain (Przybysz et al., 2014; Wang et al., 2015a; Zhang et al., 2019b). Przybysz et al. (2014) found that between 30%–40% of the PM on the leaves of *Pinus sylvestris* was removed by 20mm of rainfall (Przybysz et al., 2014). Another study reported that 28% of PM was washed off leaves of *Ligustrum lucidum* (an evergreen tree) by 10mm of rainfall, though if this increases to 32mm, then 48% of PM was removed (Wang et al., 2015a).

Leaf traits such as a wax layer, trichomes and roughness (grooves) create different contact angles between a water droplet and the leaf surface, altering the amount of deposited particles and creating different water-repellent conditions (Wang et al., 2013). For example, prolonged and low-intensity rainfall is more effective in washing PM on a smooth surface, because there are no impediments between the leaf surface and water contact. On the contrary, short but high-intensity rainfall removes PM most efficiently on rough leaves (Zhang et al., 2019b). The PM removal efficiency of rain also varies by foliage. For deciduous leaves, rainfall removes between 51% and 70% of the PM deposited on leaves, while between 30% and 41% of PM is removed on needle leaves (Przybysz et al., 2014; Xu et al., 2017).

- Wind

A higher wind speed produces a higher impact rate, increasing deposition efficiency of coarse particles, and thus providing a greater deposition, however, it can also cause resuspension of deposited particles on leaves (Mori et al., 2018; He et al., 2020b). This parameter is more influential for other mechanisms, such as dispersion, more details in **Chapter 5**.

Seasonality

Temporary variations of PM accumulation were recorded throughout the year. A monthly variation of PM deposition on leaves was found, with higher concentrations during the winter, followed by autumn, monsoon, spring, and summer (Sasmita & Pramila, 2012; Wang et al., 2013; Chaudhary & Rathore, 2018).

Seasonal vegetation cycles (dormancy, greening and maturity) are characterised by the flowering pattern and emergence of new leaves (Grote et al., 2016). For annually deciduous species, the vegetation cycle has four phases: (i) greenup, bud burst, photosynthetic initiation and increasing leaf growth, (ii) maturity, stable, maximal plant leaf area, (iii) senescence, decrease in the green leaf area (though in species displaying marcescence, the leaf area itself can remain large while biological activity decreases), and (iv) latency, a period of low biological activity. For evergreen and marcescent deciduous species, LAI varies less with the seasons, as leaves are not shed in winter months. Nonetheless, these phases lead to seasonal variations in leaf area related to leaf maturity (Kardel et al., 2011) and thus to the area available for air pollutant deposition (Abhijith & Kumar, 2020).

Canopy height

Particulate matter leaf deposition decreased with increasing height (Hofman et al., 2013; Jin S., 2014; Weber et al., 2014), though this was not an effect identified on green walls, where height was observed as not influencing measured levels (Ottelé et al., 2010). Leaves closer to the ground are closer to traffic emission sources and are subject to less traffic-generated turbulence than leaves at 2m or higher, resulting in greater PM deposition. This means that the pollution impact zone on plants is concentrated in the first 2m from the ground

(Etyemezian et al., 2004). One field measurement found greater PM deposition at 0.6m than at 1.5m on the traffic-facing side of a hedge (Abhijith & Kumar, 2020). Similarly, another field study identified a higher particle concentration at 1.5m from the ground than at 3.0m; the total PM deposited on leaves at 3.0m was 44% lower than the deposition at 1.5m (Mori et al., 2018).

Green infrastructure type

Despite the variety of study designs, there was some notable variation in deposition characteristics between green walls and street tree planting (Weber et al., 2014; Yan et al., 2016b; Lin et al., 2017). The green roof was excluded from this analysis because there was not enough information about this GI and its effect on air quality.

Selecting only comparable SEM studies, there were more particles deposited per mm^2 on street tree leaves than on green walls (Yan et al., 2016b; Lin et al., 2017; Weerakkody et al., 2017; Weerakkody et al., 2018). Green walls, shrubby, sturdy plants such as *Juniperus chinensis*, *Berberis buxifolia,* and *Berberis x media*, presented higher PM levels than other plants (Weerakkody et al., 2018). The general ‘plant type’ used in different infrastructure influences both the quantity and the PM fraction retained. Street trees seem to retain coarse particulate matter more efficiently than green walls, while the diverse species composition of green walls may retain fine PM to a greater extent (Weerakkody et al., 2017; Weerakkody et al., 2018).

Small trees or hedges and shrubs in and along streets receive the most deposition due to their proximity to the highest concentration of pollutant sources (Gromke et al., 2016; Abhijith et al., 2017; Abhijith & Kumar, 2020). Small trees (about 2 - 4.5m in height) with small crown diameters have presented high PM_{10} removal efficiency along heavily-used open roads (Chen et al., 2015).

4 Discussion

The observed deposition of PM on leaves is linked to the measuring method, site, sampling strategy, and background concentration (Corada et al., 2021). Due to the variability of study designs within the selected studies, it was not possible to develop a meta-analysis. Nevertheless, the literature reviewed suggests that some leaf traits influence PM deposition. Rough, hairy, wax layer, and sticky surface leaves with large and dense stomas are the most effective leaf traits for accumulating PM, in contrast to smooth and hairless leaves. These leaf morphological characteristics have been also confirmed by recent scientific studies (Dang et al., 2022; Xu et al., 2022).

Evergreen conifers with needle leaves may be more effective in PM accumulation than broadleaved trees, due to their thicker epicuticular wax layer, complex foliage structure, and potential for accumulating pollutants throughout the year. Despite all the effort to find the best species and influential characteristics for maximising PM removal by GI, there is no strong evidence concerning the most effective leaf trait for capturing PM. So far, **leaf traits cannot be used as a decisive factor** in selecting species for urban planting. This study, however, confirms that some leaf traits, such as a high density of trichomes and coarse leaves, can influence the level of PM capture in urban areas (Table 9), and that in the street, the use of species with these characteristics should be encouraged to positively influence air quality.

Table 9. An overview of each identified leaf trait and the quality of the evidence reported to confirm the effectiveness of PM capture.
Source: Corada et al. (2021)

Leaf trait	Evidence	Level of confidence
Trichomes (leaf hairs)	Strong evidence. The majority of studies using the SEM technique confirm higher PM accumulation on leaves with a high density of trichomes.	High
Wax cover / Epicuticular wax / Leaf wettability	Strong evidence. Most SEM studies confirm higher PM accumulation in waxy leaves.	High
Roughness	Strong evidence. The roughness of surfaces is associated with the dry deposition efficiency of PM.	High
Leaf Wrinkles/ Ridge / Furrows/ Grooves	Strong evidence. Several studies confirm higher PM accumulation on coarse leaves.	High
Leaf size	Small leaf size is associated with a complex canopy which may capture more PM. Other studies observe that large leaf size provides a major surface for PM deposition.	Conflicting evidence
Leaf shape	Subtle differences between leaf shape classification.	Conflicting evidence
Conifers/Pine species	Evergreens and conifers may be more effective in PM accumulation than many deciduous species due to their thicker epicuticular waxes and their ability to accumulate PM throughout the year. But some deciduous species can also be effective PM accumulators.	Conflicting evidence
Stomata distribution / Stomal density	Only a few studies indicated the importance of stomata distribution in capturing PM.	Lack of evidence
Leaf area index (LAI)	The relationship between LAI and captured PM on leaves is not clear. A complex canopy decreases wind speed, thus increasing PM retention.	Lack of evidence
Secretion	Sticky leaf surfaces might capture and retain more PM than smooth leaves. There is a lack of studies to confirm this trait.	Lack of evidence
Adaxial surface	Each surface of the leaf has different structures and features. Some studies described PM accumulation on each side. More PM accumulation on the adaxial sides can be explained in terms of their orientation and PM exposure relative to abaxial leaf sides.	Lack of evidence

4.1 Methodological biases

The three methods used to measure particles on leaves bring advantages and disadvantages. The gravimetric method is both time-efficient and cost-effective, whereas SIRM is the opposite. Both quantify deposited particles, but gravimetric cannot measure the soluble PM fraction, while SIRM quantifies both insoluble and soluble PM fractions. The major problem with these methods is that they cannot identify the specific leaf traits of the leaf. The

SEM method, however, captures the ultrastructure of leaves visually, making it the best technique for identifying leaf traits. Leaf traits are plastic within species (Hulshof & Swenson, 2010), and variation can respond both to inheritance and environment. The great plasticity of plants can not only facilitate PM deposition, but also optimise its function in the face of prevailing changes in environmental conditions, such as climate change (Cui et al., 2020). Trait confirmation and analysis in each study would strengthen confidence in their conclusions, especially in studies which use the SEM method (Corada et al., 2021).

Sampling height, number of leaves sampled, and background concentrations were also notable sources of variation. The species examined were mainly selected haphazardly across the sampling sites, and the number of leaves sampled for laboratory tests varied with their leaf area density. This variable sampling design affects the replicability of any study and the weight of its findings. There may also be allometry (biological scaling) in trait performance as a function of the distance from pollution source, a variable known to reflect ambient concentration, though much influenced by wind speed and direction (Power & Collins, 2010). The most effective species for eliminating PM should not only be determined by the amount of PM that their leaves can capture. There should be an understanding of planting location, ambient concentrations, leaf exposure time to PM, seasonality, leaf height, and the intensity of meteorological parameters (for example, wind and precipitation).

The substantial variation found in the PM accumulation period, varying from a few days to years, contributes further to uncertainty. Short periods may be useful for locally comparative studies, but accumulation may reflect peaks or troughs in ambient concentrations that are less representative of long-term conditions. Long measurement periods may be advantageous for the analysis of PM deposition, as these can reflect the ‘typical’ accumulation over different seasons and weather.

4.2 Which leaf traits maximise particulate matter capture?

All the species studied in this review accumulated PM on their leaves, and some leaf micro- and macro-morphologies were found to influence this. Trichomes were the most frequently cited leaf surface trait associated with the capture of all sizes of PM and are considered particularly effective at trapping fine particles ($\leq PM_{2.5}$) (Ridge, 2002). Their specific abundance and distribution are considered very influential, and those that also have dense hairs on the adaxial surface are considered to capture PM more efficiently, in comparison with leaves that are glabrous (hairless) or have abaxial or lower density trichomes (Saebo et al., 2012; Chen L., 2017; Zhang et al., 2017).

A waxy leaf surface is another potentially important trait contributing to PM accumulation. In addition, species with secretion or honeydew provide a naturally sticky surface which increases the capture of particles, but this sugar-rich sticky liquid cannot override the effect of trichomes and should be researched in considerable detail (Kardel et al., 2011). A current study calculated that leaves retain ~55% of PM in the epicuticular wax after rigorous water washing (Shabnam et al., 2021). Particulate matter may be more enduringly adsorbed or buried in waxy coatings, and ultrafine PM may become fixed on the leaf surface (Hofman et al., 2014; Song et al., 2015). Although the presence of epicuticular wax has been identified as an efficient trait in capturing PM, the efficiency of the wax relates to its thickness and surface characteristics. The composition and structure of the wax may be the more influential features in PM accumulation than the quantity of wax itself. These wax structures and their specific chemical compositions affect the interfacial area and adhesion characteristics, thereby influencing the PM fraction and quantity captured (Wang et al., 2015a). However, the epicuticular wax layer on the adaxial (upper) surface could be eroded by captured PM in polluted areas, reducing the amount of deposited particles (Singh et al., 2017), thus, tolerant air pollution species should be selected to retard wax erosion.

Stomatal density is another leaf trait which can influence PM accumulation. Leaves with large and dense stomas are more efficient at accumulating fine and ultrafine PM fractions both between stomata and, in some cases, within stomal cavities (Räsänen et al., 2013; Song et al., 2015; Wang et al., 2015b; Chen L., 2017; Zhang et al., 2017).

Leaf microstructure surface traits, such as roughness, also influence PM capture. Leaves with rough, wrinkled, ridged or furrowed surfaces can capture and retain more coarse PM fractions (PM_{10}) in comparison with smooth and unwrinkled leaves (Blanusa et al., 2015; Leonard et al., 2016; Chaudhary & Rathore, 2018). A species' ability to accumulate PM increases with an increase in groove density and furrow/ridge width, but no studies independently confirm this (Liu et al., 2018). These leaf traits were also found and confirmed by recent studies on the retention of leaf particles (Dang et al., 2022).

The accumulation of PM can be maximised using specific leaf shapes and sizes. This research indicates that acicular (needle shape) leaf shapes and smaller leaves more effectively capture PM than other leaf shapes and large leaf sizes. Species with needle-shaped leaves probably capture more PM due to their larger canopy, which provides a larger surface area for the PM to settle on (Chen L., 2017). This picture is not always clear, as needle-leaved species may be more sensitive to increased traffic since their leaf wax is more susceptible to corrosion; this means that the relative amount of PM captured may be small (He et al., 2020b; Corada et al., 2021; Jia et al., 2021b).

Some general patterns emerge despite sampling biases (see above) and context (see below). A selection of six studies employing the gravimetric method, as described in detail by Dzierzanowski et al. (2011), and which consider more than five species, each indicate traits that affect the amount of PM accumulated on leaves (Figure 24).

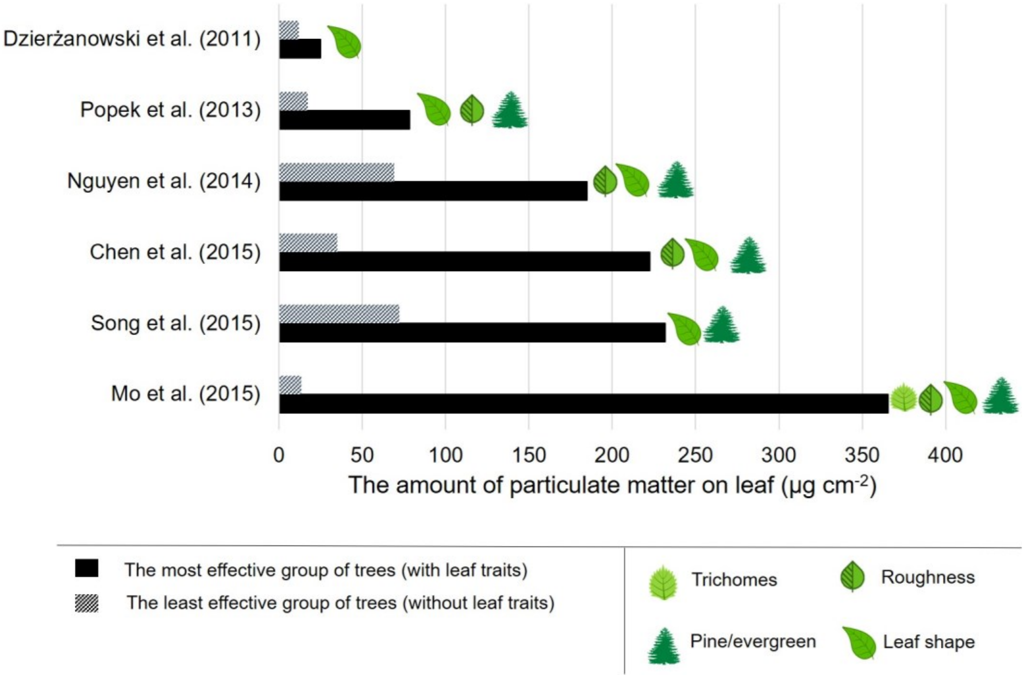

Figure 24. Leaf traits considered to influence particulate matter deposition. The data arise from comparative articles which used the gravimetric method to measure PM on leaves. Black bars (■) show deposition on street trees with the indicated leaf traits (trichomes, evergreen leaf, roughness of leaf and leaf shape (needle, ovate or lanceolate), the lighter bars (▨)show street trees without these leaf traits. Source: Corada et al. (2021)

4.3 The influence of spatio-temporal context

Location and distance of the vegetation from a polluted source are crucial points for analysing whether PM is deposited on the leaves due to their leaf traits or their proximity to pollutant sources. In most cases, placing GI as close as possible to the pollutant sources (e.g., busy roads) acts to mitigate the dispersal of particles both through airflow management and direct capture. As PM deposition is proportional to ambient concentration, the PM deposition rate is greater in GI close to roads. Although all GI types can usefully capture PM, street trees might be more effective at capturing larger PM fractions (Popek et al., 2015), while green walls, with their diverse species compositions, might effectively capture fine and ultrafine sized particles (Sternberg et al., 2010; Weerakkody et al., 2018). In addition, PM concentration increases when GI, especially trees, is planted along the streets since air circulation is reduced (Salmond et al., 2013). More turbulent mixing of the air is caused by tree species with large leaf surface areas in comparison to climbing vegetation (green walls), and PM is thus given enough time and opportunities for deposition onto the leaf (Beckett et al., 2000). However, this reduction in airflow may stagnate air pollutants, increasing pollutant concentrations at a pedestrian level; more details are provided in **Chapter 5**.

The season of sampling may affect the amount of PM observed on a leaf surface. Deposited PM may be incorporated into epicuticular wax layers during early leaf development, enhancing capture and retention; new leaves also present a new surface where particles may be deposited. That is why in spring there has been a greater retention of particles in tree species (Zhou et al., 2020). In addition, weather parameters such as rain and wind could wash off or blow particles off of leaf surfaces. Precipitation, which principally acts on the adaxial surface of leaves, removes a high proportion of deposited large and coarse PM, while fine PM may be better retained in the waxes (Zampieri et al., 2013; Wang et al., 2015a). This leaf washing does not immediately re-release PM, and the subsequent fate of PM falling from leaves in this way requires further study. This does, though, suggest that considering typical local weather parameters, such as rain, could act synergistically with leaf traits in influencing the choice of leaf traits for specific places.

4.4 The influence of green infrastructure type in the capture of particulate matter

All of the GI studies in this literature review capture different PM concentrations. Trees remove more particles than other GI, but this is probably due to the number of tree-related studies compared to other GI. For example, the only green roof study included here identified that grasses (e.g. *Agrostis stolonifera* and *Festuca rubra*) are more effective at PM_{10} capture than trees per unit of leaf area (Currie & Bass, 2008; Speak et al., 2012). Green roofs could affect the reduction of PM capture in the streets. The shape of a roof affects the wind direction inside streets, which could increase PM concentrations (Kastner-Klein et al., 2004; Baik et al., 2012). Furthermore, green roofs have other benefits, such as cooling buildings and surrounding streets. This cooling effect can decrease average pollutant concentrations at the pedestrian level by increasing the temperature gradient (Baik et al., 2012). Further work is required to investigate the effect of green roof configurations in capturing PM and to adequately evaluate the relative impact of this different GI.

Street trees and small trees (shrubs) are the most studied GI regarding their influence on urban air quality. Broadleaves, evergreens, conifers, and shrub species were the most cited, evidencing that conifer species with needle-shaped leaves may capture more PM than broadleaved species. The main reason is that needle-shaped species create a complex canopy structure which decreases wind speed, increasing PM retention (Gao et al., 2015). For trees, it is not only leaf traits that aid PM removal, but also the three-dimensional structure that may influence levels of PM removal. Trunks and branches can also capture PM and variety of chemical elements (e.g., Ni, Pb, Zn, Al, Si, Ca) on their surfaces (Chaparro et al., 2020). The roughness of these surfaces increases the contact area with pollutants, potentially influencing PM removal, especially of large particles (>10 μm) (Xu et al., 2019b). However, further research is needed that considers the entire vegetative tree structure as a sink for particles.

Green walls may capture more fine particles than street trees. This may be due to the absence of gaps in some green wall designs (in comparison with a row of trees), their distance from the source of pollution, and the nature of airflow over their largely vertical surface.

The great benefit of green walls over trees is that green walls can be used when urban space is scarce (Tomson et al., 2021). In addition, the multiple designs that can be created and the different types of species that can be used with this GI make it a highly recommended more sustainable solution for urban areas; this is not only to capture pollutants, but also to obtain other benefits, such as a reduction of urban temperatures, a reduction of noise, and improvements to the temperatures of buildings (Medl et al., 2017).

4.5 Ecological effect of particles on leaves

Although PM deposition may improve air quality, deposited particles on leaves induce damage and physicochemical changes. The black colour of particles causes shading, thus reducing the utilisation of light and prompting a decline in photosynthetic activity (Sett, 2017; Shabnam et al., 2021). The alkaline compounds of PM are also responsible for reduced photosynthetic activity and chlorophyll degradation (Sett, 2017). These compounds cause an increase in the pH of the leaf, changing the lipid and waxy components of the leaf (Rai, 2016). Particulate matter and its elemental composition cause wax degradation, a reduction of the foliar area and leaf numbers, and stomata clogging, resulting in an alteration of PM retention capacity and air exchange (Burkhardt & Pariyar, 2014; Sett, 2017). In conclusion, the effect of PM on leaves causes leaf chlorosis, defoliation, chronic injuries, and in cases of high PM exposure, necrosis (Rai, 2016). Evaluating the morphological and biochemical changes in plants upon exposure to PM is an important step in classifying species according to their Air Pollution Tolerance Index (APTI)[11] and stress tolerance in order to guarantee the survival of the species in the streets.

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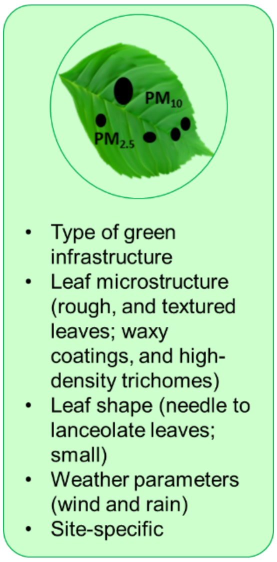
[11] The Air Pollution Tolerance Index is an indicator which describes the plant’s ability to tolerate air pollution.

5 Conclusions

Coniferous, small, rough, and textured leaves, needle and lanceolate shapes, waxy coatings, and high-density trichomes have been promoted as useful traits for maximising PM capture (Figure 25); traits which are also associated with drought tolerance. Although effective leaf traits have been identified, there is no strong evidence to identify which is the most influential leaf trait for capturing PM. Thus, **leaf traits should not be used in the primary selection of species in urban planting,** as performance depends on the spatio-temporal context. In this sense, the location of GI is an ancillary determinant factor that can influence the amount of deposited particles on leaves, since higher PM concentrations have been observed on leaf samples closer to the traffic source compared with those far away from roads.

Diverse sampling methods, wide comparison groups and a lack of background PM concentration measures were common study limitations. Further research into the structural features of vegetation as well as **standardisation of the method for measuring PM on leaves is needed**. There is an opportunity in this field to develop standardisation of sampling methodologies and to develop standardised assays to quantify the effective proportion of PM that might be removed through the action of specific leaf traits. It is currently difficult to conclude either the relative effectiveness or the absolute efficacy of leaf traits when the methodologies of sampling and estimation vary and potentially confounding measures such as background particulate density are not measured. Because of this lack of available quantification and standardisation, leaf traits cannot currently be used as a primary focus when designing plantings to mitigate air pollution. Further investigation into the role of GI as 'particle sinks' is needed.



- Type of green infrastructure
- Leaf microstructure (rough, and textured leaves; waxy coatings, and high-density trichomes)
- Leaf shape (needle to lanceolate leaves; small)
- Weather parameters (wind and rain)
- Site-specific

Figure 25. Summary of the GI characteristics and spatio-temporal context promoted to maximise deposition.

Chapter 4. Absorption and Biogenic Emissions: The natural processes of vegetation that influence air quality

This Chapter

- Explains the green infrastructure characteristics that influence the absorption of pollutants.
- Explains the green infrastructure characteristics that influence the emission of biogenic gases and particles.
- Explains the spatial and temporal contexts that affect absorption and biogenic emission.
- Discusses biogenic emissions, such as pollen and Biogenic Volatile Organic Compounds, and their influence on air quality.

1 Introduction

Previous chapters have examined a range of environmental benefits that green infrastructure (GI) offers. Nevertheless, these benefits or ecosystem services (ES) are accompanied by potential disservices (EDS) that may negatively influence urban air quality.

The improvement of air quality, through direct deposition of particles (**Chapter 3**) or through absorbing gases and fine and ultrafine particles through the stomata, is one of the ES provided by GI (Coutts & Hahn, 2015). On the other hand, deterioration of air quality from biogenic emissions, released as part of the natural functions of vegetation or caused by the deliberate manipulation of anthropogenic actions, are considerable EDS that may negatively impact on human well-being (Blanco et al., 2019). Plants naturally emit a wide range of gases, commonly termed Biogenic Volatile Organic Compounds (BVOC) and Biogenic Particulate Matter (BPM). Knowledge of the spatial and temporal context, along with the intrinsic macro- and micro-morphologies of the species, are necessary to determine the extent and balance of these positive and negative effects of GI (Escobedo et al., 2011).

This chapter reviews the positive and negative impacts of GI within the range of gaseous and particulate absorbing and emitting mechanisms. First, the literature review methodology is described. Second, the results of this review are presented in two parts; one is dedicated to describing characteristics that influence absorption, and the second part details the characteristics that influence biogenic emissions. Third, the GI characteristics that should be considered in urban planting to maximise air quality improvement are discussed, and finally, the main findings and their implications for urban planting are discussed.

2 Method

2.1 Literature review

Two separate critical reviews[12] were conducted for each mechanism: absorption and biogenic emissions. A critical review aims to critique and bring together the literature on a research topic to develop new theoretical frameworks and synthesise perspectives (Grant & Booth, 2009; Snyder, 2019). Database selection, search strategy and procedure were followed according to Atkinson and Cipriani (2018) and Cooper et al. (2018). Four phases were followed to select the articles.

Phase 1: Identification and search strategy

The review of each mechanism had separate sets of key terms, but overlapping terms, related to green infrastructure, urban setting, outdoor air pollution, pollutant, and urban planning, were included in both searches (Table 10).

Articles published between 1980 and 2021 in English-language journals were searched in ScienceDirect, Scopus, Web of Science and Google Scholar. Search terms and synonyms were specified using Boolean search methods to identify candidate articles.

Table 10. Search terms and term combinations used in this critical literature review.

Common search terms	
‘green infrastructure’ OR ‘vegetation’ AND ‘urban setting’ OR (city OR street) AND ‘outdoor air pollution’ AND ‘pollutants’ AND ‘urban planning’ AND ‘emission’/ ‘absorption’ (depending on the literature review)	
Main key term	**Synonyms**
Green infrastructure	Trees OR green walls (living walls) OR green roof OR shrubs OR hedges OR plant OR species OR vegetation OR urban vegetation OR deciduous OR evergreen
Urban setting	City OR street OR canyon street OR open road
Outdoor air pollution	Air pollution OR air quality
Pollutants	Atmospheric pollutants OR particulate matter OR PM OR PM_{10} OR $PM_{2.5}$ OR gaseous pollutants OR nitrogen dioxide OR ozone AND NOT carbon dioxide AND NOT CO_2
Urban planning	Urban planting AND NOT climate change AND NOT urban heat island
Specific research term per mechanism	
Emission	Disservices OR BVOC OR biogenic volatile organic compounds OR isoprene OR monoterpene OR pollen OR plant emissions OR allergens
Absorption	Uptake AND gases AND NOT CO_2 absorption OR sequestration

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[12] Chapters 4 and 5 follow a different literature review to Chapter 3. The systematic literature review is the most widely used literature review, however, literature reviews differ according to the research purpose. The goal of Chapter 3 was to develop a meta-analysis, but due to inconsistent method designs and the multiple variables affecting deposition, it was impossible to perform statistical analysis. Therefore, a critical literature review was selected for these chapters. The critical review aims to evaluate the extensively researched literature and critically appraise its quality. This review not only describes the selected studies but also includes analysis and conceptual approaches, identifying the most significant aspects in the field that usually end up in a model or graphical representation, providing a completely new interpretation of existing data.

Phase 2: Screening

Initial screening was based on title and abstract; if the title indicated that the article might be admissible, then the abstract was reviewed to determine whether it should be considered. Duplicate, non-peer-reviewed journal papers and articles not related to the eligibility criteria were removed.

Phase 3: Eligibility

Articles were considered eligible for each review if they: 1) focused on urban environments at street level with an interest in pedestrian well-being; 2) studied specific GI characteristics; and 3) considered their influence on urban air quality. Outdoor field experiments and indoor experiments were included. Articles based on climate change, thermal regulation, indoor pollution, and/or CO_2 uptake by GI were excluded.

The selected articles had to evaluate at least one GI characteristic relevant to air pollution, for instance, plant characteristics such as species, macro- and micro-morphologies, or characterisation in urban design, such as height, vegetation density, dimensions, and location. Articles categorised as reviews and focused on mitigating ambient pollutants were selected.

Phase 4: Inclusion

The articles that met the eligibility criteria were tabulated in Excel™ for later detailed reading and data extraction concerning the GI characteristics (intrinsic) and the spatio-temporal context (extrinsic) that influence the absorption and emission of biogenic particles and gases. Publication year, research aims, method, sampling area, studied species or GI type, the amount of pollutant removal by species (if mentioned), and characteristics addressed were extracted for each selected article.

An additional column was added next to the intrinsic and extrinsic characteristics to justify the selection of the characteristics and the manner in which it influenced the mechanism (accumulate pollutants, alter absorption, increase emissions). Once all characteristics were tabulated and justified, they were further grouped under common names and concepts (e.g., species, particle size, weather parameters, leaf traits, type of pollutants, LAD, and vegetation cover). Each characteristic was studied to understand how and to what extent it could influence air quality.

3 Results

3.1 General information

An initial screening of 146 articles led to 48 articles being selected for this study (See Appendix C, Figure 1). Thirty-five articles were found for biogenic emissions: 19 provided information on BVOC emissions, and 16 on emissions of pollen grains. Thirteen articles were included for absorption, and one study presented information for both mechanisms.

3.1.1 Source geography

The assessed studies mainly came from European countries (n = 18), with Spain being the country with the most articles studied related to pollen emissions (n = 9), and from Asian countries (n = 7). Out of 48 selected studies, 18 were literature reviews or indoor experiments that did not identify countries or geographical zones (See Appendix C, Figure 2).

3.1.2 Study designs

The sampling period varied widely among the selected studies. Sampling periods ranged from a day to several years. Absorption studies varied from a couple of days to a few months. Biogenic VOC studies varied from some days to year-round (Chen et al., 2020). The majority of the pollen studies were carried out for several years, from three to eight years (Gonzalez & Candau, 1997; Damialis et al., 2005; Emberlin et al., 2007; Fernández-Rodríguez et al., 2014). This large sampling data was usually obtained from monitored networks at the sampling site to analyse pollen seasons, their concentrations, and changes over the years.

All the selected studies used plants when their leaves were practically fully developed. The number of plant species, however, varied among the selected studies. Trees were the most common GI studied in urban areas, although a few studies included herbs, shrubs, and vines (Sternberg et al., 2010; Bracho-Nunez et al., 2011). The most comprehensive selected study sampled 70 species (35 native and 35 alien species) (Llusià et al., 2010).

The methods used varied according to the mechanism studied, but field studies (n = 27) dominated, followed by reviews (n = 17) and indoor experiments (n = 4). Absorption studies used passive samplers (n=2), indoor chambers (n=2), isotopic technique (n=1), and flux measurements (n = 1). Biogenic emissions studies used different methods depending on the emission, pollen or gases. Volumetric traps (n = 11) were standard devices for measuring pollen; additionally, two studies used a mapping technique to create a land cover map of the allergenic species (McInnes et al., 2017; Bogawski et al., 2019). Biogenic VOC emissions were measured using enclosure techniques or a chamber system (n = 10), and one study used the i-Tree software (Baraldi et al., 2019) (See Appendix C, Table 1).

3.2 Plant absorption

Plant absorption is influenced by intrinsic features (e.g., taxonomy and growth), called **GI characteristics,** and extrinsic features that can either be biotic or abiotic and are called **spatio and temporal context.** The characteristics that influence absorption are described below.

3.2.1 Green infrastructure characteristics

Type of species/foliage

From the literature so far, there is no clear emergent pattern of the effect of deciduous or evergreen species on pollutant absorption. Wang et al. (2012) studied O_3 uptake in six urban species in Beijing for almost a year, finding that overall, the annual uptake by deciduous foliage (e.g., *Ginkgo biloba, Aesculus chinensis, Magnolia liliiflora, Robinia pseudoacacia*) was similar to that of evergreen species (e.g., *Pinus tabulaeformis, Cedrus deodara*) (Wang et al., 2012). Conversely, Wieser et al. (2003), when studying the O_3 uptake of tree species in Austria for seven months (April to October), found that evergreen conifer foliage (*Picea abies, Pinus cembra*) absorbed more than a deciduous conifer species (*Larix decidua*), possibly due to differences in leaf area index, stomatal behaviour, and canopy structure (Wieser et al., 2003). However, as evergreen species have their leaves all year round, they could absorb pollutants throughout the year.

Stomata-mediated gas exchange

The absorption of pollutants is regulated mainly by stomata and the biological susceptibility of the plant to pollutants (Khan & Abbasi, 2000; Omasa et al., 2002). Stomata are tiny, leaf-surface pores that control foliar temperature and the exchange of water and gases between the internal spaces of the leaf and the atmosphere (Cieslik et al., 2009; Smith et al., 2010).

The stomatal conductance (transport of water vapour and other gasses through the stoma) is regulated by the stomatal aperture (opening size), which is, in turn, influenced by water, CO_2, and air pollutant concentrations, temperature, humidity, light intensity, and photosynthetically active radiation (PAR) (Hosker & Lindberg, 1982; Khan & Abbasi, 2000; Cieslik et al., 2009; Wang et al., 2012; Gupta, 2016). The stomatal density of a leaf also influences pollutant absorption, species with high densities are more efficient absorbers (Baraldi et al., 2018; Delian, 2020).

Vegetation surface area, leaf area density/leaf area index

A positive relationship exists between canopy volume and pollutant uptake because a greater leaf area leads to greater absorption capacity (Simonich & Hites, 1995). The canopy structure influences air flow, with a dense canopy leading to lower turbulence and increasing the residence time of air pollutants and favouring specific chemical reactions and, thus, some pollutant absorption. For example, in Baltimore, USA, O_3 concentrations were decreased by increasing the canopy cover percentage within a 50m radius of the sampling point; NO_2, on the other hand, did not vary significantly between different canopy covers (Yli-Pelkonen et al., 2017). This may be explained by photochemical reactions between NOx and O_3 (3). Nitrogen oxide (NO) released by soils or nearby pollutant sources (e.g., traffic) would rapidly be oxidised by O_3 inside the canopy to form NO_2. NO_2 photolysis[13] occurs at $\lambda<424$ nm as long as the canopy allows entry of that sunlight wavelength; otherwise, NO_2 remains or is absorbed by the plant. Therefore, depending on the sensitivity of the species to absorbing NOx, their canopy and NO_2 concentrations, species may act either as NO_2 removers or as indirect sources of NO_2 (Harris & Manning, 2010). More explanation about this reaction between NOx-O_3 and GI is explained below in the BVOC section, Section 3.3.1 of this Chapter.

$$\begin{gathered} O_3 + NO \rightarrow NO_2 + O_2 \\ NO_2 + \lambda\nu\,(< 424\,nm) \rightarrow NO + O \\ O + O_2 \rightarrow O_3 \end{gathered} \tag{3}$$

Bonn et al. (2016) quantified urban land cover types on levels of different pollutants in Berlin, Germany. They demonstrated that O_3 levels were lowest near coniferous, followed by deciduous and mixed species. However, they caution that this does not imply that increasing tree cover would reduce O_3 levels. While O_3 levels near large stands of urban trees may be reduced through absorption of O_3, biogenic emissions from these species can be transported elsewhere in a city and produce O_3 through a reaction with NOx (see below Section 3.3.1) (Bonn et al., 2016).

3.2.2 The spatial and temporal context

Pollutant identity and chemical properties

The chemical properties of pollutants, such as their solubility, lipophilicity, reactivity, size, density, and elemental composition, affect absorption by leaves due to interactions between gasses and the leaf surface (Hosker & Lindberg, 1982; Simonich & Hites, 1995). Nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) are, for example, water-soluble, so these may enter

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[13] Photolysis is a chemical reaction in which molecules are broken down into smaller molecules in presence of sunlight.

as gasses or dissolve into a water film on the plant surface before entering the stoma (Grote et al., 2016). Fowler et al. (2009) describe the interaction between vegetation-atmosphere as mainly controlling absorption (and deposition rate). This process is regulated by chemical reactions in a thin film of moisture on the leaf (Fowler et al., 2009). These chemical reactions change the pH of the leaf surface and may reduce leaf surface integrity, altering the absorption of pollutants, specifically SO_2 (Winner & Atkinson, 1986).

The absorption also depends on the sensitivity and tolerance of each plant species to absorbing pollutants. For example, *Populus* (poplar) species have a greater tolerance to moderate concentrations of SO_2, as they can decrease its absorption by closing their stomata. Conversely, needles of *Pinus* (pine) species can be damaged by absorption of SO_2, presenting a high sensitivity to this pollutant (Linzon, 1972).

The chemical reactions on a leaf are associated with its micromorphologies, such as wax content and wettability capacity. A study on the uptake of polycyclic aromatic hydrocarbons (PAHs) by different species demonstrated that leaf surface morphology, specifically the cuticular wax micro-structure, such as dense wax structure, initially accumulated more PAHs on the epicuticular wax and then diffused into the inner tissue (Li et al., 2017). However, further research is needed to confirm the effect of different leaf traits on pollutant absorption.

Weather parameters

Temperature and water availability both affect the absorption of different gaseous pollutants. Extreme variations in temperature cause a reduction in the photosynthetic rate due to its direct effects on the enzymatic phase of photosynthesis, leading to less absorption capacity (Cieslik et al., 2009; Delian, 2020).

It is necessary to clarify that not all plants have the same tolerance to pollutants. Under different environmental conditions, they open or close their stomata, firstly to regulate their photosynthesis, which in polluted areas is also linked to the absorption (or lack thereof) of pollutants, such as NOx. For example, a chamber experiment to study the absorption of a *Juniperus conferta* (a typical hanging and wall-mounted plant on buildings) showed that as temperature and light increased (from 10 to 40°C), stomatal conductance decreased (closed stoma), as did NOx absorption (Fujii et al., 2005). The cited study did not explain why this phenomenon occurred, though it may be due to changes in anatomical variables. When temperature and light increase, photosynthesis increases, but at more than 40°C, the enzymes that catalyse photosynthesis begin to denature, decreasing the absorption rate (Moore et al., 2021).

High water availability, conversely, might increase O_3 uptake (Wang et al., 2012), and when water is scarce (drought), plants close their stomata to reduce water use, thus reducing pollutant absorption (Cieslik et al., 2009).

Given the complexity of the interaction between environmental parameters and the morphological, ecological and physiological characteristics of a plant, simplifications and generalisations about the absorption susceptibility of GI should be read with caution.

3.3 Plant emissions

The intrinsic and extrinsic characteristics that influence biogenic emissions are described below. First, the influenced characteristics of BVOC emissions are described, followed by those of biogenic particles (pollen).

3.3.1 Biogenic Volatile Organic Compounds

Biogenic VOCs are a varied group of chemical compounds released by plants into the air. These compounds are byproducts of physiological activities, some BVOC are synthesised inside the chloroplasts[14] associated with photosynthesis, while others are produced as a defence against stressors (Cieslik et al., 2009). Global BVOC emissions have been estimated at around 800 - 500 Tg C year^{-1} (Fowler et al., 2009; Pacifico et al., 2009). Isoprene (C_5H_8) is the most significant contributor, contributing around 440 to 660 Tg C year^{-1} (Guenther et al., 2006); followed by monoterpenes contributing 10 - 15% of the total BVOC; and sesquiterpenes are released in small amounts by vegetation. Plants also emit oxygenated volatile compounds, including alcohols, aldehydes, and ketones, particularly during plant development or in response to environmental stress (Fowler et al., 2009). See Appendix A, Table 3 for some example structures of BVOC.

These biogenic compounds play an important role in atmospheric chemistry as they participate in several reactions producing tropospheric O_3 (See equation 3 above) (For more information, see **Chapter 2**, Section 5.3.1). As explained previously, in urban environments, NO is rapidly oxidised by O_3 to form NO_2. However, in close proximity to large NO sources, such as busy roads, the supply of O_3 may be rapidly exhausted, so that a large proportion of the NO is left unoxidised, leading to high levels of this pollutant in these areas (Honour et al., 2009). In these polluted areas with vegetation, an additional reaction occurs. Like vehicles, GI emits volatile organic compounds (VOC), which react with NOx in the presence of sunlight to form O_3. Consider isoprene as the representative compound of BVOC. Isoprene, which has

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[14] Chloroplasts are plant cell organelles that convert light energy into stable chemical energy via photosynthesis.

a short life (1 - 2h), is oxidised during the day by the hydroxyl radical (•OH) to generate various carbonyl (oxygenated) compounds (ROx). These ROx compounds interact with the reaction of NOx to generate more tropospheric O_3 (Figure 26). These reactions are not sequential and exclusive, so BVOC, NOx and O_3 can react with other pollutants in the atmosphere, increasing the level of other pollutants in the area. For this reason, understanding what intrinsic or extrinsic characteristics influence the emission of these biogenic gases could help reduce or control them to avoid increasing pollutant levels. These characteristics are described below.

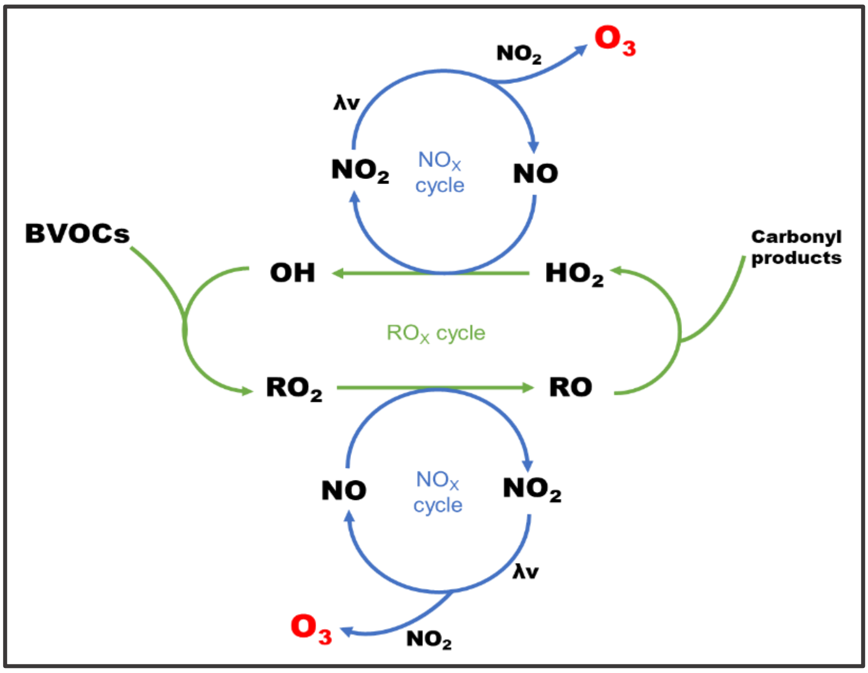

Figure 26. Schematic representation of the photochemical formation of tropospheric ozone in the presence of NOx and BVOC.
Source: Own elaboration

3.3.1.1 Green Infrastructure characteristics

Taxonomic and origin patterns

Biogenic VOC emission is species-dependent, with some indications that alien (or exotic) species may emit greater concentrations than native ones in some regions (Calfapietra et al., 2013; Prendez et al., 2013; Chen et al., 2020). A comparison of exotic and native species in Chile indicated that the alien species, *Robinia pseudoacacia* and *Betula pendula,* emitted more isoprene than native Chilean species (e.g., *Maytenus boaria* and *Acacia caven)* (Prendez et al., 2013). Similarly, emissions of exotic species were found to be double that of native species in Hawaii, USA (Llusià et al., 2010). Protection against the biotic and abiotic stressors of non-native environments or adaptation mechanisms promoting survival in these environments may be among the reasons for these high BVOC emissions (Llusià et al., 2010; Prendez et al., 2013).

There are also taxonomic patterns in BVOC emission. Broadleaved species often used in European urban environments, such as *Populus* and *Salix,* emit isoprene, while conifers generally emit a range of monoterpenes and sesquiterpenes (Steinbrecher et al., 2009; Matsunaga et al., 2013; Yuan et al., 2020). Seasonal variation has been suggested as responsible for this diversity in BVOC compound emissions between species (Kim, 2001; Matsunaga et al., 2013).

Growth stage and leaf ontogeny

The rate of BVOC emission varies with the growth stage of the plant and its leaf maturity, presenting a robust seasonal pattern: BVOC emissions increase (e.g., isoprene and monoterpenes) from spring to summer, falling to a minimum level during winter (Matsunaga et al., 2013; Chen et al., 2020). Each season is characterised by distinct weather conditions, ecological change (bud break, resin duct, leaf age, surface wetness) and patterns of daylight hours. For example, spring is the season for phenological effects, such as bud elongation and sprouting, so during this season and summer, higher monoterpene emissions are produced compared with autumn and winter, when senescence of leaves and physiological dormancy is typical (Kim, 2001; Kim et al., 2005).

Biogenic VOC emissions are associated with the age of the tree (GI) as it grows. Saplings of a seven-year-old slash pine (*Pinus elliottii*) emit approximately seven times less monoterpene than four-year-old pines in similar environments (Kim, 2001). However, the pattern differs when older species are compared; for example, the total emission of *P. elliottii* was higher in 60-year-old trees than in those 20-years old (Kim et al., 2005). This could be attributed to differences in the biological metabolisms of species and weather parameters.

At the shorter time scales of leaves, emissions from young leaves are higher than those from mature leaves in almost all plant species (Bracho-Nunez et al., 2011; Churkina et al., 2015; Li et al., 2021). There is no obvious explanation for this emission difference, but as isoprene synthesis is related to photosynthesis (Pacifico et al., 2009), young leaves and species tend to assimilate this metabolic process faster than mature leaves, emitting more isoprene. This life stage as well as temporal patterns, require further investigation that may reflect species-specific patterns interacting with environmental conditions.

3.3.1.2 The spatial and temporal context

Plant damage and pruning

In general, any biological or mechanical damage (e.g., pruning or herbivory) can cause elevated BVOC emissions (Kim, 2001; Holopainen & Gershenzon, 2010; Ameye et al., 2018). For example, on silver birch and black alder saplings, aphid infestation increases some BVOC emissions; this is a semiochemical response by the plant to the presence of a biological stress factor, influencing the behaviour of neighbouring plants, other herbivores, and their enemies. So, herbivores, for example, will move to another plant to avoid the defensive chemical response. Biogenic VOC emissions can thus act as a defence function against herbivore attack, as demonstrated by the damaged leaves of the lima bean (*Phaseolus lunatus*), which emit biogenic compounds, reducing the attack rate of herbivorous enemies (Holopainen & Gershenzon, 2010).

Plants also respond to mechanical damage and other stresses by emitting semiochemical BVOC (Holopainen & Gershenzon, 2010; Ameye et al., 2018). Wounding through pruning activities, such as hedge trimming, is functionally analogous to mechanical damage from herbivory, and plants respond similarly. Green leaf volatiles (GLV) compromise a group within the BVOC. The release of GLV is caused by mechanical damage, herbivory, fungal or bacterial infection and also as a consequence of abiotic stress, such as drought, heat and excessive light. The amount of GLV released depends on the type and intensity of the (a)biotic stress (Ameye et al., 2018). Although the substantial body of literature regarding the chemical ecology of plants falls outside the scope of this research, a useful meta-analysis by Ameye et al. (2018) and an editorial by Kessler (2018) shed much light on the area. Further research, however, is required to provide evidence of the influence of biogenic emissions on the air pollution field.

Weather parameters and seasonal influences

There is substantial evidence that BVOC emission levels are positively correlated with temperature (Harley et al., 1999; Kesselmeier & Staudt, 1999; Kim et al., 2005; Yuan et al., 2009; Holopainen & Gershenzon, 2010; Llusià et al., 2010; Loreto & Schnitzler, 2010; Calfapietra et al., 2013; Churkina et al., 2015; Chen et al., 2020). Temperature influences the enzymatic activity that catalyses the synthesis of BVOC associated with photosynthesis (e.g., isoprene synthase) (Niinemets et al., 1999; Loreto & Schnitzler, 2010). This also suggests the possible role of BVOC as a temperature stress reliever (Harley et al., 1999). Data from Beijing, China, and Rome, Italy, indicate that BVOC emission rates peak in late spring and during summer for evergreen broadleaves, evergreen conifers, and deciduous broadleaves (Calfapietra et al., 2013; Chen et al., 2020).

Some species are more sensitive to environmental temperature conditions, regardless of seasonal physiological variables. For example, the BVOC measurement of two species from the same *Pinaceae* family, *Pinus elliottii* (slash pine) and *Pinus taeda* (loblolly pine), revealed that *Pinus elliotti* emissions were strongly correlated with the temperature rather than seasons, in contrast, compared with *Pinus taeda* (Kim, 2001).

A substantial review of plant stress and BVOC emissions found that extreme environmental conditions such as drought or high soil salinity and (a)biotic stress can affect plant function and increase BVOC emissions, through potential alterations in C-metabolism (Loreto & Schnitzler, 2010; Ameye et al., 2018). Conversely, chronic or prolonged drought stress - associated with high temperatures - can subsequently reduce BVOC emissions, affecting stomatal behaviour and photosynthesis (Loreto & Schnitzler, 2010).

Ambient CO_2 concentrations

Vegetation (e.g., trees) acts as a sink for CO_2 by fixing carbon during photosynthesis. Large trees, for example, tend to store more CO_2 from the atmosphere as well as evergreen trees (Coskun Hepcan & Hepcan, 2018). However, evergreen species, such as shrubs, despite having lower CO_2 storage abilities than deciduous species, contribute to reducing CO_2 by storing carbon throughout the year (Baraldi et al., 2019).

Local CO_2 concentration is reflected in plant carbon fixation and sequestration rates, and thus in the carbon available to produce BVOC (Yuan et al., 2009; Lahr et al., 2015). A range of plant species has been seen to inhibit isoprene biosynthesis at higher ambient CO_2 concentrations, possibly due to specific enzyme inhibition (Loreto et al., 2001; Wilkinson et al., 2009; Lahr et al., 2015). The plant response to higher CO_2 levels, however, depends on the species and, with it, the type of BVOC released. For example, an evergreen *Quercus ilex* (oak) reduced monoterpene production under high CO_2 concentrations, possibly as a result of inhibited monoterpene synthases, but the emission of another BVOC compound, limonene, was enhanced under these conditions, corresponding to increased limonene synthase activity (Yuan et al., 2009). The absorption and fixation of CO_2 depend on the life cycle of the species and surrounding conditions, which may affect BVOC emission. The net effect of these interactions on air quality is often subtle and may depend on individual or population sensitivity to different compounds and ratios.

Although CO_2 fixation by different species has been studied extensively, there is a massive debate around the best species, deciduous or evergreen, to plant, especially in times of climate emergency.

3.3.2 Biogenic particulate matter emissions

Biogenic particulate matter (BPM) are natural particles such as spores (i.e., fungal propagules), plant hairs, and pollen. The aerodynamic size of BPM is typically between 10 and 150 µm in diameter, contributing to other natural particles in the urban air (Davies, 2019). Some species emit aeroallergens (pollen) and can trigger allergic reactions, such as allergic rhinitis (hay fever) and the exacerbation of asthma, with a significant impact on human health (Sedghy et al., 2018; Cariñanos et al., 2021; Stas et al., 2021).

The intrinsic and extrinsic characteristics that influence BPM emissions are described below.

3.3.2.1 Green infrastructure characteristics

Macrostructure of vegetation

The macrostructure of vegetation, such as size, crown volume and maturity, influences pollen-release capacity and dispersal (Molina et al., 1996; Cariñanos et al., 2014; Bogawski et al., 2019). Indeed, the total production of pollen is positively correlated with the diameter of the tree crown (Molina et al., 1996). More pollen is released per plant by large-crowned species as these tend to have more flowers per unit area (Cariñanos et al., 2014). Plant reproductive maturity also matters, and when plant species reach this stage[15], their pollen emissions are maximised (Maya Manzano et al., 2017a; Cariñanos et al., 2020).

Pollination strategies

Pollination requires a vector to move pollen from the male anther to the female stigma. Planting more entomophilous species (insect-pollinated) species, reducing trees with anemophilous pollination systems (wind-pollinated), and reducing/controlling male tree species could potentially decrease the amount of airborne pollen in urban environments (Maya Manzano et al., 2017b).

3.3.2.2 Spatial and temporal context

Pollutant concentration

Air pollution may increase pollinosis[16], altering the natural pollen structure. Air pollutants can be carriers of pollen (e.g., particles) or can alter the chemical components of pollen. Pollen - pollutant interaction can result in an alteration to the protein composition of the outer surface of the pollen grain, worsening its allergenic effect (Senechal et al., 2015). NOx, for example, changes the structure of a soluble protein inside pollen grains, releasing interior components accumulated on the pollen surface, increasing allergenicity (Jianan et al., 2007). An allergenicity study on *Cupressus arizonica* (Arizona cypress) indicated higher allergenicity in polluted rather than unpolluted sites (Sedghy et al., 2018).

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[15] Maturity is very plant species dependent. Some species reach this stage in a few years, while others can take 20 years.

[16] Pollinosis is commonly known as hay fever, rhinitis and other seasonal allergic symptoms (e.g., conjunctivitis). It is when respiratory symptoms appear as a result of pollen inhalation.

In addition, gaseous air pollutants, such as SO_2 and NO_2, can compromise plant development and flowering phenology, consequently reducing or altering pollen production (Sedghy et al., 2018; Oduber et al., 2019; Cariñanos et al., 2020). A study of interactions between air pollutants and pollen concentrations in Granada, Spain, highlighted that tropospheric O_3 and NO_2 influenced pollen germination and modified protein in the pollen grain, increasing pollen allergenicity (Cariñanos et al., 2021).

Weather parameters

- Temperature

Temperature substantially affects the intensity of the flowering period, altering the amount of pollen released (Gonzalez & Candau, 1997; Jianan et al., 2007; Cariñanos et al., 2021). A two-month study of *Olea europea* (olive) in Seville, Spain, showed that pollination occurred when the temperature was above 14°C. The accumulating daily temperatures directly and positively affected bud maturation and, consequently, the flowering date, increasing the duration of pollen production (Gonzalez & Candau, 1997).

Over the past two decades, rising global temperatures have already caused pollen seasons to start earlier and last longer (Emberlin et al., 2007; Jianan et al., 2007; Cariñanos et al., 2020). This effect may have more impact in cities where heat island effects intensify background climate change, and a more extended pollen season may increase the severity of allergic symptoms (Lake et al., 2017). This could affect the net balance of natural services provided by GI in many cities, skewing these towards negative services that affect human health.

- Precipitation

Precipitation (or water availability) is considered one of the most influential weather parameters affecting the flowering intensity and, therefore, the production and emission of pollen (Cariñanos et al., 2021). Rainfall regimens can influence the dispersion of pollen grains into the atmosphere and are also related to the breakdown of the pollen grains, generating sub-pollen particles (SPP) in the respirable fraction (Oduber et al., 2019; Cariñanos et al., 2021). Due to their smaller size, SPP can deliver allergens deeper into the respiratory tract than intact pollen grains and may trigger severe cases of asthma (Stone et al., 2021). Nevertheless, reduced rainfall frequency, seen in many regions, allows pollen to remain airborne longer, concentrating pollen in the air (Cariñanos et al., 2020).

Precipitation is also associated with temperature. For example, a study in Seville, Spain, associated high temperatures and rain deficit with irregular pollination periods (Gonzalez & Candau, 1997).

- Wind direction and wind speed

Pollen could be transported by wind (anemophilous), so wind persistence, direction and speed could affect pollen distribution (Damialis et al., 2005; Fernández-Rodríguez et al., 2014). Winds alter the transport of biogenic particles from their sources (plants) to humans (Maya Manzano et al., 2017b; Cariñanos et al., 2020), but they can also bring pollen from other parts of the city (Damialis et al., 2005). The distance pollen can travel depends on the species, size, shape, and density of the pollen, as well as the height of the pollen grain release. For example, pollen grains released by tall trees are released higher from the ground and are more likely to be transported long distances. Pollen has been found at distances of 20 to 40 km from the source, with the potential for pollen to travel much further (Skjoth et al., 2007; McInnes et al., 2017).

Management and maintenance

The management, inspection and maintenance of GI can ensure long-term vegetation health, managing their size and minimising risk to people and property. Usually, GI council departments are in charge of pruning, watering and caring for urban GI. Pruning is the selective human action that removes dead, dying or unwanted branches and stubs from trees and shrubs/hedges, improving the vegetation’s structure and promoting healthy growth. The most common procedure involves crown maintenance and reduction (Pietzarka, 2016). Crown control differs in method and frequency depending on the species and pollen production. For example, many trees, shrubs, and hedges are pruned according to their flowering date. Some early-flowering shrubs, such as mock orange (*Philadelphus*), are pruned after flowering, but other species, such as beautyberry (*Callicarpa*), should be pruned before spring growth begins. Thus, the ability of GI to react to pruning will depend on the season and the species’ ability to compartmentalise (isolate) a wound after pruning (Pietzarka, 2016).

Selected studies reveal that appropriate management and maintenance of GI can mitigate allergenicity, as selective regular pruning can prevent some species from achieving maturity, thus influencing the length of their pollen season (Cariñanos et al., 2014; Maya Manzano et al., 2017a). Planting and low-intervention management decisions favour flowering, increasing potential pollen emissions (Cariñanos et al., 2020). The London plane, *Platanus x hispanica* and other plane species, such as *Platanus acerifolia,* have been extensively planted as ornamental trees in many European cities because they grow rapidly, are drought tolerant and are air pollution resistant (Maya Manzano et al., 2017b). They are, however, well-recognised sources of allergenic pollens and irritant hairs, making their maintenance regimes critical to managing this disbenefit (Maya Manzano et al., 2017a; Cariñanos et al., 2020).

4 Discussion

More vegetation cover using species with high stomatal density could potentially increase the absorption of pollutants, while species selection guidance, such as for entomophilous native species with small crown sizes, could decrease biogenic emissions. Absorption and biogenic emission are primarily affected by weather parameters, especially increased temperature and pollutant concentrations. Many plant characteristics and extrinsic (meteorological/environmental) characteristics negatively and positively impact air quality (Table 11), thus underlining the complexity of designing and implementing GI in urban areas for air quality mitigation. The selection of species for urban street planting should consider species-specific characteristics and how the species is related to the spatio-temporal context in which it will be planted.

Table 11. Summary of the intrinsic and extrinsic characteristics that affect the absorption of pollutants and biogenic emissions and that influence air quality.
The symbols indicate the effect on air quality: + reduced, - increased, # no evident influence or consensus, (s) species-dependent, ↑ increase absorption/emissions, and ↓ decrease absorption/emissions

	Extrinsic							**Air quality**
	Weather				**Damage**			
Intrinsic (1)	**Increase Temp**	**Wind**	**Drought (2)**	**Pollutant (3)**	**Biological**	**Mechanical**	**Maintenance**	
Foliage (A)				(s)				**#**
Major vegetation cover (A)			(s)	(s)			↑	**+**
Increased stomatal density (A)	↓		↓				↑	**+**
Micromorphologies of the leaf (waxes) (A)				(s)				**+**
Taxonomic (B) ○ Broadleaves	(s)		(s)		↑	↑	↓	**(s)**
○ Conifers	(s)		(s)		↑	↑	↓	**(s)**
Origin patterns (B) ○ Native species	↑			(s)	↑	↑	↓	**+**
○ Exotic species	↑			(s)	↑	↑	↓	**-**
Growth stage (B) ○ Young species	↑			(s)	↑	↑	↓	**#**
○ Mature species	↑			(s)	↑	↑	↓	**#**
Leaf ontogeny (B) ○ New leaf	↑				↑	↑	↓	**-**
○ Old leaf	↑				↑	↑	↓	**+**
Macromorphologies of the species (crown) (P)	↑	(s)	↑				↓	**-**
Pollination strategy (P) ○ Entomophilous		(s)					↓	**+**
○ Anemophilous		↑					↓	**-**
Flowering period (P)	↑		↑				↓	**(s)**
Air quality	**-**	**(s)**	**-**	**-**	**-**	**-**	**+**	

(1) A = absorption mechanism, B = biogenic emissions, BVOC, P = biogenic emissions, pollen

(2) Reduced water availability.

(3) Concentration and type of pollutants in the site.

4.1 The importance of studying local conditions before GI planting

Absorption and emission have contrasting influences on urban air quality, but these are also strongly influenced by ambient pollutant concentrations and weather parameters. Plant responses vary with context. For example, high local CO_2 concentration modifies stomatal opening and plant water use, in turn affecting the absorption of pollutants (Delian, 2020). The ambient CO_2 concentration also affects the emission and production of BVOC, and these maybe are inhibited in a CO_2 - enriched atmosphere (Lahr et al., 2015; Daussy & Staudt, 2020), although the BVOC production depends on the function of these biogenic gases. For example, elevated CO_2 can increase herbivore feeding damage, thus increasing the necessity of BVOC emissions for protection (Yuan et al., 2009).

The interaction between NOx and O_3 also has to be considered in the site evaluation. The reduction of ground - level O_3 in urban areas must be viewed in the context of a substantial reduction in NOx concentrations. Limitation of VOC emissions from both biogenic and anthropogenic sources should be considered in cities. Large - scale planting of large emitter species of BVOC may need to be banned (or reduced) in cities to contribute to a reduction of VOC (Churkina et al., 2015).

Recent research has pointed to the urgency of understanding the interaction of climate change (increase in temperature) with pollutant concentrations associated with an increase in allergens allergic diseases. Rising CO_2 and temperature are associated with changes to the start, duration and intensity of the pollen season, and with it, consequences in aeroallergens and allergic disease (Ziska, 2020). Elevated CO_2 concentrations induced large increases in trees producing male flowers relative to ambient CO_2 conditions, leading to higher pollen and pollen allergen production (Kim et al., 2018; Zhang & Steiner, 2022). But not only elevated CO_2 concentrations can affect plants. In areas where there is a high level of pollution, stomatal conductance is reduced, thus reducing photosynthetic gas exchange capacity (Lu et al., 2019). Here the importance of evaluating the level of pollution in the site and the species selection that best adapt and grow in polluted environments.

Other pollutants, such as NOx and SO_2 also alter the biological function of plants. A study in strawberry plants exposed to these pollutants showed that the photosynthesis rate was slightly reduced when exposed to low doses of NOx and SO_2 (25 ppm), however, at higher doses of these gases (199 ppm) the photosynthetic rate decreased (Muneer et al., 2014). This means that the absorption of pollutants may be reduced as well as the function of the leaves (see below).

Weather parameters, such as temperature, precipitation and wind, affect the plant's function. The earth's global surface temperature has increased by circa 1.1°C compared with pre-industrial levels (IPCC, 2021). High-temperature levels reduce absorption, increase BVOC and pollen emissions, and worsen air quality. A future increase of 2.5°C over the growing season could be expected to increase BVOC emissions by 25 ± 40% (Harley et al., 1999), increasing tropospheric ozone and modifying the oxidation capacity of the atmosphere (Peñuelas & Staudt, 2010). Furthermore, an increase in temperature is also frequently associated with drought or water deficit, affecting many aspects of plant physiology, including the intensity of flowering and, thus, pollen production.

Further studies are needed to establish the consequences of climate change on future urban GI and its corresponding health effects.

4.2 Leaf damage through absorption of pollutants

Plant absorption depends on the sensitivity and tolerance of species towards absorbing pollutants. The cuticle and epicuticular wax structure, which cover the external layer of the leaf, are highly impacted by air pollutants. The epicuticular wax structure typically changes with the age of the leaf but can be rapidly altered through contact with pollutants and mechanical abrasions, changing the appearance of the leaf and its affinity to water (wettability) (Gostin, 2016). Trichomes, epidermis, and stomatal pores are also significantly affected by air pollutants. In heavily polluted sites, the absorption of particles can cause clogged stomata and decrease the size of the stoma, decreasing the photosynthetic process and reducing absorption (Gupta et al., 2015).

Some plant species present morphological changes in their leaves or present other specific symptoms, recording the occurrence of pollutants (Gostin, 2016; Birke et al., 2018; Fusaro et al., 2021). Visible damage on the leaf structure is a response to high exposure to air pollutants. Leaves exposed to a high concentration of SO_2 lose their colour, presenting irregular white spots, while in some species, red, brown or black spots develop. When enough tissue is damaged or dies, plants lose their leaves. High concentrations of NO_2 cause chlorosis in angiosperm leaves and tip burn in conifer needles. Black discolouration, bordered tip burns in needle species, slight marginal and upper surface injuries, bronzing of upper leaf surfaces, desiccation, and abscission are all effects of leaf exposure to high concentrations of NH_3 (ammonia). Common symptoms of leaves exposed to O_3 are yellowing, flecking and blotching, premature senescence, and early maturity. Ozone also interferes with pollen formation, pollination, and pollen germination. The long-term absorption of pollutants causes chronic leaf injury with visual changes, from yellowing and chlorosis to necrosis. In addition, plants in stressful sites tend to be more symmetrical, a leaf form that is less responsive to yearly variations and drought stress (Gheorghe & Ion, 2011; Gostin, 2016).

Pollutant concentrations around GI affect the response of vegetation to absorbing pollutants, and therefore the positive effect of GI for improving air quality could decrease. Proper and regular maintenance could prevent infection, saturation and foliage death and provide early warnings about pollutants around the site.

4.3 Green Infrastructure as a player in air pollution mitigation

Despite efforts and studies worldwide to find *the best* species to plant for air pollution control, the local context (pollution concentrations and weather parameters) makes identification difficult. Species, however, that are tolerant to air pollutants and urban stressors, with low biogenic emissions and a high capacity to absorb air pollution, are recommended for urban planting. Species that are O_3 - tolerant and tolerant to drought, resistant to pests and diseases, and that are non-allergenic are recommended for improving air quality. *Acer sp., Carpinus sp., Larix decidua*, and *Prunus sp.,* are some example of species with these characteristics (Sicard et al., 2018). In addition, species with high degrees of stomatal opening and a high tolerance of pollutants, such as *Populus nigra,* are also recommended (Omasa et al., 2002). See Appendix C, Table 2 for a list of high stomatal conductance and air pollution tolerant species.

Climate change and rising temperatures in cities will lead to more frequent episodes of thermal stress, which may increase BVOC emissions (Holopainen & Gershenzon, 2010). For urban planting, species with greater heat and drought tolerance and low BVOC emission profiles are preferred. Generally, native species emit less BVOC than alien species, possible as they are locally adapted (Prendez et al., 2013; Farías et al., 2022). Some low BVOC emitting species, however, are less tolerant to temperature increases, drought and other urban stressors (Calfapietra et al., 2013). Species selection, therefore, cannot be generalised due to species and site dependencies.

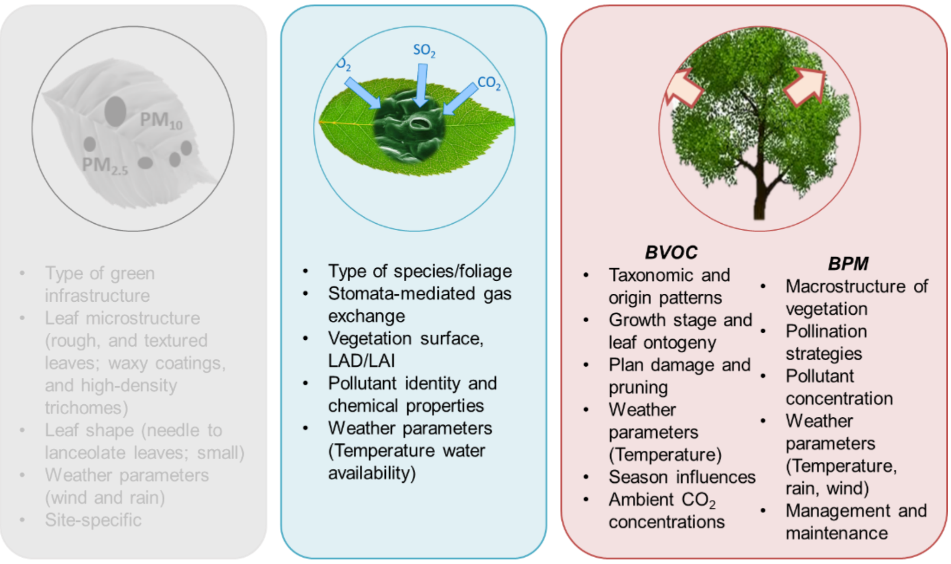
The prevalence of allergies in the world population is between 10% and 25% (Traidl-Hoffmann et al., 2003). Controlling the distribution of allergenic pollen plants and selecting allergy-friendly species to plant in cities could reduce allergenic pollen production, thereby reducing the impact on human health (Jianan et al., 2007; Stas et al., 2021). Controlling and reducing the planting of anemophilous (wind pollination) species are recommended. This species releases pollen 10 - 100 μm in diameter, causing significant allergies (Traidl-Hoffmann et al., 2003; Davies, 2019). For example, controlling the planting of *Cupressus*, *Platanus*, *Populus*, *Acer*, *Ulmus* and *Fraxinus*, as well as of ornamental trees, such as *Olea europaea, and Cupressus,* could reduce allergenic pollen (D'Amato et al., 2007; Cariñanos et al., 2021). Cariñanos et al. (2014) propose an allergenicity index to estimate and manage the allergenicity of tree species. This index, proper GI design and maintenance could help reduce pollen emissions in cities. For example, planting ornamentals species downwind and isolating them among non-allergenic plant belts may control pollen dispersion.

Maintenance of the GI planted in streets could be an excellent human activity to maximise the benefit of improving air quality. Maintenance and selective pruning alter planting density (Coskun Hepcan & Hepcan, 2018), effectively preventing some individual plants from reaching maturity, thus reducing the number of flowers and influencing the length of the pollen season, thereby reducing pollen emissions (Jianan et al., 2007; Cariñanos & Casares-Porcel, 2011; Maya Manzano et al., 2017a). Maintenance can also inform the pollutant ambient concentration, using plant absorption for biomonitoring. In addition, maintenance could prevent biological or mechanical damage to avoid increasing BVOC emissions. Further studies about the effect of GI maintenance on air quality are needed.

5 Conclusions

This review identified the GI characteristics that affect urban air quality through **absorption** and **biogenic emissions**. This knowledge and the integration of Ecosystem Services (absorption pollutants) and disservices (BVOC and pollen emissions) promote an understanding that would help maximise the benefits and minimise the detrimental effects of GI on air pollution.

Weather parameters, ambient concentrations and species-specific characteristics are essential aspects that should be considered in conjunction with **species' tolerance** to urban stressors, such as temperature, drought, flooding, and air pollution, to maximise the positive effects of GI in cities. **Stomata play a primary role, in regulating the gas exchanges** between the plant and air pollutants**, and also in controlling water loss in drought conditions by closing the pores**. This control depends on the degree of opening of the stoma, the density of stomata, and the implicit reactivity between pollutants and the plant surface. Moreover, regulation of the degree of opening is actively carried out by numerous abiotic and biotic characteristics. Biogenic emissions such as **pollen and BVOC are mainly regulated by temperature and micro and macro vegetative structures** such as canopy and leaf (Figure 27). Almost every GI characteristic for absorption and biogenic emissions, however, has a trade-off; thus, making recommendations is difficult given the number of variables and uncertainty involved in these two mechanisms. Nevertheless, appropriate maintenance and species-specific selection may help to increase absorption of pollutants and to avoid biogenic emissions. By understanding the combination of these numerous local interactions, GI can continue to provide well-being and vital benefits to the population, creating healthier and more liveable cities.



- Type of green infrastructure
- Leaf microstructure (rough, and textured leaves; waxy coatings, and high-density trichomes)
- Leaf shape (needle to lanceolate leaves; small)
- Weather parameters (wind and rain)
- Site-specific

- Type of species/foliage
- Stomata-mediated gas exchange
- Vegetation surface, LAD/LAI
- Pollutant identity and chemical properties
- Weather parameters (Temperature water availability)

BVOC

- Taxonomic and origin patterns
- Growth stage and leaf ontogeny
- Plan damage and pruning
- Weather parameters (Temperature)
- Season influences
- Ambient CO$_2$ concentrations

BPM

- Macrostructure of vegetation
- Pollination strategies
- Pollutant concentration
- Weather parameters (Temperature, rain, wind)
- Management and maintenance

Figure 27. Summary of the main GI characteristics and spatio-temporal contexts influencing absorption (blue rectangle) and biogenic emission (red rectangle).
The grey rectangle to the left presents the GI characteristics associated with deposition (See Chapter 3).

Chapter 5. Dispersion of air pollutants within a street canyon

This Chapter

- Explains the green infrastructure characteristics that influence air pollutant dispersion in a street canyon.
- Discusses the green infrastructure characteristics that influence dispersion on a street.
- Suggests possible street green infrastructure designs to reduce pedestrian pollution exposure.

1 Introduction

The three-dimensionality of green infrastructure (GI) affects the transport, velocity, and dilution of air pollutants through or around its physical structure (Janhäll, 2015; Hofman et al., 2016). Computational modelling is commonly used to assess the local effect of GI as a porous barrier which may, or not, improve air quality in streets (Gromke & Ruck, 2008b; Balczó et al., 2009; Steffens et al., 2012; Jeanjean et al., 2016; Hong et al., 2017; Wang et al., 2021).

Computational models are a useful tool because they represent and predict some of the complexity of urban environments through simplified representations of the real world. In recent years, increasing data availability and computing power have led to favourable changes in how dispersion air pollution models are developed. Nevertheless, the complexity of urban systems, the subjectivity of parametrisation, and the uncertainty of environmental data still pose a number of challenges for constructing, validating, and using computational models to study GI (Pianosi, 2014).

Green infrastructure is an important urban element in cities, providing many Ecosystem Services (See **Chapter 2**). However, regarding the improvement of air quality, further research is needed to understand how GI influences the dispersion of pollutants. Green infrastructure can have both positive and negative impacts on air quality in streets. This dichotomy is due to the complexity of pollutant dispersion influenced by GI characteristics (e.g., crown, height, porosity), GI arrangement within the street and the street design (narrow street or avenue), and weather parameters (Abhijith et al., 2017; Kumar et al., 2019b; Hewitt et al., 2020).

The large number of characteristics that influence pollutant dispersion has led most researchers to review them separately. Consequently, there is a lack of consolidated information concerning the main GI characteristics that affect dispersion. Consolidation of previous research findings is vital for researchers and practitioners to evaluate the current knowledge concerning the different types and uses of GI and to identify remaining gaps in knowledge. Poor planting decisions can lead to the deterioration of air quality, in which case, GI merely plays an aesthetic role. To help assess the impacts of GI interventions on streets, researchers and practitioners require either a comprehensive understanding or at least some idea of the limits to comprehensively understanding the GI characteristics and spatio-temporal contexts that maximise improvements of air quality (Pearce et al., 2021).

The uniqueness and value of this Chapter lies in its holistic assessment of multiple potential scenarios regarding the type and implementation of GI in different street canyons. This **Chapter** investigates the GI characteristics and spatio-temporal context that influence dispersion to improve air quality in street canyons at a pedestrian level. The method is presented below, followed by the identification and description of the characteristics and context that influence dispersion of pollutants in streets. After that, possible GI designs to block pollutants and reduce pedestrian exposure to air pollution are discussed.

2 Method

A critical review was conducted to extract the main GI characteristics (intrinsic) and spatio-temporal contexts (extrinsic) that influence dispersion. Database selection, search strategy, and procedure were followed according to Atkinson and Cipriani (2018) and Cooper et al. (2018) and the same method described in **Chapter 4** was followed. Different search terms, however, were used to identify relevant articles specifically associated with dispersion (Table 12). Articles that focused on urban areas and that were interested in studying GI-related characteristics (e.g., wind direction, GI type) influencing pedestrian-level dispersion in a street canyon were included.

The selected studies were tabulated in Excel™, together with the publication year, research aims, method, sampling area, studied species or GI type, the amount of pollutant removal by species (if mentioned), and intrinsic and extrinsic characteristics. An additional column justified the selection of each characteristic that influenced dispersion.

Table 12. *Search terms and term combinations used in this critical literature review.*

Common search terms	
'green infrastructure' OR 'vegetation' AND 'urban setting' OR (city OR street) AND 'outdoor air pollution' AND pollutants AND 'urban planning' AND 'emission'/ 'absorption' (depending on the literature review)	
Main key term	**Synonyms**
Green infrastructure	Trees OR green walls (living walls) OR green roof OR shrubs OR hedges OR plant OR species OR vegetation OR urban vegetation OR deciduous OR evergreen
Urban setting	City OR street OR canyon street OR open road
Outdoor air pollution	Air pollution OR air quality
Pollutants	Atmospheric pollutants OR particulate matter OR PM OR PM_{10} OR $PM_{2.5}$ OR gaseous pollutants OR nitrogen dioxide OR ozone AND NOT carbon dioxide AND NOT CO_2
Urban planning	Urban planting AND NOT climate change AND NOT urban heat island
Specific research term per mechanism	
Dispersion	Aerodynamic OR wind OR flow

3 Results

Dispersion is generally studied using computational models. This mechanism is difficult to assess experimentally because wind varies rapidly over a short period of time, and it requires expensive equipment to measure air quality and weather parameters (e.g., anemometer). To avoid complex experimental design, computer-aided technology, such as computational fluid dynamics (CFD) models, allows many different scenarios to be run where the wind field can be studied in detail.

Most of the model studies selected modelled the impact of GI (usually trees) in streets. The location of GI within the street influences the dispersion of pollutants, with *regular* street canyons with trees or shrubs/hedges in the sidewalk being the most commonly studied scenario. Models simulate vegetation (GI) in streets by adding deposition velocity (v_d) and LAD values (momentum source (sink) term) to fluid flow equations (Buccolieri et al., 2018b) (See **Chapter 2**, Section 5.1.1). As there are many pollutants and crowns, common values of V_d and LAD are typically used across all models to avoid complexity, though this might overestimate or underestimate the real impact of GI on streets. Vegetation (GI) is generally represented in spherical shapes or rectangular blocks with a theoretical LAD simplifying GI (especially trees) as a uniform porous medium (Gromke & Ruck, 2007; Litschke & Kuttler, 2008; Buccolieri et al., 2011; Vos et al., 2013; Hofman et al., 2016). In this sense, LAD or LAI is the parameter that represents GI in the computational domain.

The impact on air quality due to the dispersion of pollutants by GI depends on several codependent intrinsic and extrinsic characteristics. Separating each individual characteristic to understand its impact on air quality is a challenge and is not recommended since a holistic view of the effect of GI on streets is necessary to understand this mechanism. Dispersion is probably the most complex mechanism, encompassing the other three mechanisms directly and indirectly.

The results of this review are presented in two parts: 1) general information and 2) the GI characteristics and spatio-temporal context that influence dispersion.

3.1 General information

An initial screening of 304 articles led to 42 articles that met the inclusion criteria (See Appendix D, Figure 1, and Table 1). Deposition and dispersion studies often overlapped, with almost half of those studied having identified or mentioned both mechanisms; precisely, 14 selected articles focused only on dispersion, and the remaining articles (N=28) studied both.

3.1.1 Study method

Computational modelling is the most commonly used method to study dispersion (N = 29). The CFD codes FLUENT, CONVERGE, PHEONICS, and ENVI-met were the most commonly used models, followed by the i-Tree software. CFD models simulated an idealised street canyon with trees or shrubs/hedges under different wind conditions, GI planting arrangements, or GI morphologies (e.g., height or porosity).

Literature reviews (N=6) and other techniques, such as air quality sensors/monitors gravimetric and Scanning Electron Microscope (SEM) were also used to study deposition in dispersion studies (N=7).

3.1.1.1 General input for modelling studies

The information required as inputs to air quality (or dispersion) models is proportional to the complexity of the model. Generally, dispersion models are a function of street design, meteorology, type of GI, GI location, vegetation characteristics, deposition velocity, traffic volumes (or density), and emission factors. The performance of the model greatly depends on the quality of these inputs. Below are the most common entries added to the selected model studies:

- **Street design**. Built environment studies used two typical topographies: open roads and street canyons (Figure 28) (See **Chapter 2**, Section 3.2). Most of the selected studies simulated an isolated *regular* street canyon (H/W=1) with buildings of the same height. Three selected studies (Wania et al., 2012; Hong et al., 2017; Moradpour et al., 2017) simulated a street intersection with different aspect ratios. The effect of green areas (mesoscale), such as the effect of trees in a neighbourhood or urban forests, was also studied.

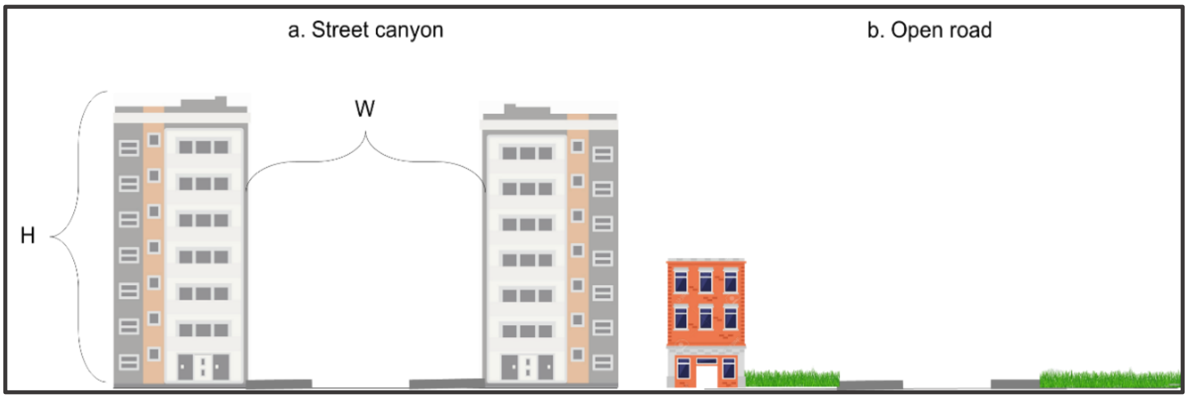


Figure 28. Representation of common types of streets.
a. Street canyon, where H is the height of the building and W is the width of the street, b. An open road, a road with buildings on only one side. Source: Own elaboration.

- **Weather parameters**. Wind direction (parallel, oblique, and perpendicular) and wind speed (e.g., 1 and 3 ms^{-1}) were required by all models. Most of the selected studies used different wind regimes to evaluate the effect of GI on streets. Other parameters, such as temperature and relative humidity, were also included in most selected studies but without any information about how these parameters could affect dispersion. The weather parameters were obtained through specific instrumentation on-site (e.g., wind anemometers) or from the nearest monitoring station to the sampling site.
- **Type of GI**. Trees and hedges/shrubs were the most studied GI; studies focused either on their individual or combined effect on air quality. Other GI, such as green roofs and green walls, were studied to a lesser extent.
- **GI location**. GI on sidewalks or in the middle of the street canyon were common places to study dispersion. Generally, hedges located on sidewalks were studied to measure the difference between pollutant concentrations behind vegetation (pedestrian side) and in front of it (facing traffic).
- **Vegetation characteristics**. Leaf area density (LAD) or leaf area index (LAI) and height were the most common inputs to simulate vegetation in model studies. In addition, and depending on the aim of selected studies, thickness, length, canopy density, crown diameter, tree cover, percentage of species, porosity, segmentation (e.g., continuous or discontinuous hedges), and vegetation cycle were also included.
- **Deposition velocity (v_d)**. Deposition velocities depend on vegetation characteristics and particle diameters, ranging from 0.02 to 28 cm s^{-1} (Freer-Smith et al., 2005). Some studies explain or define a specific V_d. For example, V_d is predicted by a model according to particulate diameters in Neft et al. (2016), and in Tiwari and Kumar (2020), a different mathematical model is used for gases and particulates. Vranckx et al. (2015) use a range of V_d depending on LAD (low V_d of 0.5 cm s^{-1} and a high V_d of 5 cm s^{-1}), and Morakinyo and Lam (2016a) used 0.1 cm s^{-1} to investigate the dispersion of $PM_{2.5}$ (Vranckx et al., 2015; Morakinyo & Lam, 2016a; Neft et al., 2016; Tiwari & Kumar, 2020). Nevertheless, a typical value of 0.64 cm s^{-1} is used in most of the selected studies (Nowak et al., 2006; Tallis et al., 2011; Pugh et al., 2012a; Jeanjean et al., 2016; Jeanjean et al., 2017). This common value is derived from Nowak's studies (Zinke, 1967; Nowak 1994; Nowak et al., 2006), which set the deposition velocity to 0.64 cm s^{-1} based on a 50% resuspension rate to study forest interception (macroscale) (Zinke, 1967)[17].

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[17] Zinke, 1967 is an American review based on water balance including interception losses by vegetation species, e.g., evaporative loss in the water balance of a forest. The percentage of resuspension depended on the species.

- **Traffic data**. Traffic information, including traffic volumes or composition, was added in some selected studies to run the models. This data was estimated from on-site measurements or national datasets.
- **Emissions factors**. All dispersion models require vehicle emission factors (e.g., g/km per vehicle) or emission rates (e.g., g/km per hour) as input, but only a few selected studies included the value in the article. Although there are other sources of pollution in urban areas, the source of pollution for all the modelling studies was traffic.

3.2 Characteristics of green infrastructure that influence dispersion

Dispersion is affected by GI (intrinsic) characteristics and spatio-temporal contexts (extrinsic characteristics) such as street configuration, weather parameters, and the GI location within the street. The intrinsic and extrinsic characteristics that influence dispersion are identified below.

3.2.1 Green infrastructure characteristics

Type of green infrastructure

Several studies concluded that street trees tend to increase local air pollution in street canyons because within a vegetated street, the wind speed is reduced and air pollutants stagnate, increasing pollutant concentrations in the area (Ries & Eichhorn, 2001; Abhijith & Gokhale, 2015; Morakinyo et al., 2016; Abhijith et al., 2017; Buccolieri et al., 2018b; Abhijith & Kumar, 2019; Lin et al., 2020). The negative impact of trees, however, depends on street design, weather parameters and type of pollutant. Generally, in a street canyon, dispersion effect of trees results in an increase in the concentration near leeward walls and a decrease in the concentration near windward walls, which overwhelms the deposition effect (Lin et al., 2020).

Other studies have shown a positive aerodynamic effect of trees, indicating that the impact on pollutant dispersion caused by obstruction becomes smaller with denser tree canopy (see below) (Gromke & Ruck, 2008b; Xue & Li, 2017) and there are other mechanisms interacting together. One study, for example, quantified $PM_{2.5}$ deposition of 2.0 ± 0.3 kg ha^{-1} $year^{-1}$ by street trees per unit of area, claimed, in addition, that street trees would facilitate dispersal (dispersion) at a pedestrian level because trees do not have leaves or branches on their lower parts. Additionally, their large crowns could help reduce pollutants such as carbon and ultra-fine particles by absorption and deposition (Jo et al., 2020). In a *narrow* street, however, this large crown could accumulate pollutants below the canopy and deteriorate the air quality accumulating pollutants. See below in Section 3.2.2.

There was less available information on the impact of hedges (hedgerows) than on trees, but the study's conclusions were the same: hedges positively affect air quality in streets. Hedges, regardless of their location within the street (on the side or in the middle), could reduce pedestrian exposure by diverting pollutants from footpath areas (Gromke et al., 2016; Li et al., 2016; Abhijith & Kumar, 2019). Though such diversion depends on aspect ratios and hedge height (Kumar et al., 2019a; Voordeckers et al., 2021). For example, in a *regular* street canyon, 1m-high hedges might be optimal for reducing pedestrian exposure to pollutants, while in *shallow* canyons 2m-high hedges might be effective (Li et al., 2016; Abhijith et al., 2017; Santiago et al., 2019). The positive effect of hedges could be increased when a combination of GI is planted in streets. For example, hedges and trees close to open roads showed the largest reduction of pollutants on the pavement (Abhijith & Kumar, 2019).

Few studies have estimated the influence of green roofs (GR) and green walls (GW) on air quality improvement (Baik et al., 2012; Tong et al., 2016; Qin et al., 2018). Vegetated roofs can change the local temperature and atmospheric thermal stability, which could alter the behaviour of airflow and air pollutants. One study indicated that GR could improve air quality near roads because they cool the air, altering street canyon airflow and improving near-road pollutant dispersion (Baik et al., 2012). The potential influence of airflow due to rooftop vegetation suggests that the effects of GR on air pollution require further study.

In addition to the individual GI, some selected studies quantified the macroscale effect of green areas on urban air quality (Selmi et al., 2016; Jo et al., 2020; Moradpour & Hosseini, 2020; Tiwari & Kumar, 2020). The main finding of these studies was that green areas improved air quality, reducing, for example, 7% - 8% of PM_{10} concentration (Selmi et al., 2016; Moradpour & Hosseini, 2020).

Macromorphological traits of vegetation

○ Leaf area density (LAD) or leaf area index (LAI)

Leaf area density values varied substantially according to the season and species being studied. It varied between 0.2 and 4.29 m^{-1} for species, ranging between 0.2 - 2.0 m^{-1} for mature deciduous trees, 0.2 - 1.1 m^{-1} for broadleaf trees, 0.22 - 0.33 m^{-1} for conifers, ~2.0 m^{-1} for shrubs, 4.29 m^{-1} for hedges and 1.0 m^{-1} for other vegetation barriers (Wania et al., 2012; Morakinyo & Lam, 2016a; Tong et al., 2016; Xue & Li, 2017; Santiago et al., 2019). In addition, LAD also varied according to the season, ranging between 0, 1.06, and 1.6 m^{-1} for winter, spring-autumn and summer, respectively (Vranckx et al., 2015; Jeanjean et al., 2017; Buccolieri et al., 2018a).

Leaf area index values used in models varied from 1.0 to 3.3 m^2m^{-2} (Neft et al., 2016), with ~3 m^2m^{-2} in early fall and between 1.0 and 2.8 m^2m^{-2} in winter for hedges (Hagler et al., 2012;

Morakinyo & Lam, 2016b). A selected study estimated the real LAI of its studied species using a ceptometer[18], ranging between 1.54 and 6.64 m^2m^{-2} (Abhijith & Kumar, 2019).

These parameters are important for estimating the amount of particles deposited or the influence of the canopy in dispersion of pollutants. For hedges, an increase in LAD/LAI is related to a reduction in pollutant concentrations behind the barrier (on the pavement) (Tong et al., 2016), associated with more leaf area being available for deposition (Neft et al., 2016; Hong et al., 2017; Xue & Li, 2017). For trees, LAD could influence pollutant concentrations on both sides of the street. Balczó et al. (2009), in their CFD study in a regular vegetated street canyon (H/W=1), showed that increasing LAD values can increase concentrations on the leeward side but decreased concentrations on the windward side of the street (Balczó et al., 2009).

- Crown

Tree crown traits include crown shape, size, and foliage distribution. These influence air turbulence, affecting pollutant dispersion (or dilution) (Ries & Eichhorn, 2001; Ng & Chau, 2012; Abhijith et al., 2017). The volume of a tree crown within a street canyon can hinder natural ventilation and reduces air exchange with the surroundings, accumulating air pollutants below the crown (Ries & Eichhorn, 2001; Gromke & Ruck, 2007; Litschke & Kuttler, 2008; Abhijith & Gokhale, 2015; Vranckx et al., 2015; Abhijith et al., 2017). Hong et al. (2017) simulated conical, cylindrical, and spherical tree crown morphologies. They found that a cylindrical crown had the highest $PM_{2.5}$ dispersion effect on an avenue (H/W=0.5), followed by spherical and conical crowns (Hong et al., 2017).

None of the selected studies considered the complete structure of a tree. The trunk was neglected in modelling studies, and only tree crowns were modelled (Morakinyo & Lam, 2016b; Morakinyo & Lam, 2016a; Neft et al., 2016; Selmi et al., 2016; Jeanjean et al., 2017; Xue & Li, 2017; Santiago et al., 2019).

- Porosity

Porosity and crown density greatly impact dispersion and may be the most influential macromorphological traits because they affect wind speed (Shan et al., 2007; Bitog et al., 2011; Baldauf, 2017; Xue & Li, 2017). Dense vegetation (low porosity) diverts pollutants away from pedestrian areas but also reduces wind speeds. With this speed reduction, two actions can happen. First, higher pollutant concentrations near pedestrian levels may stagnate and/or second, the amount of time that pollutants reside inside GI may increase, increasing the possibility for other mechanisms such as deposition and absorption to take place, though this

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[18] A device that measures photosynthetically active radiation (PAR) as a measure of light interception in plant canopies.

is dependent on the species (Ng & Chau, 2012; Baldauf, 2017). Therefore, vegetation porosity should be low (dense vegetation) enough to divert pollutants but high enough to allow deposition of particles and absorption of gases (Baldauf, 2017). Dense vegetation is like a porous obstacle in streets. In a field measurement study, Shan et al. (2007) found that between 50 and 60% of total particles were removed, with the optimum intervals of canopy density and vegetation porosity falling between 0.70 - 0.85 and 0.25 - 0.33, respectively (Shan et al., 2007).

- *Height*

Height was a specific characteristic studied for hedges/shrubs. The optimal height for hedges varies according to the specific street design, GI arrangement and weather parameters. Tall hedges can act as a semi-solid barrier forcing the pollutant plume to rise above the barrier, and pollutants that pass through the vegetation can be absorbed or deposited (Li et al., 2016; Tong et al., 2016; Baldauf, 2017). For a *regular* street canyon with side hedges, increasing its height by 0.75 m resulted in pollutant reductions of up to 17% (Gromke et al., 2016). According to the aspect ratio, different optimal hedge heights were found:

- Regular street canyon (H/W = 0.3 to 1.67) optimal height: 1.1m up to 2m
- Avenues (H/W < 0.3), optimal height: 0.9m to 2.5m
- Open roads, optimal height: 4m to 5m or higher

- Thickness

Thickness (or depth) was a specific characteristic studied for hedges/shrubs. Thickness reduces the turbulence and wind speed of air that passes through the hedge/shrub, which influences the residence time of pollutants in or around the hedge. Less turbulence and wind speed, and thus longer residence time, allow for the deposition of particles and the absorption of gases (Baldauf, 2017), but probably disrupt dispersion. In addition, hedges with a thicker width force air to flow a longer distance over the vegetation, increasing separation between air pollution sources and pedestrian areas (Morakinyo & Lam, 2016a; Baldauf, 2017). An increase in the thickness of vegetation can substantially decrease pollutant concentrations by drawing pollutants away from the sidewalk (Neft et al., 2016; Tong et al., 2016). A minimum thickness of 1.5m for hedges has been suggested for street canyons, and between 1 to 5m is recommended for hedges along open roads (Kumar et al., 2019a).

3.2.2 Spatial and temporal context

Street configuration

In open roads, hedges at a roadside can act as a barrier between traffic sources and pedestrians or residential areas, as the hedges act as a barrier, deflecting the plume of pollutants upward (Tong et al., 2016), as a result, less pollution reaches pedestrians as it is either diverted upwards or partially captured by being filtered through the vegetation (Tiwary et al., 2008; Tong et al., 2016).

In street canyons, the presence of trees alters airflow patterns and changes the dispersion of pollutants and ventilation (Vardoulakis et al., 2003; Tomson et al., 2021), but in many cases, it is still unclear how GI affects the airflow within street canyons with different aspect ratios. Vranckx et al. (2015) modelled the impact of two avenues of trees placed in a *broad* street canyon (H/W=0.5) and found that these triggered increases in the street concentration of elemental carbon (8%) and PM_{10} (1.4%) (Vranckx et al., 2015). Similar results were found by Buccolieri et al. (2009) using a modelling study. They found that the flow rate in a *shallow* street canyon was reduced by 35% compared to the treeless scenario and by 72% in *regular* streets (H/W=1). This means that trees reduce ventilation in *narrow* street canyons (Buccolieri et al., 2009).

According to some authors, in comparison to trees, hedges can positively impact air quality at a pedestrian level in *regular* and *shallow* street canyons (Gromke et al., 2016; Li et al., 2016; Kumar et al., 2019a). For example, Wania et al. (2012) simulated *regular* street canyons (H/W = 0.9 and 1.2) with hedges, finding a slightly reduced PM_{10} concentration compared to trees (Wania et al., 2012).

Green roofs (GR) and green walls (GW) could also influence airflow, but more information is needed to confirm this. So far, a CFD study conducted by Pugh et al. (2012a) suggested that GW in a *regular* canyon might reduce NO_2 and PM_{10} concentrations by 35% and 50% respectively. In another modelling exploration comparing the influence of GW with GR at the pedestrian level under three aspect ratios (H/W=0.5, 1 and 2), the authors found that GW decreased particle concentrations on the streets independent of the aspect ratio, in comparison to GR (Qin et al., 2018).

These findings should be interpreted cautiously due to the multiplicity of factors that influence pollutant concentrations; this includes not only street design, but also wind speed and direction, GI type, and the characteristics of specific vegetation.

Weather parameters

Weather parameters such as wind direction and speed are the most influential parameters in dispersion (Gallagher et al., 2015; Abhijith et al., 2017; Tiwari et al., 2019). In **Chapter 2** the typical airflow in streets was discussed; in particular, it was noted that winds that flow perpendicular to the street canyon increase air pollution compared to parallel winds (Nowak et al., 2006; Hagler et al., 2012; Abhijith & Gokhale, 2015; Jeanjean et al., 2017).

The presence of GI can alter wind flow patterns, increasing or decreasing dispersion. Under perpendicular winds, trees can increase pollution concentrations near the windward wall, while limited improvements are made near the leeward wall; this effect strengthened as the tree canopy increases in density (Vranckx et al., 2015). For example, a wind tunnel experiment involving a row of densely foliated trees along the centre of the street canyon found that, in comparison with a treeless scenario, the averaged pollution concentration increased to 58% on the leeward side, while decreasing to 49% on the windward side. For loosely foliated trees, concentrations increased to around 35% and decreased to around 40% at leeward and windward walls, respectively (Gromke & Ruck, 2008b).

Under oblique winds, ventilation is also reduced by trees. Oblique winds with trees have been identified as the worst scenario, accumulating pollutants on both sides of the street (Wania et al., 2012; Abhijith & Gokhale, 2015; Morakinyo & Lam, 2016b; Abhijith et al., 2017). However, under parallel winds, hedges (hedgerows) can have a positive impact since flow channelling and turbulence distribute pollutants along the canyon, leading to a pollution reduction of up to 60% at the pedestrian level (Hagler et al., 2012; Gromke et al., 2016; Hong et al., 2017; Buccolieri et al., 2018a). However, under this condition, other GI studies using trees have reported an opposite effect (Abhijith & Gokhale, 2015; Gromke & Blocken, 2015; Vranckx et al., 2015).

Green infrastructure can also alter wind speed. At lower wind speeds, trees may increase pollutant concentrations, as air exchange is reduced within the street canyon (Buccolieri et al., 2009; Wania et al., 2012; Morakinyo et al., 2016; Buccolieri et al., 2018b; Abhijith & Kumar, 2019; Tiwari et al., 2019). Though increasing the wind speed from 0.3 m s^{-1} to 1.5 m s^{-1} also increases the deposition efficiency by 7% (Neft et al., 2016). Nevertheless, it is important to note that the description of high or low wind speeds is frequently subjective and depends on the authors and the study's aims.

Planting management and GI location within the street

The location and type of GI within a street canyon is critical, as it can have either a positive or negative effect on air quality (Litschke & Kuttler, 2008; Hagler et al., 2012; Ng & Chau, 2012; Gromke et al., 2016; Morakinyo & Lam, 2016b; Abhijith et al., 2017; Rafael et al., 2018; Abhijith & Kumar, 2019; Tiwari & Kumar, 2020).

The use of hedgerows as a barrier (i.e., natural wall/barrier) is gaining momentum as a promising GI for reducing pedestrian exposure to pollutants, as reported by field experiments and computational models. On an open road, continuous hedges on a sidewalk can block pollutant concentrations, reducing pedestrian exposure more efficiently than tree-only configurations (Abhijith & Kumar, 2019). This decrease in pollutants is more noticeable when hedges and trees are combined on the sidewalk. This combination forms a natural barrier that can reduce between 45% and 66% of black carbon concentrations in the pedestrian zone behind the barrier (Hagler et al., 2012; Tong et al., 2016; Santiago et al., 2019).

One wind tunnel experiment concluded that within a *shallow* street canyon, one central hedgerow in the middle of the street provided a more significant reduction (up to 61%) of traffic pollutants than sidewalk hedgerows (Gromke et al., 2016). The positive effect of hedges, however, depends on the prevailing wind direction, street configuration, planting arrangement, and hedge thickness and height so that this type of GI should not be taken as the best and only GI option for air pollution improvement.

Regarding trees, several studies have reported that a tree-only scenario close to a road increased pollutant concentrations, especially on the leeward side with perpendicular winds (Gromke & Ruck, 2008a; Buccolieri et al., 2009; Salim et al., 2011a; Abhijith & Gokhale, 2015; Vranckx et al., 2015; Abhijith & Kumar, 2019). Under parallel winds, however, trees on the sidewalk may have a positive effect due to flow channelling and less air entering the street, resulting in an average pollution reduction of up to 18% (Buccolieri et al., 2018a). It should also be noted that while ‘tree’ is a common term, this can represent a wide range of sizes, shapes and canopy configurations and that the definition of these by different authors varies substantially.

Planting arrangements such as tree spacing can also influence pollutant concentrations in street canyons. Increasing spacing between tree crowns allows for greater air exchange and lowers pollution at pedestrian levels (Abhijith & Gokhale, 2015; Tomson et al., 2021). However, discontinuous hedges, placed along both sides of a street canyon can increase pollution concentrations by 3 - 19% compared with a hedge-free scenario (Gromke et al., 2016). Therefore, spacing and structure can influence the ability of traffic-related pollution to pass through or around the vegetation (Hagler et al., 2012).

4 Discussion

Dispersion is the GI mechanism that most influences air pollutants according to local context and GI characteristics. However, the GI characteristics that influence the dispersion of pollutants are not fully understood, and mixed results presenting both an improvement and a deterioration of urban air quality have been reported across dispersion studies. The multiple GI characteristics associated with pollutant dispersal make this the most context-dependent, spatio-temporal, and species-specific mechanism. In particular, the impact of GI on air quality is predominantly influenced by street design, road design, weather parameters, type of GI, and vegetation characteristics, such as crown size, leaf porosity and density, tree height, and spacing (Table 13). All these intrinsic and extrinsic characteristics interact constantly and synergistically. No research, so far, has considered all these characteristics together due to the high complexity of their interaction. However, general principles can be inferred. A full site-specific appraisal would need to consider, in particular, street design and local meteorology to assess dispersion patterns in conjunction with the characteristics of other existing and proposed GI elements. Table 13 briefly explains how each characteristic individually influences air quality.

Hedges, shrubs, hedgerows or vegetative barriers and their traits, such as height, density, porosity, and thickness are influential characteristics in dispersion. The height of hedges should be greater than the traffic-derived dust plume; the recommended range is between 1-5m, depending on road speeds and other contextual factors (Baldauf, 2017).

The porosity of GI can also be a determinant characteristic for positive or negative attenuation on the pavement, as well as the location of GI withing the streets. For example, a recent field measurement investigation has shown that dense vegetation (trees or hedges) could negatively impact air quality, increasing pollutant concentrations on the roadside by 35% when GI is located as a fence to protect residents (building dwellers) instead of pedestrians (Zheng et al., 2021). Several factors could contribute to this phenomenon, such as traffic density, height, GI density, and GI location. Therefore, if the objective of urban planting is to protect dwellers, dense hedges and trees should be planted between the sidewalk and buildings (or houses), but this could deteriorate the air on the sidewalk worsening the air for pedestrians (or cyclists) (Zheng et al., 2021). If the purpose of GI is to protect pedestrians, dense hedges should be planted between the road and the pavement. This dense canopy (or vegetation structure) will block pollutants, but attention to the species because dense canopy might reduce turbulence which increases the residence time of the air, and favour chemical reaction between gaseous pollutants and emitted BVOC (Grote et al., 2016).

The thickness of the vegetation barrier should be between 1 and 5m, which may be impractical for some *narrow* streets, but where possible, a vegetation barrier between the road and pavement is a potential GI roadside design that could reduce pedestrian exposure to pollutants.

Table 13. The effect of intrinsic and extrinsic characteristics of green infrastructure on air quality via dispersion.

Intrinsic and extrinsic characteristics	**Evidence (1)**	**Agreement (2)**	**Specific characteristic**	**Method (3)**	**Species (4)**	**Pollutant (5)**	**Concentration/ particles on a leaf, capturing efficiency (%), absorption or emission of pollutants (6)**	**Comments**	**Author**
Street configuration	R	H	H/W = 1	CFD - Pheonics	Green wall	PM_{10}	(-) from 9.3 to 29.3%	In the deep canyon, more green walls were covered; therefore, there was a greater reduction.	Qin et al., 2018
			H/W = 2		Green wall	PM_{10}	(-) from 28.3 to 43.8%		
			H/W = 0.5		Green wall and roof	PM_{10}	(-)17.1%	Concentrations were lower in the middle of the street when a green wall and roof were installed.	
			H/W = 0.5, wind direction 90°	CFD - OpenFoam	Avenues of light trees	TPs	(+) 56% leeward wall (-) 16% windward wall	In parallel winds, tree avenue configurations tend to enhance the air quality on the windward side of the street but, at the same time, increase the concentration of pollutants on the leeward side of the street.	Vranckx et al., 2015
					Avenues of dense trees	TPs	(+) 81% leeward wall (-) 29% windward wall		
			H/W = 0.5, wind direction 45°		Avenues of light trees	TPs	(+) 48% leeward wall (+)269% windward wall	In oblique winds, dense and loose-crowned trees tend to accumulate higher concentrations of pollutants in streets, mainly on the windward wall.	
					Avenues of dense trees	TPs	(+) 34% leeward wall (+)269% windward wall		
			H/W = 0.5, wind direction 0°		Avenues of light trees	TPs	(+) 106% leeward/ windward wall	In parallel winds, independent of canopy density, trees in avenue configurations increase pollutant concentrations on both sides of the streets.	
					Avenues of dense trees	TPs	(+) 109% leeward/ windward wall		
Meteorological parameters	M	L	Wind direction / perpendicular	standard k-ε turbulence model	Two tree rows in the canyon	APs	(+) 27 to 105% leeward wall (-) 3 to 19% in windward wall	Two lines of trees in the canyon can improve the air on the windward side but deteriorate it on the leeward side with perpendicular wind direction.	Abhijith & Gokhale, 2015
			Wind direction / oblique		Two tree rows in the canyon	APs	(+) 2 to 119% in leeward wall (+)34 to 246% in windward wall	In oblique wind direction, two lines of trees in the canyon deteriorate air quality along both walls.	
			Wind direction / parallel (H/W=0.5)	WT	Continuous hedges arranged sideways	TPs	(-) 30% at the façade	Hedges on the sidewise of the road in parallel wind direction improve air quality close to the building façade and in the footpath, limiting the lateral dispersion in the bottom part of the street.	Gromke et al., 2016
						TPs	(-) 60% at the footpath		

Intrinsic and extrinsic characteristics	Evidence (1)	Agreement (2)	Specific characteristic	Method (3)	Species (4)	Pollutant (5)	Concentration/ particles on a leaf, capturing efficiency (%), absorption or emission of pollutants (6)	Comments	Author
			Wind direction / perpendicular (H/W=0.5)		Continuous hedges arranged sideways	TPs	(+) 4-5% at the façade	Hedges located at the sidewise of the road in the perpendicular direction of the wind can increase the concentration of pollutants near the building wall area, but there is an improvement adjacent to the sidewalk, especially in the centre of the street.	
						TPs	(-)11-27% at the footpath		
			Wind speed 3m/s, LAD = 1.6 m^2 m^{-3}	CFD - OpenFoam	Trees	$PM_{2.5}$	(+) 16.7% dispersion and (-)3.4% via deposition in summer	Trees can increase road concentrations in summer whilst providing a beneficial abatement through deposition. This is due to the full development of the canopy during that season.	Jeanjean et al., 2017
GI location within the street	R	H	GI location within a street (H/W=0.5)	WT	Hedges arranged in the middle of the road	TPs	(-)46 – 61%	In a common canyon in a perpendicular wind, continuous central hedges had larger pollutants reduction than the sidewise hedge arrangements.	Gromke et al., 2016
					Hedges arranged sideways	TPs	(-)18 – 39%	Continuous hedges adjacent to footpaths can improve air quality in a common canyon in a perpendicular wind. This effect is stronger with decreasing hedge permeability.	
					Discontinuous hedges arranged sideways	TPs	(+)3 – 19%	In a common canyon in a perpendicular wind, discontinuous hedges adjacent to footpaths can increase pollutant concentration.	
			High polluted site	G	Trees	PM	31.75 - 179.41 µg cm^{-2}	The effect of trees retaining PM is higher in polluted sites. This is independent of the species and wind directions.	Chen X. et al., 2015
			Less polluted site		Trees	PM	3.29 - 43.29 µg cm^{-2}		
Type of GI	R	L	Type of GI in a busy road	AS	A mix of trees and hedges	TSP	(-) 12 – 65%	Barriers with trees and hedges along the roadside improve air pollution near the road, especially in the summer months.	Islam et al. (2012)
			Trees in a regular canyon (H/W=0.5)	CFD - OpenFoam	Trees	EC	(+) ranging from 1% to 13%	Trees in a regular canyon street in a parallel wind, the simulation shows an increased annual concentration of EC and PM_{10},	Vranckx et al., 2015
					Trees	PM10	(+) ranging from 0.2% to 2.6%		

Intrinsic and extrinsic characteristics	Evidence (1)	Agreement (2)	Specific characteristic	Method (3)	Species (4)	Pollutant (5)	Concentration/ particles on a leaf, capturing efficiency (%), absorption or emission of pollutants (6)	Comments	Author
			Replacement of a non-porous material by porous (tree)	CFD - VADIS	Green areas	PM_{10}	(-) 16%	When green cover areas replace buildings, there is a reduction in PM_{10}, and NOx concentrations compared to the control scenario. This, however, depends on the percentage of area covered and the direction of the wind because trees can cause spots where increased concentrations of air pollutants.	Rafael et al., 2018
					Green areas	NOx	(-) 19%		
			Trees with parallel wind	CFD - OpenFoam	Trees	APs	(-) 18%	Trees sideways of the road during the summer and in a parallel wind could improve air quality on the sidewalk due to flow channelling and high turbulence.	Buccolieri et al., 2018
			Trees with perpendicular winds		Trees	APs	(+) 108%	Trees sideways of the road during the summer and in a perpendicular wind could increase pollutant concentration on the sidewalk due to a recirculation zone that they create, reducing the dispersion mechanism.	
			GI at 15 m from road in the presence of a row of trees and a 2 m-height and 2 m-width hedges	CFD	Tree and hedges	BC	(-) 45%-66%	Barriers with hedges and trees in the sidewise are effective in locally reducing BC concentrations. This improves by increasing the deposition and LAD.	Santiago et al., 2019
			GI at 10 m from the pollution source	CFD – ENVI-met	Hedge (2m height)	NO_2	~ 22 ug m^{-3}	Hedges, regardless of their height, in a perpendicular wind, increase NO_2 concentrations compared to the scenario without a hedge barrier.	Taleghani et al., 2020
					Hedge (4m height)	NO_2	23 ug m^{-3}		
					Tree (10m height)	NO_2	~ 19.8 ug m^{-3}	Trees 20m in height, in a perpendicular wind, reduce NO_2 concentrations compare to smaller trees. This could be due to the higher canopy that can absorb more gases.	
					Tree (20m height)	NO_2	15.7 ug m^{-3}		
			Open road with an average	S	Hedge (*Fagus sylvatica*)	$PM_{2.5-10}$	13 - 17 ug cm^{-2}	Quantifying particle deposition on leaves on both sides of the hedge (facing traffic and	
						$PM_{1-2.5}$	4 - 5 ug cm^{-2}		

Intrinsic and extrinsic characteristics	Evidence (1)	Agreement (2)	Specific characteristic	Method (3)	Species (4)	Pollutant (5)	Concentration/ particles on a leaf, capturing efficiency (%), absorption or emission of pollutants (6)	Comments	Author
			height of 2.2m and thickness of 1.5m			PM_1	0.5 – 0.6 ug cm^{-2}	behind) shows that coarse particles are preferentially deposited on leaves facing traffic rather than smaller particles.	Abhijith & Kumar, 2020
Macro morphological traits	M	M	Low porosity / Canopy porosity ($Cx=1.33m^{-1}$)	CFD - Pheonics	Tree [a]	APs	(+)54% leeward wall (-)39% windward wall	Canopy porosity has a great impact on mean-wall mean concentrations. The impact increases less with lower porosity canopies. Trees improve windward wall concentrations but increase them in leeward walls	Xue & Li, 2017
			High porosity / Canopy porosity ($Cx=1.0m^{-1}$)		Tree [a]	APs	(+)42% leeward wall (-)32% windward wall		
			LAD 3.33 m^2m^{-3}	RANS model	Tree	PM_{10}	(-)10%	High LAD acts as a solid barrier that deflects the wind upward	Ghasemian et al., 2017
			LAD 1.0 m^2m^{-3}		Tree	PM_{10}	(+)15%	Low LAD reduces wind speed and creates smaller eddies behind vegetation with weak recirculation, increasing concentrations	
			Thickness increase from 1m to 10m LAD = $5m^2\ m^{-3}$	CFD - Converge	Vegetation model	Particles 5nm	Filtration capacity increased from 3% to 30%	Increasing vegetation thickness may linearly change the particle filtration efficiency.	Neft et al., 2016
					Vegetation model	Particles 10nm	Filtration capacity increased from 1% to 10%		

(1) Evidence refers to the set of information available in the selected articles that indicates how valid the characteristic is. R = Robust, M = Medium, L = Low

(2) Agreement refers to the level of consensus across the selected articles, H = High, M = Medium, L = Low /

(3) G = Gravimetric, S = Scanning Electronic Microscopy, AS = Air Samplers, CFD = Computational Fluid Dynamic model, RANS = Reynolds Averaged Navier-Stokes (RANS), WT = Wind Tunnel experiment

(4) a) Trees located in a *regular* canyon street (H/W=0.5)

(5) TSP = Total Suspended Particles / APs = Air Pollutants, TPs = Traffic pollutants

(6) Given the wide variety of methods and study designs, a single unit is impossible to define. Capturing efficiency is the percentage of air quality improvement (-) or deterioration (+) with GI. NA = Information not available. * Data extracted from a graph

4.1 Computational models to study green infrastructure in cities

Most studies investigating the aerodynamic effect of GI on streets use a modelling technique. Most of the studies performed by CFD models were limited to local domains (microscale), such as isolated street canyons with parallel same-size buildings, nearby roads, and different GI layouts. Other CFD studies, however, have also modelled the effect of GI on air quality at larger urban scales (mesoscale). For example, in neighbourhood-scale studies. Microscale (< 1km) and mesoscale (10 - 100 km) are the two typical scales used to study the effect of GI on air quality (Figure 29). Microscale studies aim to study the reduction or blocking effect of GI on pedestrian exposure to air pollution (without considering other mechanisms such as biogenic emissions). In contrast, mesoscale studies quantify the “reduction” of pollutants due to green areas.

Meso and microscale studies have sought to identify the impact of GI designs for improving air quality in urban areas. Mesoscale studies have indicated that GI provides an important improvement in urban air quality when extensive green areas are near roads, probably because they are in an open space that allows for more dispersion of pollutants, decreasing concentration locally (Jeanjean et al., 2015; Selmi et al., 2016; Nowak et al., 2018; Rafael et al., 2018). On the other hand, microscale studies have identified various effects of GI on air quality because of local context (Escobedo & Nowak, 2009). In some scenarios, GI worsens air quality by reducing local ventilation and thus increasing pollutant concentrations, while in others, a beneficial impact is provided by GI due to its blocking of pollutants on the pavement. This difference between scales may likely be obvious, but it is important to recognise the studied scale of GI to understand its impact on air quality in cities.

The parameters considered in each scale might be responsible for the variety of results obtained. For example, the percentage of the area covered by GI, crown density, and topographical conditions are dominated by mesoscale studies (Selmi et al., 2016; Tiwari et al., 2019). Instead, species-specific, LAD, deposition velocity, street design, pollutant characteristics, and emission traffic rates are the expected input for microscale studies (Buccolieri et al., 2018b; Tiwari et al., 2019). It is important, therefore, to identify if stand-alone GI or green areas should be discussed in urban planning for air quality improvement at an urban (meso) or a local (micro) scale.

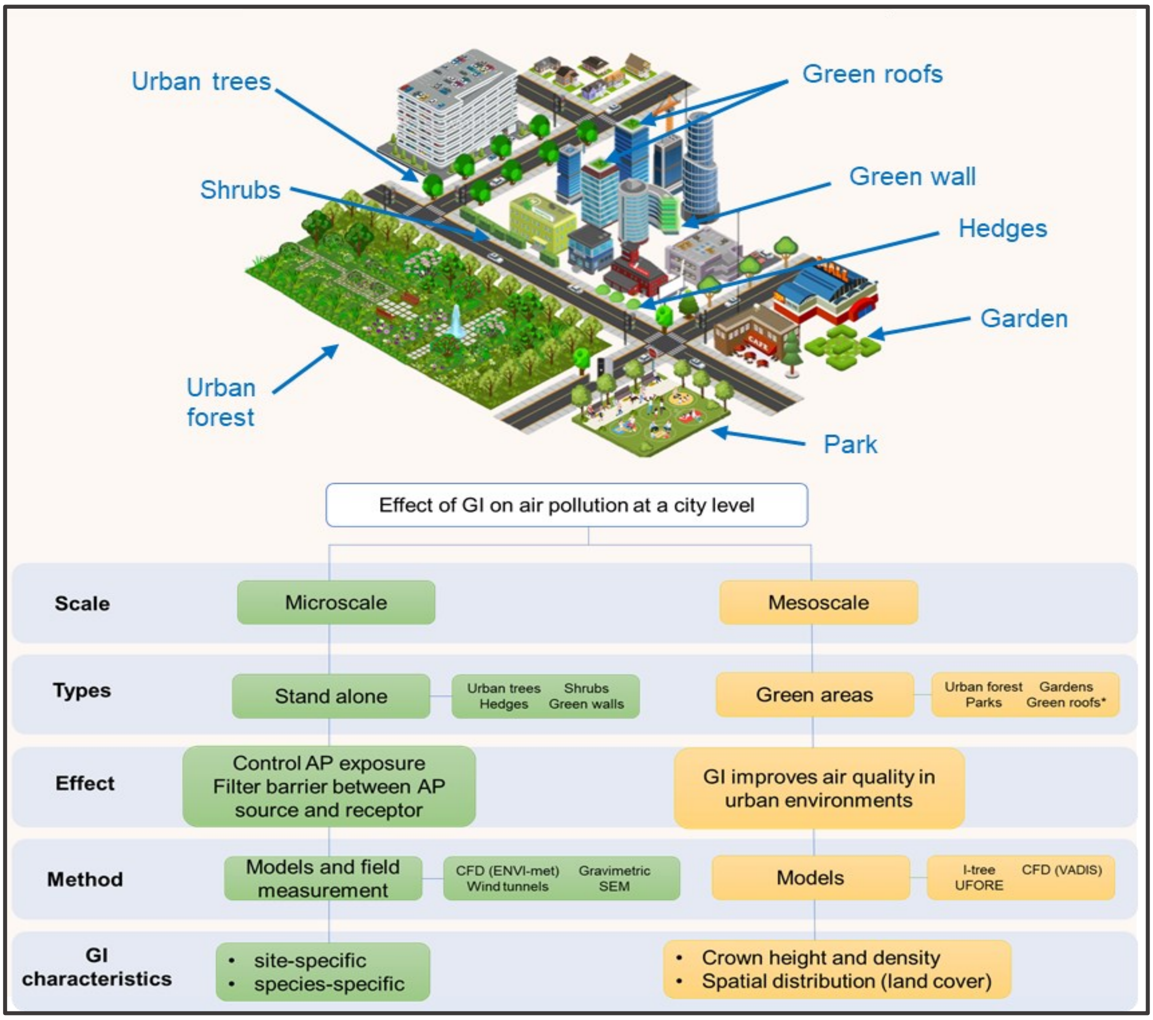

Figure 29. Two scales of research are generally adopted to study the effect of Green Infrastructure (GI) on air quality or the control of air pollution (AP) exposure in cities.
**** Green roofs are considered stand-alone elements in this research, but they are also an area of vegetation, so they are considered green areas in some studies. Source: Own elaboration***

The scale of the study determines the amount of improvement (or deterioration) by GI. Different units (e.g., %, kg/m^2, µg/m^3) provide different perspectives, and only through understanding the variety of units (mechanisms and methods) can a comprehensive view of GI be achieved (Lin et al., 2019). For example, focusing on street canyons, a general conclusion is that trees negatively impact air quality, increasing pollutant concentration on the leeward side of the street (Wania et al., 2012; Vranckx et al., 2015). This certainly, does not indicate that trees in urban forests, neighbourhoods and parks have a similar effect (Vos et al., 2013; Xing & Brimblecombe, 2018). The percentage of reduction or increase is often used to register the effect of stand-alone GI in streets (microscale). Mesoscale studies also use percentages, but since they focus on tree survey data and green cover areas, the results are expressed in terms of the mass of pollutants (g, kg, tonne) per area (m^2, km^2) at a particular time (monthly, annually). Appropriate differentiation between scales is needed to conclude the real effect of GI in a city, a neighbourhood, and a street, a difference that often is not appreciated across GI studies (Donovan et al., 2005; Taleghani et al., 2020; Tiwari & Kumar, 2020).

Challenging aspects in the modelling of GI were identified. Computational models require and improved representation of GI before they can be deemed useful. Clearly, these models try to simplify the complexity of interactions in the real world, but the common values of LAD, for example, may over or underestimate the real impact of GI on streets. Avoiding 'common' vegetation values could provide greater accuracy to the model outcomes. A model study modelled the effect of 'real trees' (trunk, branches, and canopy) using a CFD model (OpenFOAM). The authors found that the canopy influences turbulence distribution in the middle part of the canyon, while the trunk affects pollutant distributions at the pedestrian level (Su et al., 2019). In this work, all the selected studies avoided representing the actual trunk and canopy in the model, so it is strongly recommended that modelling studies include the complete structure of the tree for a better understanding of their influence on air quality.

Under real conditions, vegetation changes the characteristics of the leaves, so depending on the season, different LAD values should be used (Jeanjean et al., 2017). This, however, is a challenge in CFD models, and it is currently not feasible to model individual leaves. Further, this would imply the evaluation of each tree or GI on the street under different seasons, which is impracticable. However, similar or specific LAD values associated with the species under study are highly recommended to evaluate the effect of GI in streets.

Another challenging aspect of modelling studies is simulating more realistic scenarios, including different building heights, construction materials, street configurations, and roof shapes. Roof shapes, slopes, and building height influence the air dispersion inside a street canyon (Takano & Moonen, 2013; Aristodemou et al., 2018). These different street layouts were not considered in any of the selected studies. In general, GI studies remain distant from reality, making it very difficult to provide recommendations to practitioners and authorities on the use of GI to improve air quality.

4.2 Dispersion versus deposition

Modelling the effect of GI on air pollution has focused on deposition (and absorption) *or* dispersion of pollutants, with a reduced number of studies investigating the combined effect of dispersion and deposition (Jeanjean et al., 2017; Xue & Li, 2017; Santiago et al., 2019). So far, there is consensus among researchers that GI affects air quality; however, it is not entirely clear how and to what extent GI helps improve urban air. For some researchers, dispersion prevails over deposition, the latter being four times less important than aerodynamic effects (Jeanjean et al., 2017; Buccolieri et al., 2019), but this depends on the specific scenarios. Other research confirms the opposite or the importance of combining both mechanisms as equally important (Xue & Li, 2017; Santiago et al., 2019; Tiwari & Kumar, 2020). Indeed, a current review conducted by Xing and Brimblecombe (2020a) concluded that studies which included dispersion in their analysis of GI less consistently reported air quality improvements than those focusing on deposition (Xing & Brimblecombe, 2020a).

The porous medium offered by GI influences local dispersion patterns and aids the deposition of pollutants in urban environments (Freer-Smith et al., 1997; Escobedo & Nowak, 2009; Janhäll, 2015). While deposition captures some particles from the local polluted air, dispersion causes particles to redistribute through the air layer in the atmosphere. It is important to note that pollutant reduction efficiency should not be confused with the mass reduced but should rather be measured in terms of the mass blocked or prevented from reaching pedestrians or receptors. For example, hedges, shrubs and hedgerows can decrease concentrations on the pavement but increase concentrations on the road. This should not be forgotten because people still occupy the road and will be breathing in this elevated concentration even while driving their cars (or cycling).

A software tool widely used across academia, and public sectors is the i-Tree/UFORE[19]. The software estimates the percentage of air quality improvement due to dry deposition and quantifies other Ecosystem Services, such as stormwater impacts and energy savings (Nowak, 2020). The i-Tree software does not evaluate the effect of GI ventilation (dispersion) and uses the concept of dry deposition to estimate roadside GI removal. Several studies have used this software to assess the potential removal of air pollutants by green spaces, estimating, for example, that the urban canopy in London could remove between 852 and 2121 tonnes of PM_{10} annually and tree alley in Dublin could remove approximately 3 kg of $PM_{2.5}$ on a yearly basis (Tallis et al., 2011; Riondato et al., 2020). There is considerable uncertainty in these estimates and other estimations given by other CFD models. It should be noted that commonly used models and i-Tree use the PM deposition velocity reported from an old, rural, closed-canopy forest that may not accurately represent real-world conditions at the modelled sites (Lovett, 1994; Hirabayashi et al., 2015) (See Table 2 and Figure 30).

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[19] It was originally developed in the 1990s as the Urban Forest Effects model (UFORE).

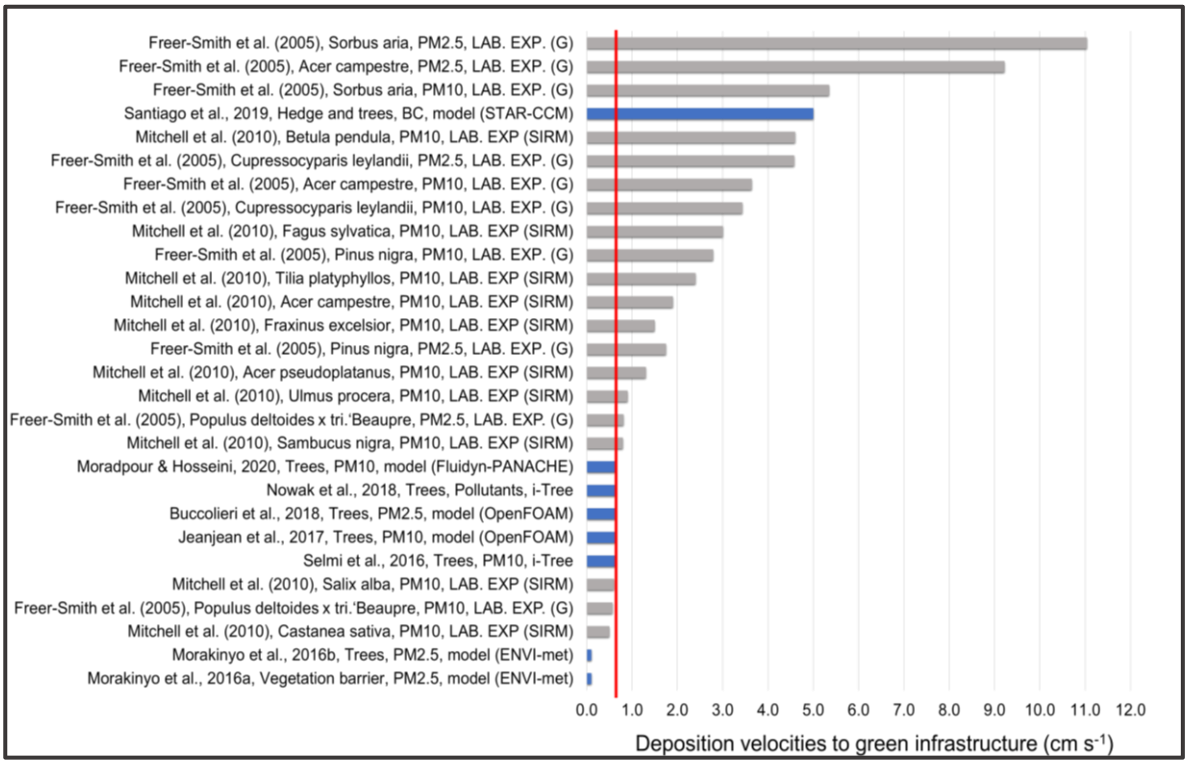


Figure 30. Pollutants deposition velocity for urban green infrastructure reported by modelling studies (blue bars) and laboratory experiments (LAB.EXP.) (grey bars).
The red line shows the average deposition velocity (0.64 cm s^{-1}). Laboratory experiments were performed through saturation isothermal remanent magnetisation (SIRM) or gravimetric (G). Source: Own elaboration.

The selection of deposition velocity in models requires more accuracy since it is associated with leaf traits. In a laboratory study using the SIRM method, Mitchell et al. (2010) measured deposition velocity, using the particles deposited on the leaf. The authors observed that the highest rate of deposition velocity was on leaves with a ridged and hairy morphology; conversely, the lowest deposition velocity was observed for leaves with smooth, waxy surfaces (Mitchell et al., 2010). The common value reported by Lovett (1994) and widely used by modelled studies may be overestimating (or underestimating) removal by GI vegetation. To judge the effect of GI on streets, moreover, to assert the prevalence of dispersion over deposition, or *vice versa*, a better parametrisation in modelling studies is required.

4.3 Linking green infrastructure to air pollution and human health

Green spaces have been recognised for their support in improving physical and mental health and delivering many other benefits (see **Chapter 2**). However, it remains uncertain how GI can provide better health by improving air quality (Nieuwenhuijsen, 2021). According to this literature review, GI through the dispersion mechanism cannot "reduce" pollutant concentrations but instead displaces (disperses and transports) pollutants. The impact of GI on air quality is sensitive to local environmental conditions and street design. Therefore, offering specific recommendations about where and what to plant is currently unfeasible (Tomson et al., 2021). Important findings, however, could be considered for a successful urban planting offering pedestrian-level protection (See Table 13):

- Vegetation barriers (e.g. hedges) located close to the traffic pollution source may provide the best pedestrian attenuation (Baldauf et al., 2013; Abhijith & Kumar, 2019). A barrier (up to 2m) is a good planting option to reduce pavement-side pollutant accumulation in a narrow street, though trees can also play their part along wider open roads.
- In *regular* street canyons, trees with dense and large canopies should be avoided, especially when perpendicular wind prevails. Trees may accumulate pollutant concentrations on the leeward side of this street configuration.
- In open roads and *shallow* street canyons, continuous hedges with a minimum of 2m height and 1.5m thickness should be located close to the roadside.

In all cases, planting decisions must be made in the context of the locally prevailing weather parameters, street design, species characteristics, and the impact on different receptors (pedestrians, cyclists, dwellers).

5 Conclusions

This literature review demonstrates that the effect of GI on air quality in streets is strongly dependent on site and vegetation characteristics. Street design, meteorological conditions, GI location, type of GI and macromorphological traits (LAD, crown, height, porosity, and thickness) influence the dispersion of pollutants (Figure 31). Therefore, the **positive effect of GI on local air quality will be maximised by understanding a variety of physical influences on a highly site-specific context.**

Most authors have adopted different combinations of monitoring and **modelling techniques to assess the effect of GI on pollutant dispersion**. As dispersion is highly context-dependent, the results for one specific type of street and GI should not be extrapolated to other situations. Therefore, **specific studies are necessary to confirm the effectiveness of GI in the streets.**

Research in this area is gathering momentum to investigate the effectiveness of GI in influencing human exposure to street-side air pollution. The utility of CFD models in the design of GI for planting purposes is that they provide science-based knowledge to support implementing actions for improving air quality. **A unified approach and interdisciplinary work** to create more realistic scenarios in modelling techniques are needed for a better understanding of GI's effect on streets. Improving the parametrisation of computational models will enhance urban planting design and help urban GI meet multiple objectives, including helping to improve the air quality in cities.

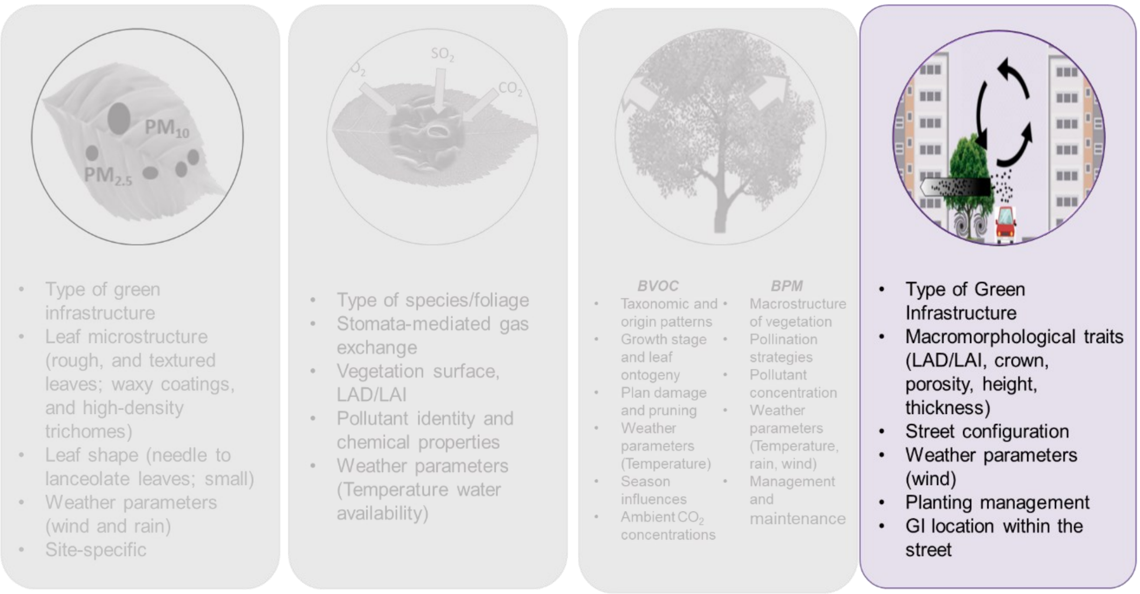


Figure 31. Summary of the main GI characteristics and spatio temporal contexts influencing dispersion (purple rectangle).
The grey rectangles to the left present the GI characteristics associated with deposition, absorption, and biogenic emissions (See Chapter 3 and Chapter 4)

Chapter 6. Analysis of the decision-making process of tree officers in the United Kingdom

This Chapter

- Presents the result of a survey of relevant practitioners aimed at understanding how planting decisions are currently made in the UK.
- Evaluates the weight given to the green infrastructure characteristics influencing air quality improvement.
- Assesses the importance of air pollution mitigation of green infrastructure in the UK.
- Identifies the most common tree species planted in urban areas of the UK.
- Presents a framework to help practitioners incorporate air pollution mitigation into their planting decisions.

1 Introduction

Street-side trees are an integral part of the urban planting designs of many council strategies. According to these strategies, trees offer both aesthetic and wildlife value and environmental, economic, and social benefits, enhancing the quality of life of people living in the city, borough, or street. According to various UK strategy guides, one of the most notable benefits that trees provide to citizens is air pollution control (Mayor of London, 2012; Ealing Council, 2013; Borough, 2015; Manchester City Council, 2017; North Hertfordshire District Council, 2017; Oxford Council, 2021; Reading Borough Council, 2021; Bristol Council, n.d.). In addition, the England Tree Action Plan 2021-2024 encourages the planting of more street trees explicitly for these benefits, particularly improving people's health and well-being (UK Government, 2021).

Planting more trees (GI) or increasing green areas in cities, however, does not ensure air quality improvement. As previous chapters show, the interactions among the urban context, weather parameters, pollutants concentrations, atmospheric chemistry, and GI micro and macro characteristics influence the absorption, deposition, transport of air pollutants and biogenic emissions, creating a complex relationship between GI and air pollution mitigation. These interactions are currently not fully considered in the urban planting resources, strategies, or guides available to practitioners (Barwise & Kumar, 2020).

Little is known about the use of GI and its application in urban design and planning to promote some specific Ecosystem Services (ES), such as air pollution mitigation. Urban planting not only seeks to improve air quality and provide other ES, but it also has to deal with numerous site-specific urban stressors that can impact the growth and survival of GI, including poor air and soil quality, drought, shade, flooding, root compaction and urban heat island effect (Hirons & Sjöman, 2019; Kumar et al., 2019a). Therefore, practitioners such as tree officers must balance multiple considerations for successful urban planting.

This Chapter explores how GI is considered in urban planting for air quality improvement. A questionnaire was provided to practitioners involved in urban planting in the United Kingdom. Practitioners were consulted on the challenging aspects of urban planting, the ES they pursue, and how influential the identified intrinsic and extrinsic characteristics are to their planning of street-side GI. In addition, a comparison was made between some of the typical decisions of practitioners who claim air pollution mitigation as a priority for planting GI and the decision of those who did not. Finally, a holistic framework is introduced to support practitioners of GI implementation in maximising the improvement of air quality.

2 Method

An online questionnaire to exploring how ES, especially air pollution mitigation, is included in the design of urban street-side GI. This was sent to practitioners who work in charities, councils, or organisations across the UK. The questionnaire received ethical approval from Imperial College London in October 2021 (ethics approval number 21IC7186, See Appendix E).

2.1 Questionnaire development

The questionnaire was composed of closed-ended questions and included multiple-choice and Likert-type scales. A total of 17 questions were divided into six sections:

1) **Respondent information.** At the beginning of the questionnaire, respondents stated demographic and professional details, such as the organisation's name, their position, years of experience, and qualifications.
2) **GI definition.** A question asked about the common understanding of GI in their workplace.
3) **Guides, recommendations, and resources available to practitioners.** Three questions were provided about the type of guidance that practitioners usually use for urban planting decisions and what information they contain.
4) **Planting decisions making.** Six questions concerned the practitioner’s experience in urban planting, such as challenging aspects and how to improve planting decisions. They also focused on the benefits (ES) they pursue in urban planting and important site characteristics considered for urban planting.
5) **Species selection and air quality-related questions.** Five questions inquired about the type of street-side GI planted, species characteristics (e.g., size, leaf surface, leaf

shape, tolerance, aesthetics, longevity), and how often air pollution mitigation is considered when practitioners are planning street-side GI.

6) **Final comments.** At the end of the questionnaire, respondents were invited to leave general comments or provide extra information.

Some questions contained an option for 'other' within their provided answer alternatives so that respondents could specify another preference or alternative in free-form text. See Appendix E for the complete questionnaire.

Five of the 17 questions were Likert scale questions. A Likert scale is an ordinal scale that measures beliefs, attitudes, or opinions. The Likert scale uses categories labelled, for example, *'strongly disagree', 'disagree', 'neutral', 'agree',* and *'strongly agree'*, which are assigned a conventional number from 1 to 5 (5-point Likert scale). One question used a 5-point Likert scale in the questionnaire, and the other four questions used a 10-Integer preference scales (10-points). The numeric scores for each point Likert scale were ranked by their median values, and 95% confidence intervals (CI) were calculated to assess the most prioritised option/feature/characteristic consulted.

The remaining questions had answer alternatives that the respondents identified as the most suitable according to their knowledge or experience.

2.2 Questionnaire distribution, target group and recruitment method

The questionnaire was distributed online via the Qualtrics platform to urban planting-related practitioners. Practitioners responsible for or involved in the decision-making process around GI planting on the street in the UK were included in the sample. The practitioners, charities, and organisations in charge of urban planting in the UK were searched, and a list of names and contact details was created. After that, the online questionnaire was sent to practitioners such as arboricultural officers, tree officers, and technical managers. Students or academic researchers interested in urban planting and people under 18 years old were excluded from participation.

The questionnaire was distributed in two waves. The first wave was distributed only in London between July and August 2021. Before distribution, the questionnaire went through several stages of iteration to reduce ambiguities. Once the questionnaire had been adequately prepared, emails with the questionnaire link were sent to tree officer members of the London Tree Officers Association (LTOA). This wave provided an overview of the planting decision in London and highlighted possible inaccuracies in the questionnaire (e.g., order of questions, alternatives). This first wave was supported by the work of an Imperial College London MSc student, Talia Shehadeh, who also conducted interviews that supplemented the survey.

Following an evaluation of the London-based questionnaire based on the answers and comments of practitioners, minor modifications were made to the questionnaire (See modifications in Appendix E, Table 1). The second wave was distributed across the UK and targeted a range of council tree officers, organisations and charities related to urban planting between October 2021 and January 2022. This wave enlarged the sample size from the first wave providing geographical coverage across the UK. It also mitigated any geographic bias towards London and allowed for nationally relevant conclusions on practitioner knowledge about how planting GI delivers benefits (ES) such as air pollution mitigation.

2.3 Data collection

Once the participant opened the questionnaire link, a general explanation of the project, a downloadable participant information sheet and the contact details of the researchers involved appeared. After reading the information, participants had to sign a consent form if they chose to participate in the survey.

Participation in the survey was entirely voluntary and anonymous. The participants were free to withdraw the questionnaire at any time and without giving a reason.

According to Imperial College policies, the data was stored on the Qualtrics platform, and only researchers involved in the project had access to the survey information.

2.4 Data analysis

Descriptive analysis was carried out to assess the questionnaire responses on SPSS (Statistical Package for the Social Sciences) software and Excel^{TM}.

Three statistical analyses were carried out for the air pollution-related questions. See Appendix E, questions 3.4, 3.6, 4.3, 4.4 and 4.5.

The first statistical test used a Chi-square test (X^2) to evaluate whether the two waves of results varied or whether pooling would be possible. Question 4.4 of the questionnaire (see below) was used to run this test.

The second and third statistical analyses were a parametric statistical analysis using the t-test and a non-parametric analogue using the Mann–Whitney U test. The survey data was ordinal, thus a normal distribution could not be assumed. In this case, using a t-test should be used with caution because it is not the preferred method, however, this test is more robust than the non-parametric test and provides quantitative inference (Sullivan & Artino, 2013; DeWees et al., 2020). There is an ongoing discussion about which statistical tests, parametric or not, are better for evaluating surveys (Sullivan & Artino, 2013; Wu & Leung, 2017). So, the tests were used to compare the alternatives selected by two groups (G1 and G2) of respondents.

Question 4.4 in section five was *"How often is air pollution mitigation the main consideration when planning street-side GI?"* followed by five alternatives: *'Always', 'Most of the time', 'Very rarely', 'Never',* and '*Prefer not to say*'. The answers selected by the respondents were grouped into two groups: G1, which represents respondents that always or most of the time consider air pollution mitigation in their planting decisions, and G2, which represents the alternatives *'Very rarely'* and *'Never'*. The last alternative, *'I prefer not to say'*, was not used by any respondent in the survey, so it was not included.

These two groups of respondents, those that prioritise (G1) air pollution mitigation in their planting decision and those who do not (G2), were used in order to evaluate differences in their decisions related to intrinsic and extrinsic characteristics that can influence air quality. The questions and answers of these two groups are presented below (Table 14).

Table 14. Questions and answer alternatives included in the questionnaire to conduct a statistical analysis.

Question	Response format	Characteristics evaluated $^{(1)}$	Aim $^{(2)}$
3.4.How often do you aim to provide the following benefits when planting street-side green infrastructure?	5-point Likert scale	1. Urban cooling 2. AP mitigation 3. Airflow manipulation	Understand variation in views between G1 & G2
3.6. For each site characteristic below, please rate how important or influential each characteristic is to your planting decisions.	10-point Likert scale or 10 points proxy-continuous scale *	1. Urban morphology 2. Street type 3. Meteorological conditions 4. Type of AP present	Evaluate the relative importance of these characteristics to those who do consider AP in their planting (GI)
4.3. For each species characteristic below, please rate how important or influential each characteristic is to your planting decisions.	10-point Likert Scale or 10 points proxy-continuous scale *	1. Size 2.Structural density 3. Leaf surface traits 4. Leaf shape 5. BVOC 6. Pollen emissions 7. Flowering characteristics 8. Fruiting characteristics 9. Adapted to future climate conditions 10. Drought tolerant 11. Pollution tolerant 12. Species tolerant to traffic 13. Pest and disease resistant 14. Maintenance needs 15. Experience/familiarity with the species 16. Evergreen/deciduous 17. Native species	Evaluate the relative importance of these characteristics to species selection
4.5. How important do you think each of the following features are to consider when selecting street-side green infrastructure for air pollution mitigation?	10-point Likert Scale or 10 points proxy-continuous scale *	1. Type of GI 2. Plant species selection 3.Species-specific leaf features 4. Street/road type 5, Location of GI 6. BVOC 7. Pollen emissions	Evaluate the relative importance of these characteristics to those who do consider AP in their planting (GI)

(1) AP = Air Pollution, BVOC = Biogenic Organic Volatile Compound / (2) G1 = respondents that always or most of the time consider air pollution mitigation in their urban planting. G2 = those who very rarely or never do so. * 10 points is not really a Likert scale. Traditionally, the number of points on a Likert scale is three or four, but it is recommended to increase it to ten or eleven to treat the data as a continuous measure, and thus arithmetic operations can be used (Wu & Leung, 2017).

3 Results

The 526 requests to national arborists, organisations, and charities led to 87 completed responses. There was no evidence in the arising data the first wave sample differs from the second wave (X^2=1.38, d.f.=3, ρ=0.71). Both waves were then merged.

The first wave in London gathered 24 responses, and the second wave at the national level had 63 responses.

3.1 Respondent information

The majority of the respondents were tree, arboricultural, green infrastructure, landscape, planning and environmental officers (N=57, 66%); 80% worked in UK district, county or city councils; 18% worked in organisations (e.g., Trees and Design Action Group, Parks for London, Veolia); and the remainder were independent tree/arboricultural officers. See Appendix E, Figures 1, 2, and 3 for more respondents' information.

Seventy-nine per cent of the respondents (N=69) had experience in planning/planting street-side GI in cities, with an average of over 20 years of experience. See Appendix E, Figure 4.

3.2 Green infrastructure definition

More than 60% of respondents thought there was generally a common understanding of the definition of GI in their workplace, but there were some differences among colleagues or departments (N=53, 61%). In contrast, 13% of the respondents indicated there was no consensus about what GI means in their workplace (N=11).

3.3 Planting resources: Guides, recommendations, and resources available to practitioners

The majority of respondents (N=67, 77%) consulted guides for appropriate street-side GI planting. These guides derive mostly from professional bodies and their local council's strategic guides (Figure 32). The most used guides are Trees and Design Action Group (TDAG) (TDAG, 2012, 2021), Hillier Design Guide (Hillier Nurseries & RHS, 2019), GreenBlue Urban Design Guide (GreenBlue Urban, n.d.-b, n.d.-a), Trees in Towns II (Britt & Johnston, 2008), Tree Species Selection for GI (Hirons & Sjöman, 2019), council guides and nursery/planting catalogues. A group of respondents (N=33, 12%) do not follow any specific guidance and instead follow their own knowledge, personal experience of success/failure, and word-of-mouth from colleagues.

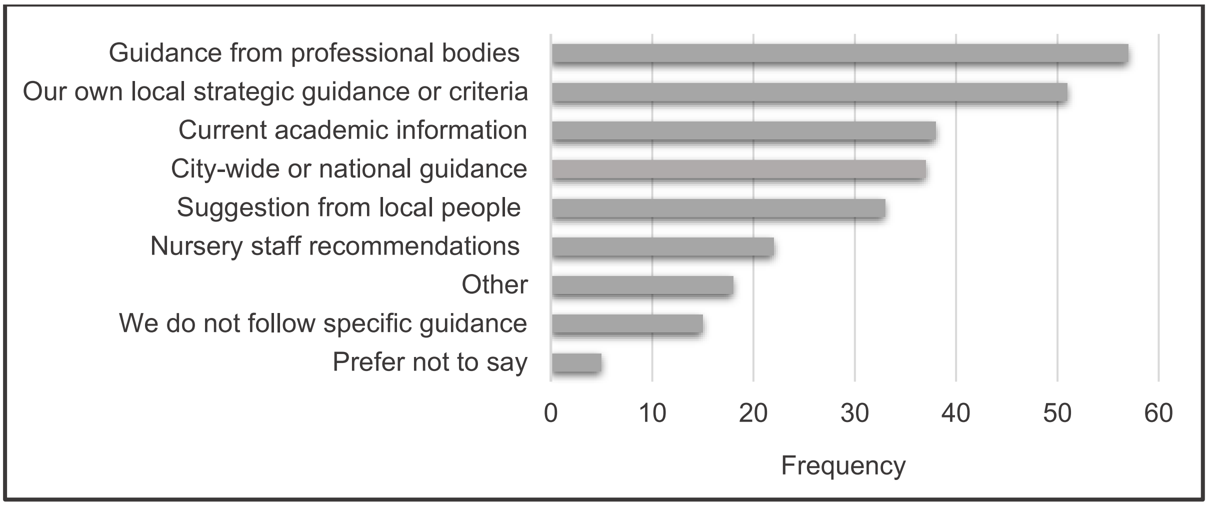


Figure 32. Types of guides, recommendations, and sources used by the respondents (Question 2.2).

Overall, respondents felt that the guidance or resources available are free to access and are easy to navigate and read, although many technical details are sometimes incorporated. These resources follow a species selection principle, identifying a range of GI benefits provided by urban planting. For example, air pollution mitigation is usually considered in the resources available, but biogenic emissions such as pollen and biogenic volatile organic compound (BVOC) emissions are generally not included (Figure 33).

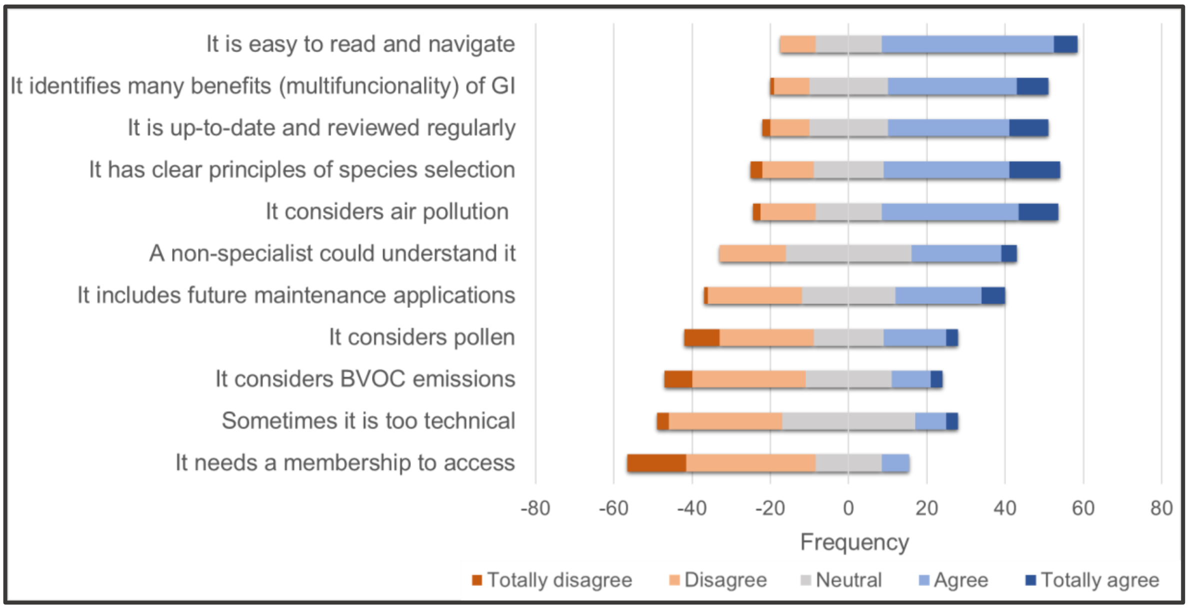


Figure 33. Perceived consideration of the information provided by the resources available to practitioners (Question 2.3).

In a list of additional resources to improve planting decisions, respondents would like to have access to practical workshops (N=33, 29%) and an easy-to-use modelling tool (N=31, 27%) (Figure 34). Access to academic seminars and scientific journals were ranked more poorly, 19% and 12%, respectively. In free form text, respondents also mentioned other resources that they would like to have access to, such as informed specialist advice and political support through clear strategic/policy/legislative directives from government to facilitate urban planting (N=16, 14%).

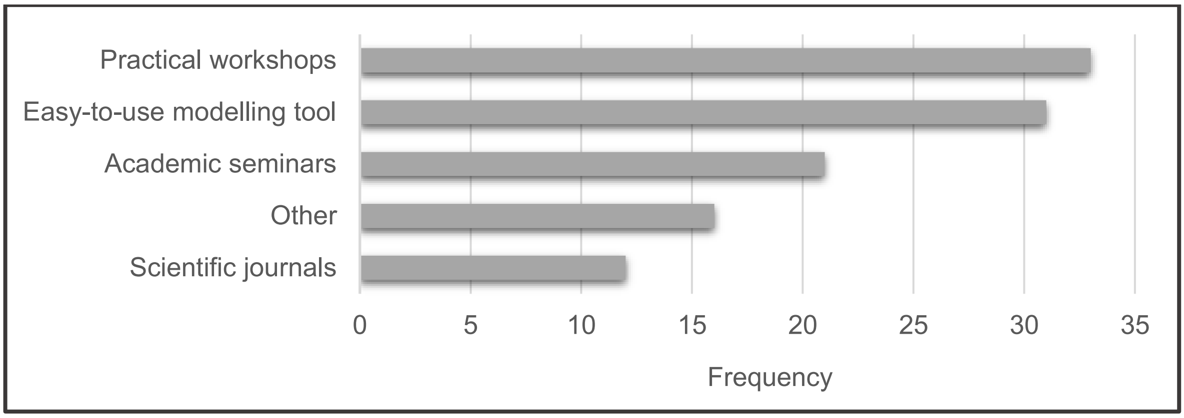


Figure 34. List of options that respondents would like to have access in order to improve their planting decisions (Select two options) (Question 3.3).

At the end of the questionnaire, some respondents expressed other aspects necessary for successful planting. Some of the thoughts were that there is a lack of knowledge about how to design a successful planting, and a multidisciplinary approach is required to achieve it successfully. Additionally, more research is needed on the species and how it might affect air/soil pollution. Some of the comments were:

"There is a total lack of understanding or incentive, and so trees are very much an afterthought" (ID respondent R_2uOla5MzodfOT6i)

"There is a real lack of knowledge about how to design successful tree pits in the landscape architecture industry" (ID respondent R_1LYBrxnBImm03Jx)

"A multidisciplinary approach and agreement is required to achieve a successful outcome" (ID respondent R_2uOla5MzodfOT6i)

"There needs to be more research available for individual tree species regarding air/ soil pollution and how they might affect air pollution/soil pollution" (ID respondent R_3KHZCAFIp7mfpyy)

3.4 Planting decisions

Aesthetics was the most frequently mentioned benefit (ES) pursued by respondents, closely followed by improved health and well-being and then biodiversity. Improved air pollution appeared in fourth position. Airflow manipulation, which would impact air quality, was the least frequently mentioned benefit (Figure 35). In the free-form text, respondents additionally mentioned other GI benefits such as encouraging active travel (walking and cycling), improving the relationship between people and trees, mitigating pollution around schools and nurseries, providing multifunctionality, disguising traffic noise, resilience to climate change, healthy eating (fruits and nuts), traffic calming, educational purposes, and biodiversity connectivity (data not presented in Figure 35).

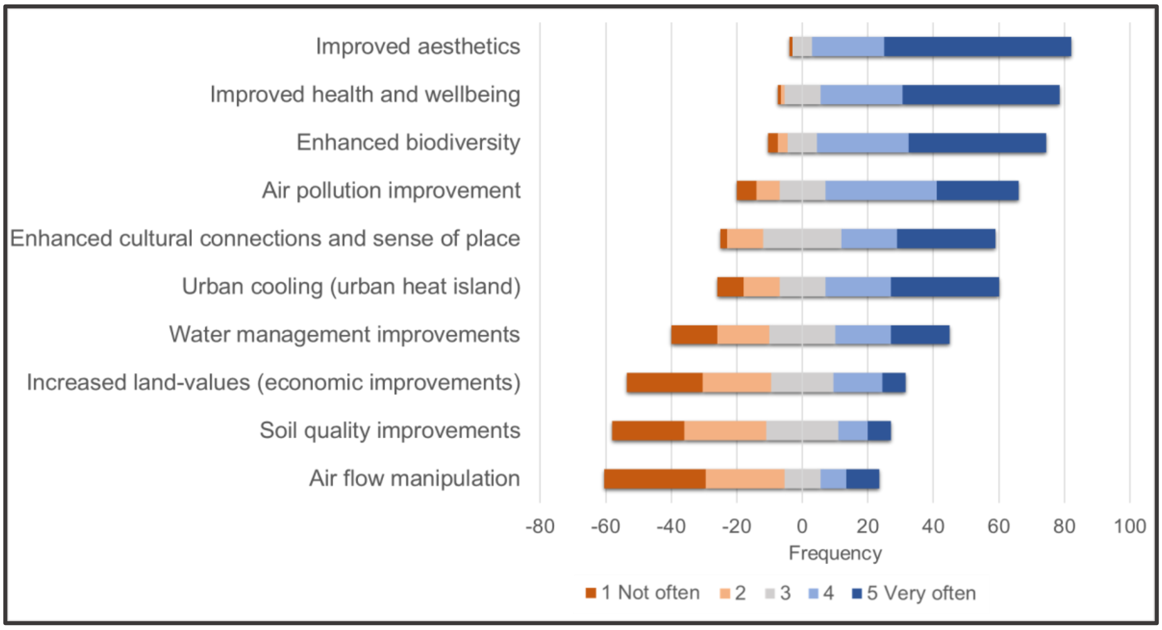


Figure 35. Frequency of specific benefits pursued when street-side green infrastructure is planted (Question 3.4).

Of all the challenges in planting decisions ranked by respondents (asked to select the top three in a list), identifying the most suitable location was the most frequently cited in the first option, followed by future maintenance and, with equal frequency, in the third option, social and economic aspects (Figure 36). Identifying the best species to plant, considering and optimizing multiple co-benefits, and time available for planting were mentioned least often. In the free-form text, respondents identified other challenging aspects, such as a small budget for urban planting:

"Management and maintenance budgets (lack of)" (ID respondent R_2veNqQNXkzY7pPQ)

"As mentioned in the survey the main constraints are the cost to plant with proper root management and the ongoing maintenance" (ID respondent R_1FzGSW986vnn0kM)

"[…] Often due to lack of funds there is little or no budget for tree planting […]" (ID respondent R_2fq6CT5j7741RzA)

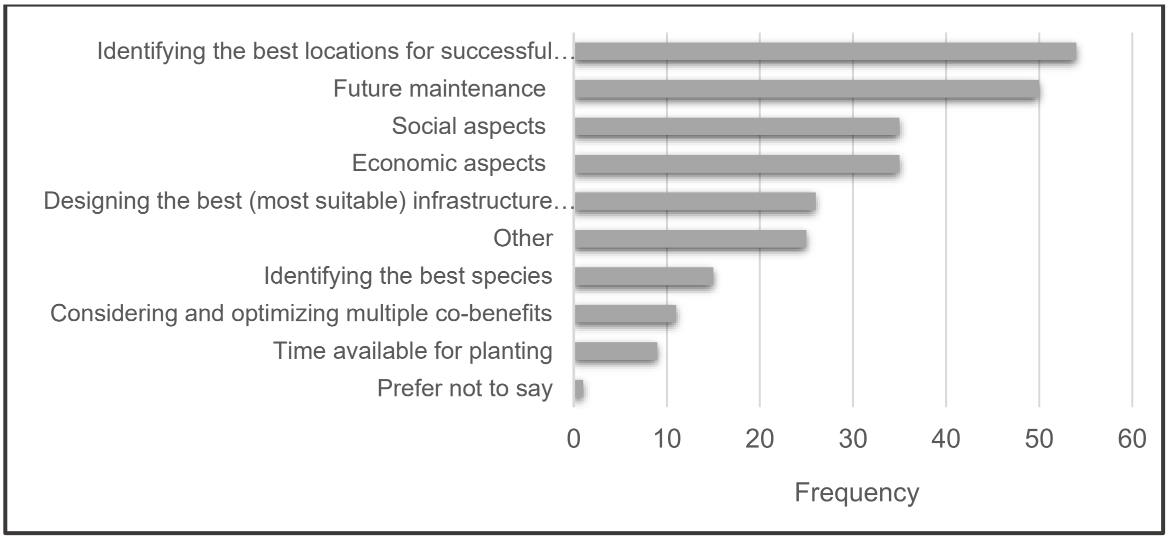


Figure 36. The most challenging aspects of planting decisions perceived by respondents (asked to rank top three) (Question 3.2).

Rooting environment (e.g., underground service cables), followed by the use and type of street (residential, shopping, quiet, busy), increasing biodiversity and budget were the most frequently cited as extremely important site-specific characteristics for planting decisions. Present air pollution concentrations were at the bottom of the list in frequency of importance, followed only by present soil pollution (Figure 37). In free-form text, several respondents (N=25) expressed concern about the rooting environment. Underground services, utilities, and existing infrastructure (e.g., services, drainage, highways) present challenges when selecting a site to plant GI. Some of the comments written are below:

"The biggest problems are underground services and the difficulty of getting sufficient space for large planting pits for trees" (ID respondent R_ONHufD190mWXFdv)

"Planning around existing infrastructure constraints/demands e.g., services, drainage etc. and highways constraints" (ID respondent R_r6fus1Yuvj73Q7T)

"The main impact arises from existing underground service utilities" (ID respondent R_3ho9PPZuCeE37rv)

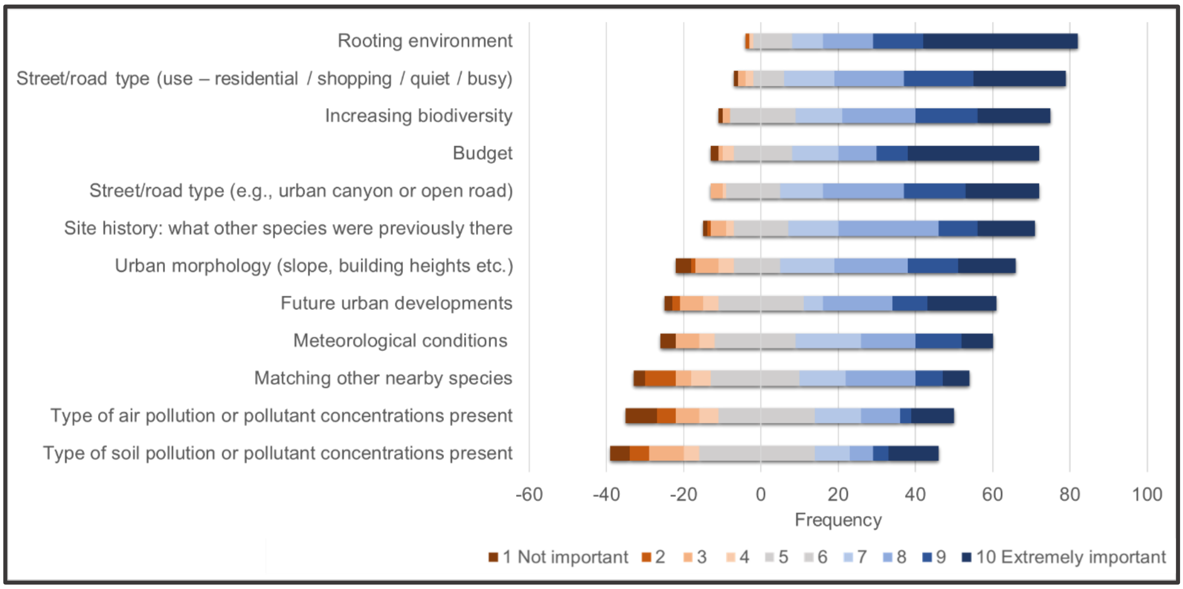


Figure 37. Importance of specific site characteristics in planting decisions (Question 3.6).

3.5 Species selection

The most frequently planted GI on streets is trees, followed by shrubs and hedges, and after that, as four and fifth options, are verges and green walls. The respondents' top five tree species commonly planted in the streets were *Acer spp.* (maple), *Prunus spp.* (cherry), *Tillia spp.* (lime), *Betula spp.* (birch), and *Sorbus spp.* (rowan or whitebeam). Other species, such as *Quercus spp.* (oak), *Carpinus spp.* (hornbeam), *Liquidambar spp.* (sweet gum), *Platanus spp.* (London plane) and *Pyrus spp.* (pear tree) were also widely mentioned for designing street-side planting (See Appendix E, Table 2).

In a list of twenty-three species-specific (intrinsic) characteristics, crown shape and height of the species were the most influential intrinsic characteristics in planting decisions, followed by species tolerant to pests and diseases, those adapted to future climate conditions, maintenance needs and aesthetic attributes. The four least important, according to respondents, were pollen emissions, leaf surface traits, BVOC emissions, and leaf shape (Figure 38).

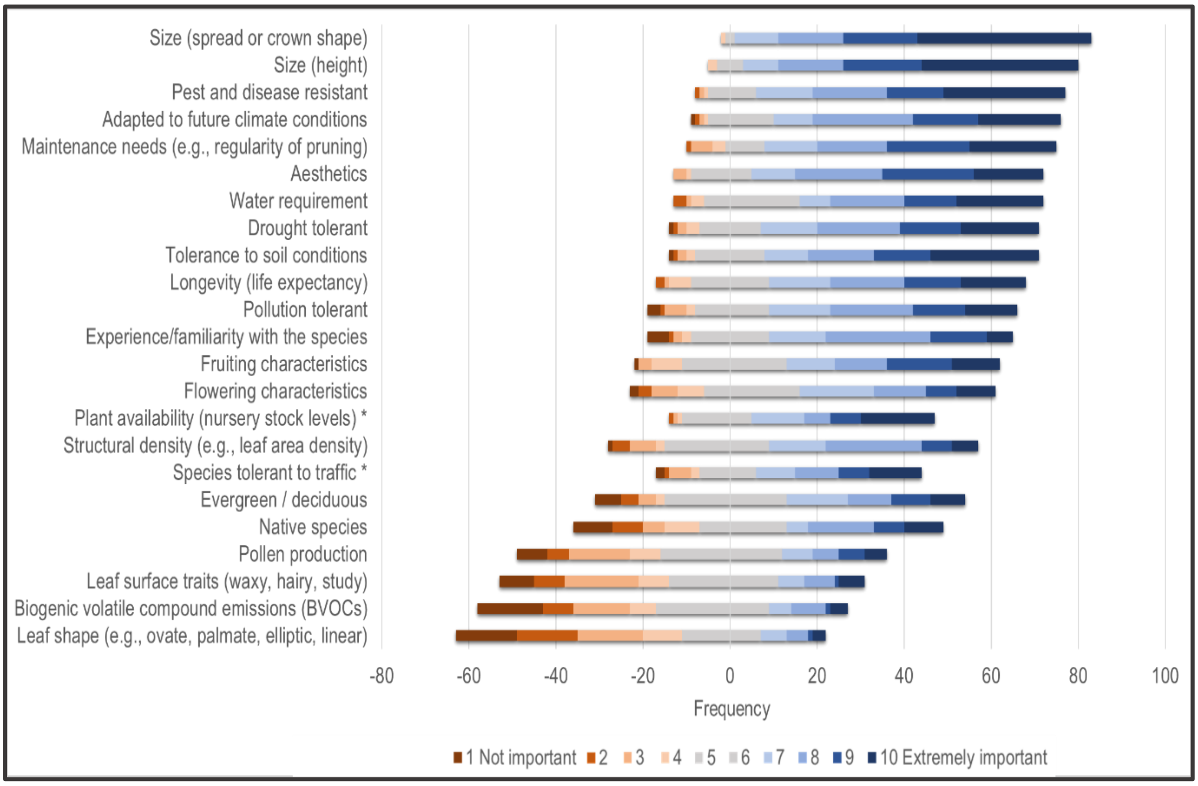


Figure 38. Importance of specific species characteristics in urban planting decisions.
**** 'Plant availability' and 'species tolerant to traffic' alternatives were only asked in the second wave (Question 4.3).***

3.6 Air pollution mitigation

Sixty per cent of respondents considered air pollution mitigation in their GI urban design *'Always'* or *'Most of the time'*. The remainder (N=35, 40%) *'Very rarely'* or *'Never'* considered air pollution mitigation when planning street-side GI (Figure 39).

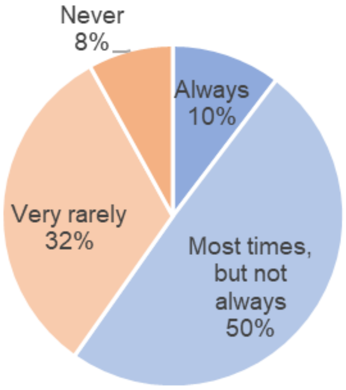


Figure 39. How often air pollution mitigation is considered in GI urban designs (Question 4.4).

When selecting street-side GI for air pollution mitigation respondents felt that location of the GI, followed by the type of street (canyon or open road), plant species selection and the type of GI were the most important characteristics to consider. The last three in the list were species-specific leaf traits, BVOC and pollen emissions (Figure 40).

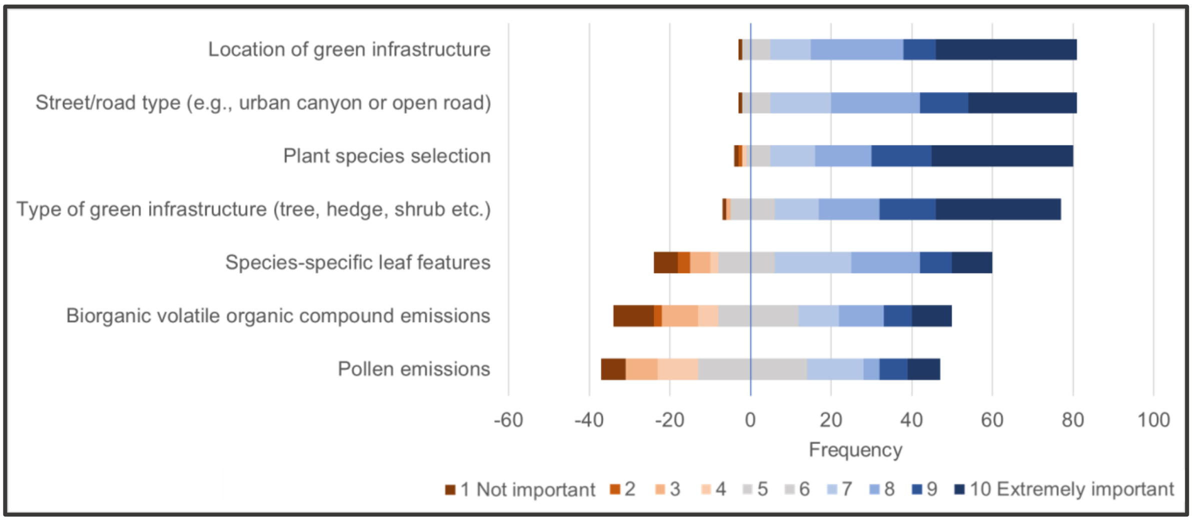


Figure 40. Features considered when selecting street-side GI for air pollution mitigation (Question 4.5).

3.7 Characteristics selected in urban planting when air pollution mitigation is prioritised

Differences in the appraisal of planting characteristics between those who reported frequently incorporating air pollution goals into their planting decision-making were compared with those who did not typically consider air pollution mitigation as an objective. According to Question 4.4. in the questionnaire (*How often is air pollution mitigation a main consideration when planning street-side green infrastructure?*), two groups of respondents were created. Group 1 (G1) represents respondents who always and most of the time considered air pollution mitigation in their planting decisions, representing 60% of the respondents. Group 2 (G2) represents respondents who rarely and never considered air pollution mitigation in their planting decisions, representing 40% of the respondents (Figure 39). Below, these two groups are presented in terms of their responses concerning the benefits, GI characteristics and site-specific alternatives that could influence air quality. See Appendix E, Figures 5 and 6 to see the statistical analysis for all the questions and alternatives.

Regarding the two groups of respondents, both stated having experience planning/planting street-side GI in cities. G1, however, comprises 35% of respondents with more than 30 years of experience in the field, unlike G2, which only has 17% of respondents with more than 30 years of experience.

Both groups indicated following their own local strategies or guidance from professional bodies to inform their planting decisions. However, the guidance of these two groups differs in their content. 38% of G1 respondents confirmed that the guidance they use includes future green infrastructure maintenance applications; in contrast, 60% of the respondents in G2 disagreed with the inclusion of this information in their guidance. Similarly, 63% of respondents of G1 confirmed that their guideline considers air pollution information, for example, specific species or characteristics of plants. However, 49% of G2 respondents feel that their guide does not contain information on air pollution. Additionally, G1 uses more comprehensive and updated guidance than G2. 60% of G1 respondents agreed that the guide is up-to-date and regularly reviewed. In contrast, 49% of G2 respondents believe that their guide is not regularly updated.

Regarding biogenic emissions, BVOCs and pollen, both groups felt that this information is not included enough in their guidelines. 31% of the G1 respondents remained neutral regarding the BVOC information contained in their guides, and 29% felt that only sometimes pollen information is included. However, the G2 group respondents were more categorical, confirming that BVOC and pollen information is not considered in the guides they use for urban planting. 63% of G2 respondents felt that BVOC is not considered, and 57% confirmed the same for pollen information.

G1 consider other benefits related to air quality more often than G2. For example, G1 considered urban cooling (urban heat island) ($U = 536$, $\rho = 0.001$), air pollution improvement ($U= 331.5$, $\rho = <0.001$) and airflow manipulation ($U = 560$, $\rho = 0.007$) more important than G2. These three benefits, however, had the lowest preferences in both groups (Figure 41).

In terms of addressing air pollution mitigation, meteorological conditions (weather parameters) ($U = 750.5$, $\rho = 0.21$) and the place where GI will be planted (location of GI) ($U = 804.5$, $\rho = 0.72$) were assigned an almost equally high level of importance by both groups. However, respondents from G1 considered site-characteristics, such as urban morphologies (e.g., urban elements around, slope, building height) ($U = 458$, $\rho = <0.001$) and the type of street (street canyon and avenues) ($U = 616.5$, $\rho = 0.019$), more important than respondents from G2.

Another site characteristic valued as being more important in G1's decision-making process than for G2 was the pollutant concentrations present at the site ($U = 322.5$, $\rho = <0.001$) (Figure 41).

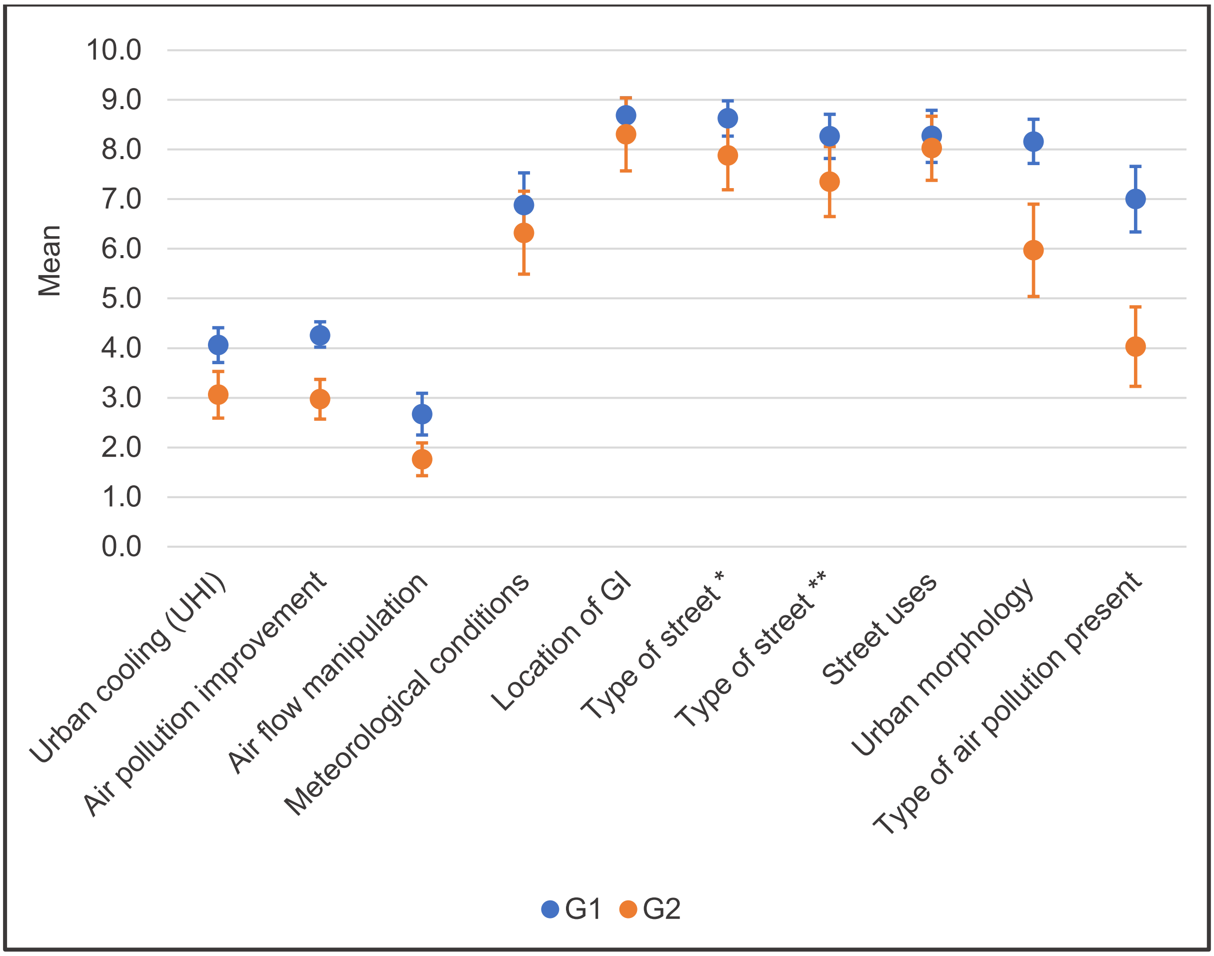


Figure 41. Mean score from 1-10 scale with 95% coefficient intervals (CI) for site-specific characteristics related to air quality.
Type of street was asked in two questions: Question 4.5 How important the type of street (urban canyon and open road) is considered when selecting street-side green infrastructure for air pollution mitigation (*) and Question 3.6., rate how important or influential type of street is in planting decisions (**)

Some selected species characteristics were also different between the two groups. For G1, in comparison to G2, the more important species characteristics included species height (U = 635, ρ = 0.03), structural density (e.g., LAD) (U = 563, ρ = 0.01), habit of the species (evergreen or deciduous) (U = 622.5, ρ = .003), tolerance to soil conditions (U = 525.5, ρ = <0.001), drought (U = 473.5, ρ = <0.001), pollution (U = 349.5, ρ = <.001), and traffic (U = 235.5, ρ = <0.001), adaptation to climate conditions (U = 476.5, ρ = <0.001), and pest and disease resistance (U = 444.5, ρ = <0.001) (Figure 42).

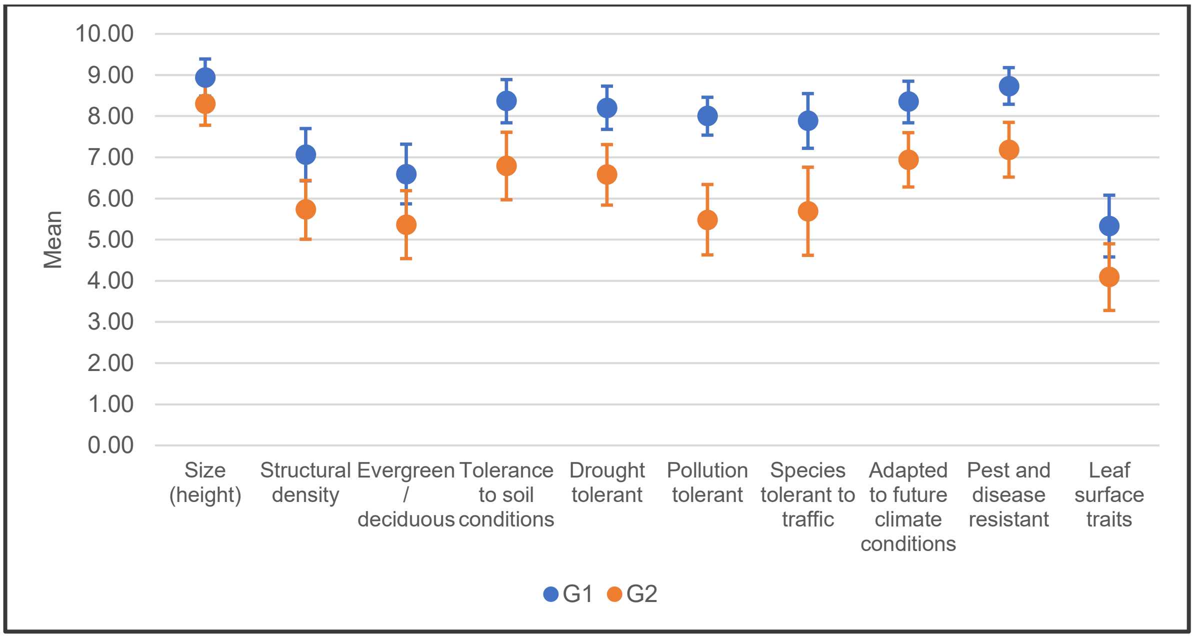


Figure 42. Mean score from 1-10 scale with 95% coefficient intervals (CI) for species-specific characteristics related to air quality.

The specific characteristics of biogenic emissions, such as pollen and BVOC emissions, were presented as answer alternatives in two questions. First, in Question 4.3, where biogenic emissions were associated with species characteristics in planting decisions, and second, in Question 4.5, which detailed specific characteristics to consider when selecting GI for air pollution mitigation. In both questions, G1 ranked pollen emissions as an important species characteristic to consider in their urban planting decisions, in comparison with G2 (U = 568.5, ρ = 0.01). Hence, species characteristics associated with pollen production, such as flowering (U = 486 ρ = <0.001), fruiting (U = 507.5, ρ = <0.001) and maintenance (e.g., regular pruning) (U = 548, ρ = <0.001), were considered more important in G1 than G2 (See Appendix E, Figure 6).

The results were slightly different with regard to BVOC emissions. Similar to pollen, BVOC emissions were included as options in two questions. The first question (Question 4.3) was about the relative importance of a list of species' (intrinsic) characteristics for planting decisions. In this case, G1 considered BVOC emissions more important or influential in planting decisions than G2 (U = 568.5, ρ = 0.01). However, in the second question (Question 4.5), BVOC emissions were consulted as a specific characteristic for air pollution mitigation. In this case, G1 did not present a distinct result from G2 (Figure 43). Therefore, there was no evidence that BVOC emissions were considered part of species selection in this context.

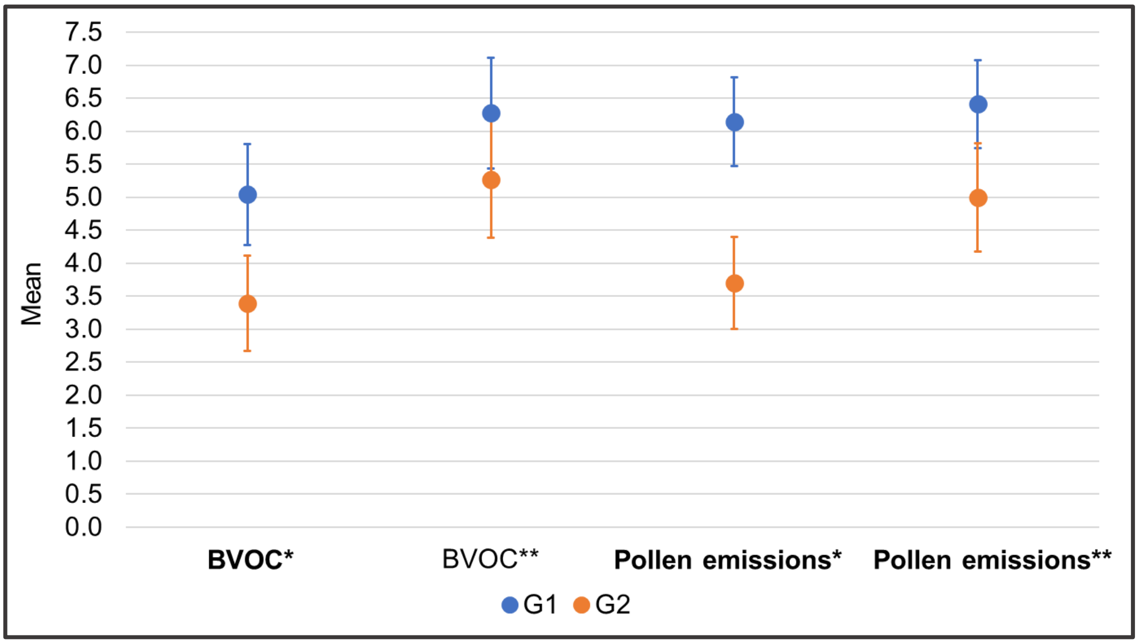


Figure 43. Mean score from 1-10 scale with 95% coefficient intervals (CI) for biogenic emissions, biogenic organic volatile compounds (BVOC) and pollen emission.
The asterisk represents the same alternative in different questions. Bold biogenic emissions are statistically significant. * Question 4.3 refers to species characteristics in planting decisions, and ** Question 4.5 refers to considered features when selecting street-side green infrastructure for air pollution mitigation

The parametric and non-parametric statistical analysis can be found in Appendix E, Tables 3 and 4.

4 Discussion

Online questionnaires have become an important tool in social research as many respondents can be reached at a minimal cost (Van Selm & Jankowski, 2006; Stockemer, 2019). Using an online questionnaire was possible to gather answers from different tree practitioners in UK districts over a few months. The questionnaire was anonymous, so respondents were more likely to provide honest answers and information about practical urban planting (Van Selm & Jankowski, 2006; Fogli & Herkenhoff, 2018). In addition, the questionnaire was sent by email, so the respondents faced a relatively simple task of completing and returning it according to their time availability (Van Selm & Jankowski, 2006).

The questionnaire revealed that among all the benefits that GI brings to the streets, the most sought-after benefits, according to respondents, are improving the aesthetics, improving the health and well-being of people and enhancing biodiversity, with improving air pollution as the fourth option. More than half of the respondents always or most of the time consider air pollution mitigation in their urban designs for GI.

For a successful planting, multiple aspects need to be evaluated in terms of the site and species to be planted. According to respondents, identifying the best location for successful planting is the most challenging aspect of urban planting. The location is associated with searching for a suitable place for the species (including its roots) to grow, the ways in which the street is being used, increasing biodiversity and the budget. Identifying the species is also a challenge. The size of the crown, height, resistance to pests and diseases and adaptation to climatic conditions are considered the most influential species characteristics.

4.1 Conceptualising green infrastructure for practical uses

The variation in the definition of GI is a common situation across workplaces, since the definition and interpretation of GI differ across disciplines (Wright, 2011; Matthews et al., 2015). Finding common understanding among other departments or professionals is an important challenge, as GI can help alleviate a wide range of urban problems, such as air pollution, heat and noise levels, streetscape beautification, and flooding, which often require the input of other actors in urban planting decisions. Defining GI for a specific targeted aim accentuates the strategic benefits of GI and improves planning interventions (Wright, 2011; Matthews et al., 2015).

Within urban planting, the common understanding identified by respondents could be attributed to them all being tree/arboriculture officials or related practitioners with experience in planning/planting street GI. They regularly follow guidance from professional bodies or local guides, which provide substantial standardisation of the concepts and language. However, the guides used by practitioners only provide information oriented towards urban trees. Developing other urban planting guidelines that consider the wide range of GI, such as shrubs, hedges, green roofs, and green walls, could increase, diversify, and maximise GI benefits.

According to most of the respondents, additional tools, such as practical workshops and easy-to-use modelling tools could improve the planting decision. Practical workshops could help address some of the challenges faced by local authorities through facilitating discussions of urban planting case studies and collective decision-making processes (Ordóñez, 2021). Improving knowledge of GI in a practical way helps local authorities and practitioners to develop high-quality GI, to maximise its benefits, and to give a solid response to climate, ecological and public health emergencies (BwN, 2022). For example, Building with Nature, a conservation centre collaboration between Gloucestershire Wildlife Trust and the University of the West of England, offers practitioners a series of online training courses for practitioners (https://www.buildingwithnature.org.uk/).

Easy-to-use modelling tools could help practitioners identify suitable types of GI and locations in a street. As discussed in **Chapter 5**, this is particularly relevant to making sense of GI and its effects on air pollution dispersion in site-specific contexts. The high respondent ranking of this option (27%) may indicate a recognition on the part of practitioners of the high complexity of making planting decisions as well as the local specificities that render generalised rules inadequate. For these site-specific conditions (extrinsic characteristics), computational tools could help contextualise the location of GI to maximise air pollution mitigation and study the dispersion of pollutants. Other researchers have become aware of this requirement, releasing a prototype software last year. Green Infrastructure for Roadside Air Quality (GI4RAQ) seeks to reduce exposure to road transport pollution using GI. The software quickly estimates the impacts of roadside vegetation barriers (focusing solely on bushes and hedges) on air quality (Pearce et al., 2021). According to the software authors, the software is still under evaluation but will be released to researchers and practitioners soon.

4.2 Planting decisions

4.2.1 Benefits pursued when planning streetside green infrastructure

Improved streetscape aesthetics is the main benefit that practitioners pursue in urban planting, followed by improved health and well-being, both highly related benefits. Adding GI to our living space is associated with a positive change in cognition and emotion, impacting mental health and well-being. Todorova et al. (2004), in a photomontage-based study of street-planting simulations in Sapporo, Japan, found that street trees had the main effect of improving visual comfort (Todorova et al., 2004). Similar results were presented by Schroeder et al. (2006) in a survey conducted among residents in North Somerset and Torbay in southwest England and Chicago, USA. The authors found that the main benefit provided by street trees was that they were pleasing to the eye (Schroeder et al., 2006). Although to date the connections between aesthetic pleasure, health and well-being to street trees and other GIs have not been thoroughly researched, the aesthetic value of GI for life-enhancement and the improvement of cognitive function is well known (Cooper et al., 2016; Kondo et al., 2018).

The third benefit pursued by practitioners is the improvement of biodiversity. Although street-side GI, especially trees, has been recognised as important for aesthetic and human well-being in cities, their capacity for increasing biodiversity has been subject to less exploration (Liu & Slik, 2022). Moreover, other street-side GI, such as shrubland, verges, and grassland, are infrequently studied, so their effects are unknown (Filazzola et al., 2019). Other GI, however, has been studied. A green roof, for example, brings about substantially more biodiversity than a conventional roof (Wooster et al., 2022). These two types of roofs were studied in Sydney, Australia, where at the green roof sheltered four birds, two gastropods and 26 arthropod species compared to one bird, zero gastropods and three arthropod species on a conventional roof (Wooster et al., 2022). It would be interesting to study the potential of roadside GIs to affect biodiversity due to the large area they occupy in cities.

It remains unclear why respondents indicated this benefit for roadside GI, probably by the common understanding that vegetation contributes to biodiversity, but it will depend on the environment where GI is found. In the highly stressed urban roadside environment, insects and pollinators (bees, flies, wasps, beetles, butterflies and moths) struggle to survive, and traffic-related pollution can negatively impact biodiversity on streets (Fisher et al., 2022). Increased biodiversity will also depend on the pollination strategy of the species. If the species is pollinated due to the wind (anemophily), as most of the species planted in the UK (Table 15), pollinators are not required, and thus animal biodiversity is minimised. Further research on the potential of roadside GI to increase biodiversity is needed.

Air pollution improvement was the fourth most popular benefit pursued in urban planting, and 60% of the respondents '*Always*' or '*Most of the time*' considered this benefit while planning street-side GI. Green infrastructure policies and guidance emphasise this benefit in their information on GI plantings. For example, the 25 Year Environment Plan of England or the London Plan 2021 states that urban GI helps cleanse pollutants, thus improving air quality (HM Government, 2018; GLA, 2021). However, how many air pollutants can be removed by GI is still uncertain because this is dependent on site and species characteristics.

Quantifying the air pollution mitigation benefits of specific GI planting designs would require the individual assessment of a planting scheme, and practitioners are unlikely to have the budget and computational technologies to carry this out. i-Tree, however, is a software that has been used among practitioners to quantify ES, such as air pollution removal, carbon storage and sequestration, among other benefits (Nowak, 2020). The software results are largely determined by the location and characteristics of species (so far, only trees), taking into account the height, trunk diameter, crown, sun exposure, and tree condition, thus limiting the transferability of the results to other cities or areas (Barwise & Kumar, 2020; Tomson et al., 2021) (See **Chapter 5**, Section 4.2 for more discussion about i-Tree software).

4.2.2 The challenges of urban planting in the UK

Finding the most suitable location was the most frequent challenge identified by respondents. The spatial scale and distribution of GI reflect socioeconomic dynamics and historical planning decisions made by councils. In addition, GI may also present disservices, such as tree/branches falls, root damage, pollen allergies, and maintenance concerns. These disservices will necessarily constrain the location of GI in the built environment (Pataki et al., 2021). Identifying the most suitable location for GI includes two approaches. First, to find a place where GI does not interfere with the street's functioning, such as traffic lights, CCTV, parking spaces, underground services and utilities, spaces for rooting, highway constraints, and the requirements of pedestrians and wheelchair users (BS 8545:2014; GreenBlue Urban, n.d.-a). Second, as street GI is exposed to multiple urban stressors such as traffic, injuries, poor irrigation, and lack of space, the species should be tolerant of urban environments to ensure survival on that site (Tan & Shibata, 2022).

Identifying a proper GI location is also associated with the spatio-temporal context that influences air quality. As the effect of GI on air quality improvement is highly context-dependent (**Chapter 5**), selecting a suitable location for air pollution mitigation purposes adds another requirement to the two approaches discussed above. These multiple considerations for planting GI in the right place, whether for improving air quality and/or planting successful urban plants, could be targeted with an easy-to-use modelling tool.

Maintenance was the second challenging aspect identified by respondents and was associated with extra resources and costs. Arboricultural budgets are often under-resourced, restricting the work of practitioners and site and species selection. In addition, poor GI maintenance can extend the flowering period, increasing pollen emissions and worsening air quality.

4.3 Consideration of air pollution mitigation in street design

4.3.1 Species selection for designing street-side planting

Trees are the most planted GI, and the ten most planted tree species are deciduous, and only a few species have leaf traits such as surface roughness, trichomes, and waxy coating (Table 15). Leaf traits, such as leaf shape and leaf surface, were not important to respondents, and were thus not deciding factors for species selection, with the opportunity lost for capturing particles through deposition (**Chapter 3**).

The most commonly used street trees planted emit low or medium rates of BVOC and pollen. Although BVOC is among the three least important species characteristics and is also not often considered in planting guides, this result demonstrates that respondents have, unknowingly, selected low-emitting species. A similar selection is the case for pollen. The most common species have low pollen emission, except for one species, *Platanus hispanica* (london plane), known as a high pollen emitter. This species is the main trigger agent of pollen allergies (Cariñanos et al., 2019) and is one of the most common species in Inner London (Rogers et al., 2015). According to the Woodland Trust, a British conservation charity, the london plane is valued for its aesthetic attributes and ability to adapt to urban conditions, with a tolerance to air pollution, saline soil and severe pruning, making it widely planted in large streets (Hillier Nurseries & RHS, 2019; Woodland trust, 2022).

Nearly all of the most commonly planted species have visual attributes that reflect the benefits aimed for when planting GI. Visual attributes such as leaf colour, height, and canopy size could affect people's preferences and could bias individual species selection. The problem with planting trees based solely on their aesthetic appeal is that other benefits (ES) are neglected. Therefore, effective tree selection should consider four factors: 1) Constraints, 2) Tree ecophysiology, 3) Ecosystem Service, and 4) Aesthetics (Hirons & Sjöman, 2019).

In addition, to ornamental qualities, tolerance and adaptability for urban environments should also be considered in urban planting. Tolerance to drought, pollution and traffic, resistance to pests and diseases, the size and characteristics of the crown, maintenance and longevity of the species are the main characteristics for ensuring the survival of a species on the streets (Hirons & Sjöman, 2019). However, eight out the ten most common species selected by respondents are medium or highly susceptible to pest or diseases (Table 15). For example, *Acer campestre* is susceptible to mildew, a fungus that only attacks maple species. *Prunus avium* is infected with the honey-dew produced by aphids, especially in late summer. *Betula pendula* is very sensitive to various pests that affect tree health and aesthetics, causing injuries and death of the tree (Hillier Nurseries & RHS, 2019; Hortipedia, 2022). Inappropriate species selection, favouring only one tree characteristic, may reduce the benefits delivered and cause economic losses due to high maintenance or tree replanting.

Table 15. The ten most commonly planted tree species in urban areas of the UK with their botanical information, biogenic emissions, and tolerances.

					Leaf traits				Biogenic emissions			Tolerance			
Species (common name)	**Habit** (1)	**Size**	**Crown shape**	**Crown density** (2)	**Leaf shape** (3)	**Leaf surface**	**Presence of trichomes** (4)	**Waxes**	**BVOC** (5)	**Pollen**	**Pollination strategy** (6)	**Air pollution**	**Drought**	**Aesthetic attributes**	**Pest and disease resistance**
Acer campestre (field maple)	De	Medium	Oval	D	Lobed	Soft	Pubescent	Yes	Low	Medium	E	No	Strong	Yes	Medium (mildew)
Prunus avium (wild cherry)	De	Medium	Ovoid to round	M	Oval	Smooth	No	No	Low	Low	A	Yes	Low	Yes	Highly susceptible (aphids)
Tilia europaea (lime)	De	Large	Pyramidal	D	Cordate	Rough	Yes	Yes	No found	Medium	E	Yes	Medium	No	Medium (aphids)
Betula pendula (silver birch)	De	Medium	Oval to pyramidal	M	Ovate	Soft	Pubescent	Yes	Medium	Medium	A	Yes	Medium	Yes	Highly susceptible (F/A)
Sorbus aucuparia (mountain ash)	De	Small to medium	Spherical	M	Pinnate	Soft	Pubescent	Yes	Low	Low	A	Yes	Medium	Yes	Highly susceptible (B/F)
Quercus robur (English oak, red oak)	De	Large	Oval, round	M	Obovate	Rough	Yes	Yes	Medium	Low	A	No	Strong	Yes	Highly susceptible (fungus)
Carpinus betulus (hornbeam)	De	Medium to large	Oval	D	Ovate	Rough	Yes	Yes	Low	Medium	A	Yes	Strong	Yes	Medium (F/A)
Liquidambar styraciflua (sweet gum)	De	Large	Pyramidal	M	Lobed	Rough	Yes	Yes	Medium	Low	A	No	Medium	Yes	Medium (fungus)
Platanus hispanica (london plane)	De	Large	Round	M	Palmate	Soft	Pubescent	Yes	Medium	Very High	A	Yes	Strong	Yes	Tolerant
Pyrus calleryana 'Chanticleer' (pear)	De	Medium	Conical	M	Oval	Smooth	No	No	Low	Low	A/E	Yes	Low	Yes	Tolerant

References: Yang et al. (2015); Cariñanos et al. (2019); Hillier Nurseries and RHS (2019); (Hortipedia, 2022); Woodland trust (2022) / (1) De: deciduous, (2) D = dense, M = Medium, O = Open, / (3) See Appendix B for leaf shape / (4) Pubescent = Covered with short soft hair / (5) Low: emission rate of isoprene and monoterpenes less than or equal to 1g day^{-1} tree^{-1}, Medium: emission rate of isoprene and monoterpenes between 10 to 1g day^{-1} tree^{-1} / (6) A = anemophily (wind pollination), E = entomophily (insect pollination), (7) F/A = fungus and aphids, B/F = bacteria/ fungus

4.3.2 How is air pollution mitigation included in the urban planting design of green infrastructure?

Despite most respondents claiming to consider air pollution mitigation in their urban planting, there was little identifiable influence on the selection of site- and species-specific characteristics that can help with this benefit. The low priority placed, for all respondents, on airflow manipulation, weather parameters, type of air pollutants, BVOC and pollen emissions emphasises the general lack of understanding and of a holistic view of GI to support optimum GI design for enhancing air quality. Additionally, the poor selection of species demonstrates that the main benefit pursued by practitioners is the aesthetic attribute (Table 15).

However, respondents who consider air pollution mitigation in their planting decisions prioritise GI characteristics and local factors that influence air pollution over practitioners who do not consider this benefit. Practitioners who consider air pollution (G1) are more aware of GI characteristics that can influence air quality, such as size (height) and biogenic emissions. This awareness is probably a result of the guidance that this group (G1) uses to inform their planting decision, which is constantly updated and often contains information about some GI characteristics that influence air quality, such as leaf shape and constraints. This tendency was also reflected in the local context: urban morphology (slope, building heights), type of street (canyon or avenue), and air pollutant concentrations on the site were more important to those practitioners that prioritise air quality. This result, however, cannot be taken as a general practice. Most of the respondents from G1 cited all the species and site characteristics (alternatives) with a higher rank of importance than G2, so it is not evident that they have sufficient knowledge, in this particular topic, of the characteristics that could improve air quality.

Although practitioners expressed a consideration for improving air quality in their planting decisions, specific characteristics, such as leaf traits, biogenic emissions, and flow manipulation, were cited as less important for both groups (G1 and G2). This reveals a lack of importance attributed to these characteristics or perhaps that there is a gap between the current academic evidence and its application. This gap may be partially explained by the insufficient or ambiguous evidence supporting these characteristics’ capacities for improving air quality and a lack of up-to-date information circulating among practitioners. Therefore, it is unknown if practitioners from G1 have managed to improve air quality by considering the site and species-specific characteristics that influence air quality in their planting decisions. Barwise and Kumar (2020) highlight the need to enhance the communication of current air pollution mitigation evidence, and this research reaches the same conclusion. Holistic guidance to inform practitioners of the benefits, trade-offs and maintenance considerations necessary for successful urban planting is needed.

4.3.3 Framework to incorporate air pollution mitigation in street planting decisions

Despite all the GI characteristics reviewed, it is impossible to advertise generic characteristics to improve air quality. Urban planting professionals should think strategically about why the GI element is required and what benefits it is expected to provide. However, based on the literature reviewed in previous chapters and the survey that was conducted, a framework was developed for practical uses (Figure 44).

This framework is based on the questionnaire developed in this Chapter and the evidence collected in the previous Chapters. Holistically, vegetation area, water availability, foliage, season, weather parameters and air pollutant concentrations in the site are characteristics that influence all mechanisms (Table 16). Increasing vegetation area is associated with more effective absorption and deposition. Water availability is associated with biogenic emissions and absorption. When water is scarce, plants close their stomata to regulate transpiration, thus also reducing absorption. Also, under drought conditions, plants release some BVOC for protection. The foliage has a different influence on air quality. Evergreen species, for example, offer year-round leaves where particles can be deposited and gases absorbed. The foliage is also associated with the natural emission of pollen and BVOC, which is highly associated with the seasons. In spring, new leaves sprout, which is related to more particles deposited on leaf surfaces or immobilized in waxes. Spring, however, is the pollen season, where there is usually abundant pollen in the air. During spring and summer, the temperature also increases and with it, BVOC emissions. For this reason, the use of low-pollen and BVOC-emitting species is recommended for urban planting.

Weather parameters, such as temperature, precipitation, and wind direction, influence biogenic emissions, deposition, and dispersion. Pollutant concentrations interact, chemically and physically, with the micro and macrostructures of plants, and depending on this interaction is the influence on air quality. Nevertheless, all these characteristics require further research to confirm their impact on air quality by using GI in streets. Furthermore, the effect of maintenance and/or damage, whether physical or biological, on GI in relation to air quality is another gap that future research should fill.

Table 16. Summary table of the GI characteristics and spatio-temporal context that influence air quality in streets, indicating the quality of the evidence associated with their impact.
Light green represents robust evidence, yellow some evidence and red weak evidence. The symbols indicate the effect on air pollution concentrations: + reduced, - increased, # no evident influence or consensus, (s) species-dependent, (l) location dependent

GI characteristics and spatio-temporal context		Mechanisms				
		Absorption	Biogenic emissions		Deposition	Dispersion
			BVOC	Pollen		
Stomatal density		🟩 +				
Stomatal conductance		🟩 +				
Pollutant chemistry		🟩 (s)				
Vegetation area		🟨 +	🟥 (s)	🟥 (s)	🟨 +	
Meteorological influences	High temperature	🟨 -	🟩 -	🟩 -		
	High water availability [(1)]	🟨 +	🟨 -	🟩 -	🟩 +	
	Relative humidity				🟨 +	
	Extreme environmental conditions [(2)]	🟥 -	🟨 -	🟨 -		
	Season	🟥 (s)	🟨 (s)	🟩 (s)	🟨 (s)	
	Wind direction			🟩 -	🟥 #	🟩 # (s,l)
	Wind speed			🟩 -	🟥 #	🟩 # (s,l)
Leaf macrostructure features	Type of foliage	🟨 #	🟨 (s)		🟥 #	
	Small leaf size				🟥 +	
	Leaf shape				🟥 #	
Leaf surface microstructure	Trichomes				🟩 +	
	Leaf roughness				🟩 +	
	Leaf-wax content				🟩 +	
Taxonomic origin patterns			🟩 (s)			
Growth stage		🟥 (s)	🟨 #	🟩 (s)	🟨 (s)	🟥 (l)
Leaf ontogeny			🟨 #	🟨 #		
Foliage	Deciduous	🟨 #	🟨 -	🟩 (s)	🟨 -	
	Evergreen	🟨 #	🟨 -	🟩 (s)	🟨 +	
Plant damage		🟥 -	🟥 -		🟥 -	
Stress environment			🟩 -			
Higher CO_2 concentrations		🟩 (s)	🟩 -			
Pollutant concentrations		🟨 (s)	🟥 #	🟨 #	🟩 (l)	🟩 (l)
Maintenance [(3)]			🟥 -	🟩 +	🟥 +	
Macrostructure of vegetation	High porosity			🟩 -	🟩 (l)	🟩 (l)
	High LAD/LAI [(4)]			🟨 -	🟩 # (s,l)	
	Height			🟨 (s)	🟩 # (s,l)	
	High crown			🟨 -	🟩 # (s,l)	🟩 (l)
	Thickness				🟩 # (s,l)	🟩 (l)
Pollination strategies				🟩 (s)		
Particle size					🟩 (s)	
Site-specific. Species close to road					🟩 +	🟩 (s)
Type of green infrastructure	Tree	🟨 +	🟩 (s)		🟨 # (s,l)	🟩 # (s,l)
	Hedge/shrub				🟨 # (s,l)	🟩 # (s,l)
	Green wall				🟥 +	🟥 # (s,l)
	Green roof				🟥 #	🟥 # (s,l)
Street configuration	Street canyon					🟩 # (s,l)
	Open road					🟩 # (s,l)
GI location within a street	Middle of the canyon					🟩 # (s,l)
	Roadside arrangement					🟩 # (s,l)
Planting management	Discontinuous arrangement					🟨 # (s,l)
	Continuous arrangement					🟨 # (s,l)

[(1)] Includes precipitation, [(2)] E.g., drought and high soil salinity, [(3)] Includes pruning, [(4)] LAD = Leaf area density, LAI=Leaf area index

The use of a framework is supported by available resources, including practitioner-specific experience and planting guidance and publications, particularly those that list pollen volumes (Cariñanos & Casares-Porcel, 2011) and BVOC emissions (Steinbrecher et al., 2009). The framework proposes extending the GI and spatio-temporal context characteristics that practitioners should consider when selecting GI for air pollution mitigation purposes. Additional urban planting considerations may maximise the net positive effects of GI on cities. Most respondents ranked survival features, such as rooting environment, crown shape and height, drought and soil conditions tolerance, and pest and disease resistance as important or influential characteristics in their planting decisions, and thus these features were added to the framework (Figure 44 and Box 2).

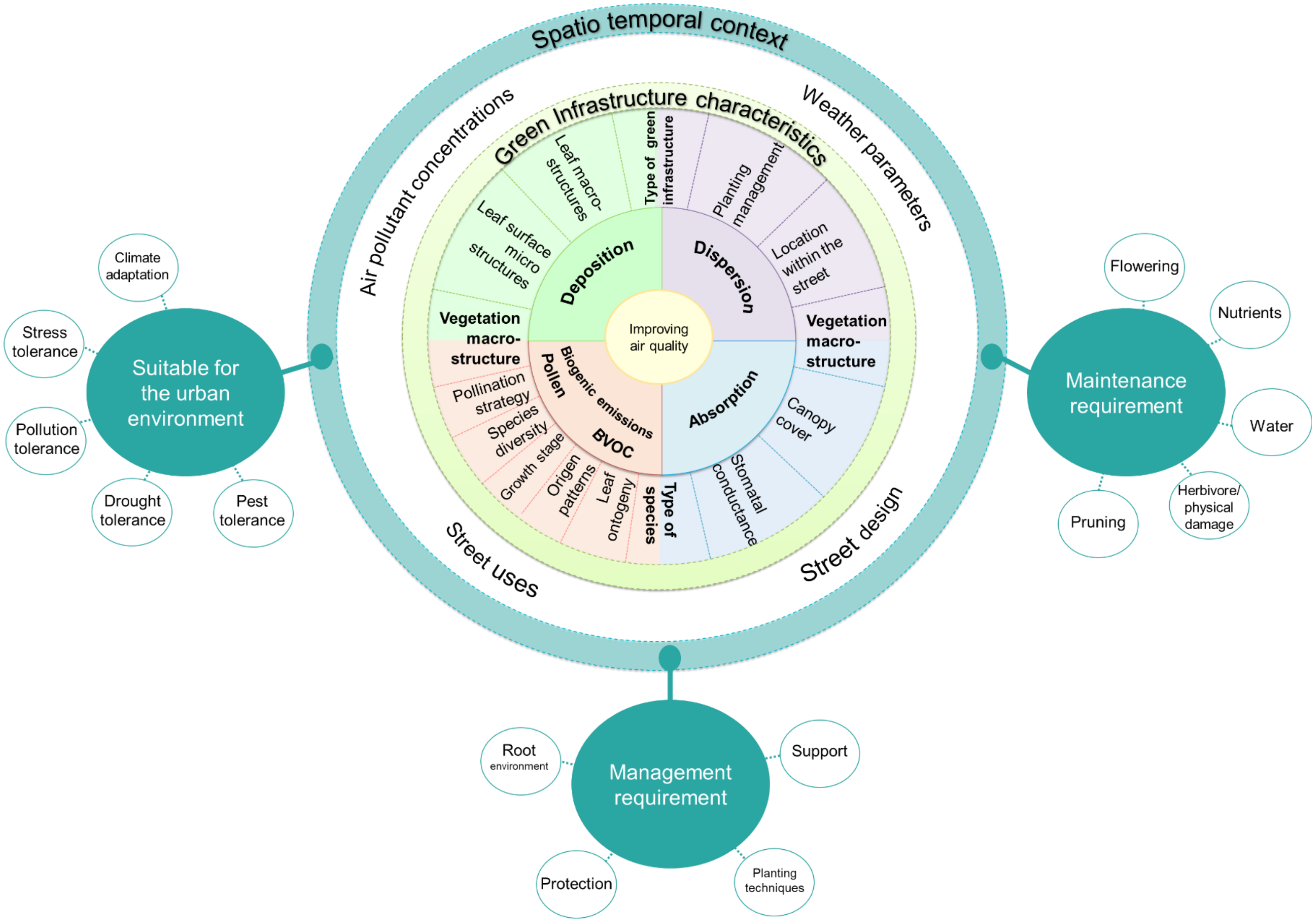
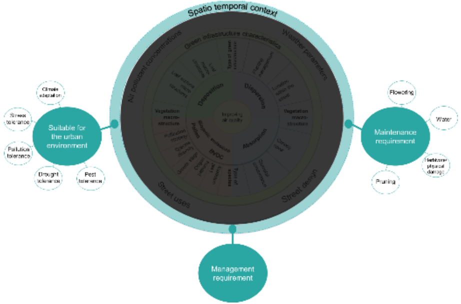


Figure 44. A holistic framework to outline the mechanisms by which green infrastructure may influence air quality and the associated characteristics that should be considered in urban planting.

Box 2. Framework for maximising air pollution mitigation in urban planting

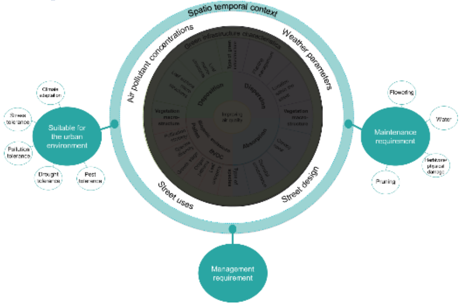
Step 1. Species selection



Select species according to management requirements, suitability to the urban environment, and maintenance requirements.

Species tolerant to drought, urban stress, pests/diseases, and air pollution should be prioritised, with particular attention to the flowering and pruning period. Establishing a schedule to perform periodic visual inspections of the planted species is recommended. Consider keeping a record of water requirements and herbivore or other physical damage.

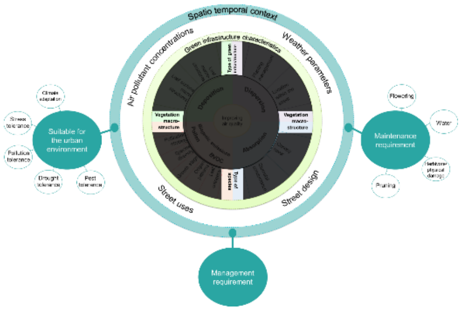
Step 2. Characterise the context



Once priority species have been identified, it is important to characterise the spatio-temporal context.

Here, the aim is to identify the type and usage of the street, any weather parameters that can potentially accumulate pollutants (e.g., wind direction), and the type and concentration of pollutants present at the site.

Step 3. Maximise the GI characteristics



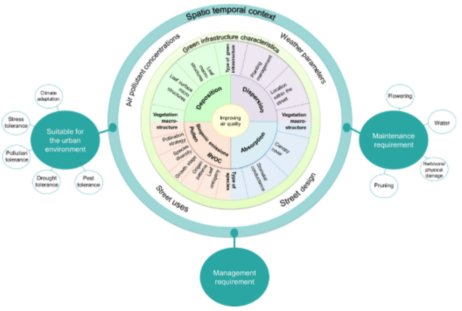
Common GI characteristics that affect all mechanisms, such as GI type, and species should be considered. These aspects are presented in the vertical and horizontal markers of the inner circle.

- **Height.** Up to 2m in narrow streets and 5m in avenues.
- **Porosity.** Low shrub/hedge porosity is recommended.
- **Crown.** A high crown might reduce ventilation.
- **Thickness.** From 1 to 5m is recommended, but it depends on the street and space available.

Questions that could help to maximise GI characteristics:

- Does the selected species interfere with street ventilation?
- Does the selected species protect pedestrians?

Step 4. Maximise the mechanisms



The inner circle can be used to maximise mechanisms.

- If the site has high concentrations of particles, then deposition should be prioritised, using species with specific leaf surface traits (e.g., roughness, wax and trichomes).
- If the site has high concentrations of gases, then absorption should be prioritised, using species with high stomatal conductance and, if appropriate, species with high leaf area density.
- If pollen reduction is desired, then species' pollination strategies, along with the various growth stages of flowering, should be considered.
- Consider controlling BVOC emissions by using low-emitter plants.
- Consider facilitating dispersion by planting short vegetation and planting according to wind direction.

5 Conclusions

The practical decision-making process of practitioners is a dynamic and multifaceted task as it must adapt and respond to the numerous challenges of the urban environment that has largely dictated GI plantings. **The primary Ecosystem Services sought by GI planting schemes are to improve aesthetics**, health and well-being, leaving behind, in three minor preferences, other benefits such as economic and soil improvement and airflow manipulation. Air pollution mitigation is not the main benefit pursued, though it is included in the decision-making process by the majority of respondents. Site- and species-specific characteristics that are important for enhancing the dispersive and depositional effects of GI are often considered by those practitioners that frequently design street-side GI for air quality improvements. However, **species characteristics that cause negative implications for air quality**, including the emission of BVOC and pollen and airflow manipulation, **do not influence planting decisions**. Green infrastructure characteristics and the spatio-temporal context that influence air quality were not more important than other sites or species features. This reveals other factors affecting the extent to which air pollution mitigation is incorporated into the current GI design, including planting budgets and the quantifiable benefits of these characteristics and context to improve air quality.

It is unclear if a lack of consideration about GI characteristics and the local context for improving air quality is due to other preferences or a lack of knowledge and certainty about current evidence. It is likely that there is currently little confidence in claims that site- and species-specific characteristics, such as leaf traits and local context, affect air quality. These characteristics could be most effectively communicated and understood through an easy-to-use modelling tool that could help incorporate GI into streets and assess its benefits.

A holistic view of the mechanisms and site- and species-specific characteristics that influence air pollution mitigation is crucial to maximising the benefits of GI planting and should be included in the decision-making process. Further studies are needed to support the applicability of knowledge in urban planting that adequately addresses the complex interplay between species selection and Ecosystem Services.

Chapter 7. How good is 'Good Enough'? Using practical and accessible pollution modelling tool to plan urban plantings

This Chapter

- Presents one easy-to-use computational fluid dynamic model to simulate green infrastructure in a street canyon.
- Explains the method and results of a validation exercise of the ENVI-met model against wind tunnel data.
- Evaluates the use of the ENVI-met model as an easy-to-use tool for air pollutant dispersion in urban planting decision-making.

1 Introduction

Environmental issues such as air quality assessment in urban environments are gaining increasing attention from urban planners, city authorities and academics due to rising urbanisation and traffic-related pollution (Liang & Gong, 2020; Zhang et al., 2022). The **previous Chapter** showed that practitioners related to urban planting in the UK would like to have access to other resources to improve their planting decisions, such as an easy-to-use modelling tool. This tool might help evaluate the impact of GI in real street conditions (street design, wind flow patterns, traffic emissions), allowing practitioners to enhance site-specific planting schemes with reliable and quantifiable benefits to citizens (Pearce et al., 2021).

According to **Chapter 5**, dispersion is a mechanism that is highly dependent on the macro morphologies of vegetation and the spatio-temporal context, such as weather parameters and street design, highlighting that the effect of green infrastructure (GI) on streets should be studied locally. Different methods have been used to understand how air pollutants are affected by GI in street; these include field measurements, wind tunnel experiments and computational models. Field experiment studies are time-consuming and expensive depending on the scale; however, accurate, local, and real-world data is obtained. Wind tunnel experiments (WT) use small scale models of buildings, streets, and trees (GI) to study the interaction between these urban elements and the air moving around them (Gromke & Ruck, 2008b) (See Figure 8 and Figure 9 in Chapter 2 for typical flow field and fundamental vortex structures in street canyons). Although WT can also be expensive, it has comparative advantages over field experiments such as cost-effectiveness optimisation and maximum design freedom to test (e.g., different street configurations). The main advantages of a WT are that the flow of the wind can be controlled and that the effect of different urban elements on dispersion or pollutant concentrations can be investigated. The influence of building geometry (building height, width, shape of roof), street dimensions, vegetation, and traffic composition on air movement can be investigated by controlling each urban element individually (Ahmad et al., 2005). Computational modelling studies encode physical and mathematical equations to simulate complex environmental systems. For example, air pollution modelling has been used to understand or predict how air pollutants behave in a current environment or to anticipate the future impact on air quality of planting GI in urban environments (Jeanjean et al., 2017; Tiwary et al., 2019a).

Modelling tools support planning decisions for a range of policymakers, urban planners, and scientists by creating predictions and helping determine practical solutions for specific environmental problems (Government Office for Science, 2018). These predictions, however, must include a comprehensive evaluation of the limitations and uncertainties of the models through a validation of their results. Validation is the process of determining whether a simulation model is a sufficiently accurate representation of the system (real world) for the particular objective of the study (Law, 2014). Therefore, the validation ensures reliable results.

This Chapter aims to validate a computational fluid dynamic (CFD) model selected for studying traffic-related particulate matter (PM) dispersion in a street canyon with trees. The purpose of the validation is to provide an accurate representation of the real world from the perspective of the intended uses of the model (SEG, 2014). The ENVI-met model (ENVI-met, 2022) was selected, and it was validated against a wind tunnel dataset named CODASC (CODASC, n.d.) to corroborate the pollutant dispersion capability of the model.

After this introduction, brief descriptions of the ENVI-met model and the WT experiment are provided. The method section then presents the WT scenarios used to study the model and describes the setup of the ENVI-met scenarios. The results are then divided into three parts. First, a general air flow study of the model is carried out. Second, the general results of ENVI-met in terms of $PM_{2.5}$ concentrations in the model with and without trees are then presented. Third, the statistical validation of ENVI-met against CODASC is presented. Finally, a discussion of the performance of the ENVI-met model for practitioner use is provided.

1.1 Before starting

The initial goal of this research was to simulate different scenarios to evaluate the optimal type of GI and its location in a specific street canyon in terms of pedestrian exposure to air pollutants. **This Chapter**, however, will not discuss that original idea because the statistical analysis of the model validation did not yield acceptable results for our purposes. Although there was no favourable validation of the model, other questions arose, such as

- Is the ENVI-met model acceptable for evaluating pollutant dispersion at the microscale?
- What is a "good enough" validation in terms of model performance?

1.2 Why ENVI-met?

ENVI-met was selected for its ability to model surface-plant-air interactions using an integrated mass-based dispersion-deposition approach and for its availability as a potential easy-to-use model also for practitioners involved in planting decision-making. The easy-to-use ENVI-met model does not require expert knowledge in computational resources and air quality modelling for simulating scenarios.

ENVI-met is a three-dimensional (3D) computational fluid dynamic (CFD) model which uses the Reynolds - average non-hydrostatic Navier-Stokes (RANS) equations. These equations describe how the temperature, pressure, velocity, and density of a moving fluid are related in each grid cell of the model (Bruse & Fleer, 1998). It uses a Geographic Information System (GIS) and bitmaps to model 'real' streets with 'real' locations and the dimensions of buildings, roads, and GI. Additionally, the model uses hourly meteorological data, which provides 'real' weather conditions at the simulated site of interest (Nikolova et al., 2011; Hofman et al., 2016; Morakinyo & Lam, 2016b; Deng et al., 2019; ENVI-met, 2022).

The ENVI-met model is useful for tree planting decisions as it can simulate 'real' scenarios at the microscale. Unlike other CFD models, it incorporates various features relevant to tree planting decisions, including a tree calendar to identify leaf type according to seasons, different types of crown shapes and plant type, stomata resistance[20], and isoprene emissions (BVOC emissions). Furthermore, a vertical description of the species crown can be added to the model using the 'real' leaf area density (LAD) of the studied species (Bruse, 2007). The model has the most common tree, bush, grass, green roof and green wall plants in its database, and specific GI can also be created according to user requirements. Different soil and building materials can be selected from its database, enabling site-specific features relevant to planting decision-making.

This model might provide a comprehensive GI benefit for air quality, integrating GI characteristics and spatio-temporal context. As recognised in the previous chapters, characteristics, such as macro-morphological features, LAD, type of GI, foliage (evergreen/deciduous), stomata resistance, BVOC (isoprene) emissions, street configurations, and weather parameters are integrated into the model for simulations.

For more details on ENVI-met and surface-plant-air equations, see Appendix F.

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[20] This is used to calculate the transpiration of plants and depends on environmental parameters, such as solar radiation, air temperature, and soil water content.

1.2.1 Previous validation of the ENVI-met model

According to the ENVI-met website, the model has been validated for urban climate modelling (ENVI-met, 2022). A general validation of ENVI-met was performed within the European research project 'Benefits of Urban Green Spaces' (BUGS) (de Ridder et al., 2004). The BUGS project was funded by the European Union (EU) to investigate the potential role of green space in alleviating the negative effects of urbanisation and to infer a set of guidelines regarding the use of green space as a design tool for urban planning (EU, 2005). A validation exercise was performed, comparing model outputs against field measurements of wind speed, wind direction, temperature, and humidity. The project summary report stated that the ENVI-met model reflected the trends induced when vegetation was present in the study area, demonstrating a satisfactory model performance for weather aspects (de Ridder et al., 2004). Detailed data on these validation tests, however, was not presented in the report and hence the difference between the model outputs and the real situation could not be verified. Moreover, the report did not indicate that any validation on air pollution concentrations was conducted.

Despite BUGS not having performed a validation on air pollution concentration, a few studies that have used ENVI-met have validated the model for their purposes (Table 17). Most of the studies that validated ENVI-met against field measurements concluded a poor agreement for modelling pollutants concentrations, especially PM. Morakinyo and Lam (2016b), however, validated the ENVI-met outcomes against the WT experiment, CODASC. According to the authors, their results were considered acceptable for their purposes, although some criteria were not met (Morakinyo & Lam, 2016b). More discussion on this topic is found in Section 4 of this Chapter.

Other studies have omitted any validation analyses in their work, arguing that ENVI-met has already been validated (Table 17). Wannia (2007), for instance, used ENVI-met for her Ph.D. thesis but did not validate the model output for pollutant concentrations. She argues that as local concentrations are, above all, a result of dispersion depending on neighbouring pollution sources outside the model area, it is much more important to validate the general flow regime (wind flow) than absolute concentration values (Wannia, 2007). This research disagrees with her explanation, because while the flow regimen might be correct in a model, the dispersion of pollutants at the microscale (street) could be altered, especially in the presence of trees (GI) due to the several GI characteristics that influence air quality improvement. Therefore, a validation of the ENVI-met model against the WT experiment was performed here.

Table 17. Previous ENVI-met studies in the literature.

Reference	**Goal**	**Computational domain (Δx,Δy,Δz, m) (1)**	**Resolution (x, y,z, m) (2)**	**Validation**	**Validation results**
European project 'Benefits of Urban Green Spaces' (de Ridder et al., 2004; EU, 2005)	Evaluate urban planning scenarios. Analysis of local-scale effects of vegetation in urban street canyons and parks	Not mentioned	Not mentioned	Yes - field measurements	No validation results were found.
De Maerschalck et al. (2008)	Investigate the effects of vegetation along a motorway on local air quality	200x600x50	6x6x2	Yes - field measurements	Normalised model results and measurements best fit NO_2, but ENVI-met underestimates the concentration. For PM, the model did not agree with the measurement data. No statistical results were found.
Nikolova et al. (2011)	Investigate the dispersion of ultrafine particles and their spatial distribution on a street canyon	Not mentioned	1x1x from 20cm the first 2m	Yes - field measurements	The modelled UFP concentrations compare well with the measured data (correlation coefficient R from 0.44 to 0.93).
Wania et al. (2012)	Evaluate the effect of two types of urban vegetation (trees and shrubs) on air pollution in built environments	180x180x72	3x3	No	No validation was performed.
Vos et al. (2013)	Investigate how urban vegetation can be used to improve local air quality	Not mentioned	0.5x0.5	No	No validation was performed.
Hofman and Samson (2014)	Validate the PM distribution modelled by a pollutant dispersion CFD-model	486x486	2x2x from 20cm the first 2m	Yes - Biomonitoring campaign	Quantitative ENVI-met validation showed significant correlations between modelled and measured results throughout the entire in-leaf period for 96 species.
Zölch et al. (2016)	Quantify the effectiveness of three types of UGI in increasing outdoor thermal comfort	174x200x50	2x2x 0.2, 0.6, 1.0, 1.4 and 1.8 m height	No	No validation was performed.
Paas and Schneider (2016)	Evaluate the performance of two German models: Austral2000 and ENVI-met.	250x250 514x514 380x256	2x2	Yes - field measurements	ENVI-met overall performed inferior to Austal2000. ENVI-met underestimated data of particle in comparison to Austal2000 (factor of two). No statistical results were found.
Hofman et al. (2016)	Evaluate the effect of a tree crown representation on the ambient PM10 concentration	100x100x50 750x250x50	1x1x1 5x5x2	Yes - field measurements	An overall poor agreement was obtained between the gravimetric and modelled leaf-deposited particulate mass (underestimation).

<table>
<thead>
<tr><th>Reference</th><th>Goal</th><th>Computational domain (Δx,Δy,Δz, m) (1)</th><th>Resolution (x, y,z, m) (2)</th><th>Validation</th><th>Validation results</th></tr>
</thead>
<tbody>
<tr><td>Morakinyo and Lam (2016b)</td><td>Investigate the options of vegetation about the near-road pollutant dispersion and deposition</td><td>20x30x(20-50)</td><td>05x0.5x2 (0.4m for the first lowest five-grid cells)</td><td>Yes - CODASC</td><td>According to the author, the validation results were reasonable between the wind tunnel data and the model results for their purposes, although some criteria were not satisfied.
<table>
<tr><th rowspan="3">Metric</th><th rowspan="3">Range of acceptance</th><th colspan="4">Results of the statistical evaluation of the model</th></tr>
<tr><th colspan="2">Leeward wall</th><th colspan="2">Windward wall</th></tr>
<tr><th>Without tree</th><th>With tree</th><th>Without tree</th><th>With tree</th></tr>
<tr><td>R</td><td>>0.8</td><td>0.86</td><td>0.83</td><td>0.81</td><td>0.80</td></tr>
<tr><td>NMSE</td><td><4</td><td>0.09</td><td>0.44</td><td>2.47</td><td>9.12</td></tr>
<tr><td>FB</td><td>[-0.3;0.3]</td><td>0.14</td><td>0.47</td><td>1.13</td><td>1.75</td></tr>
<tr><td>FAC2</td><td>>0.5</td><td>0.87</td><td>0.70</td><td>0.12</td><td>0.05</td></tr>
</table>
</td></tr>
<tr><td>Deng et al. (2019)</td><td>Investigate the concentration and diffusion of atmospheric PM in green spaces with different structures</td><td>70x40x30</td><td>1x1x1</td><td>Yes - field measurements</td><td>The simulated $PM_{2.5}$ concentrations were ‘*lower*’ than the measurements (no numerical data was found to compare).
No statistical results were found.</td></tr>
<tr><td>Taleghani et al. (2020)</td><td>Evaluate the temporal variations of NO_2 in a Manchester neighbourhood</td><td>100x100x30</td><td>Not mentioned</td><td>Yes - field measurements</td><td>Measured and simulated air temperature datasets were compared.
Simulated air temperatures were higher than the measured data.
R=0.91, so the model was accepted.</td></tr>
<tr><td>Xing and Brimblecombe (2020b)</td><td>Study the exposure to traffic air pollutants and examine how $PM_{2.5}$ concentrations and user distribution is affected by the park design</td><td>960x320
560x320</td><td>5x5x2</td><td>Yes - field measurements</td><td>The statistical evaluation was satisfactory:
r=0.89, FB=0.19, NMSE=0.18 and FAC2=0.77.</td></tr>
</tbody>
</table>

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(1) Dimensions of the model length x width x height (meters).

(2) In ENVI-met, all grid cells have an identical vertical extension, except the lowest five cells, with a vertical extension of $\Delta z = 0.2\Delta z$. This help to increase the accuracy of the model.

1.2.2 ENVI-met for non-expert users

The ENVI-met model was chosen for three main reasons: its ability to simulate pollutant dispersion and deposition at a microscale, to simulate 'real' tree properties, and because it is an easy-to-use model. The model is commonly used by architects, landscape architects, stakeholders, and researchers in a variety of disciplines focused on the urban environment. This demonstrates that using the model does not require a solid understanding of fluid mechanics principles or being an expert in mathematical models.

ENVI-met simulates dispersion and deposition of typical traffic pollutants, including particles ($PM_{2.5}$ and PM_{10}), CO_2, NO/NO_2, and O_3, which facilitates the practical study of air pollution in streets. The model considers particle deposition on leaves and some chemical reactions, such as the photochemical reaction between NO/NO_2 and (B)VOC, to form tropospheric ozone (O_3). Additionally, BVOC emissions through plants are incorporated into the model to calculate the effects of isoprene (BVOC) on the formation of O_3.

Three-dimensional representation of trees using 'real' skeleton models is included in ENVI-met. The model has a plant tool with more than 100 species of trees, shrubs, and grasses in a catalogue. These plant species can be selected, or another type of GI can be created according to the structure and dimensions needed (Figure 45). Photosynthetic rate, evapotranspiration rate, and water availability – which affect absorption - are calculated in ENVI-met, considering the leaf temperature individually for each model grid box.

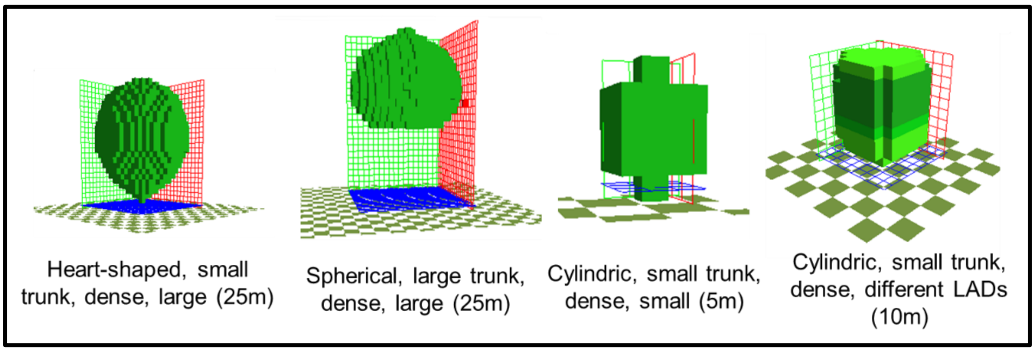
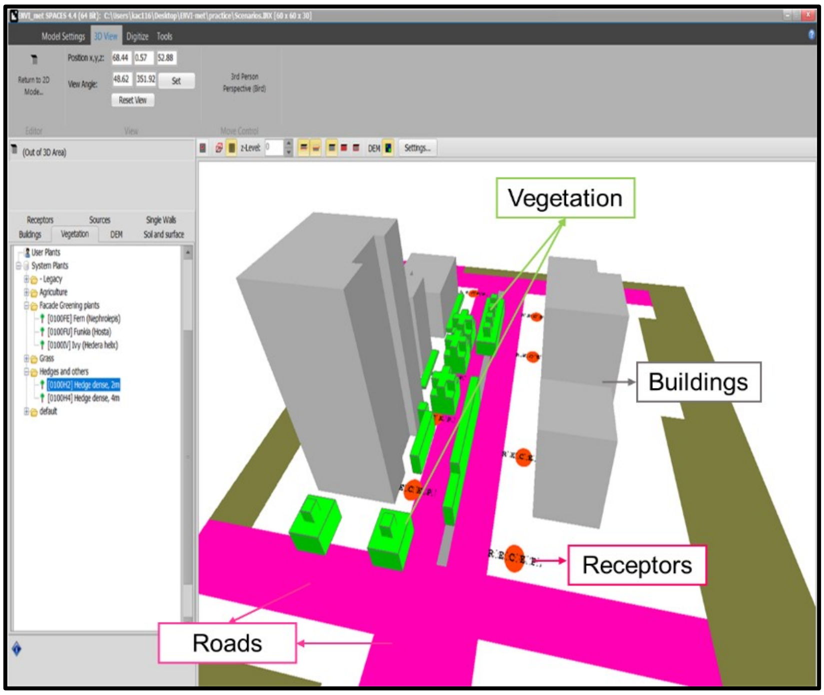

Heart-shaped, small trunk, dense, large (25m)
Spherical, large trunk, dense, large (25m)
Cylindric, small trunk, dense, small (5m)
Cylindric, small trunk, dense, different LADs (10m)

Figure 45. Different tree geometric representations in the ENVI-met model. Source: Own elaboration based on ENVI-met model ®.

ENVI-met offers large versatility to simulate scenarios, from hypothetical to real urban areas. A map or screenshot (bitmap) is digitised to build the model area, and thus, the urban areas of interest can be easily modelled. In addition, a wide variety of model sizes can be created, from isolated canyon streets to entire cities (Figure 46). The model area size typically ranges from 50×50 to 500×500 grid cells horizontally and 20 to 50 grid cells vertically. ENVI-met has a typical horizontal resolution of 0.5 m to 5 m and a typical time frame of 24h to 48h with a time step of 1s to 5s, making it suitable for neighbourhood-scale microclimate studies (microscale) (Gatto et al., 2021).


ENVI_met SPACES 4.4 (64 Bit): C:\Users\kac116\Desktop\ENVI-met\practice\Scenarios.INX [60 x 60 x 30]

Position x,y,z: 68.44 0.57 52.88

View Angle: 48.62 351.92

z-Level: 0

Figure 46. 3D display scenario in ENVI-met model.
Source: Own elaboration from ENVI-met model ®.

The holistic approach of ENVI-met regarding GI sets it apart from other environmental simulation models. Many models calculate the dispersal of pollutants, but there are very few, if any, that include plant conditions. Furthermore, using this model, the four mechanisms can be studied: particle deposition on leaves, photosynthetic rate (absorption), isoprene (BVOC) emissions, and dispersion of pollutants due to the influence of 3D trees or other GI.

1.3 Why CODASC? Description of the wind tunnel experiment

Concentration Data of Street Canyons (CODASC) is a wind tunnel concentration database accessible to anyone working on urban air quality issues with a particular interest in validating numerical simulations or experimental investigations (CODASC, n.d.). Therefore, the CODASC dataset has been used in several CFD studies to validate modelling results (Table 18). CODASC was selected as a validation dataset for this work as it provides traffic pollutant concentrations in urban street canyons obtained from a wind tunnel dispersion experiment. The database provides simulated traffic pollutant concentrations in two different urban street canyons (H/W= 1, H/W=0.5) subjected to three wind directions (0˚, 45˚ and 90˚) for street canyons with and without a tree-avenue (CODASC, n.d.) (Figure 47). More details about the CODASC dataset are found in Appendix F.

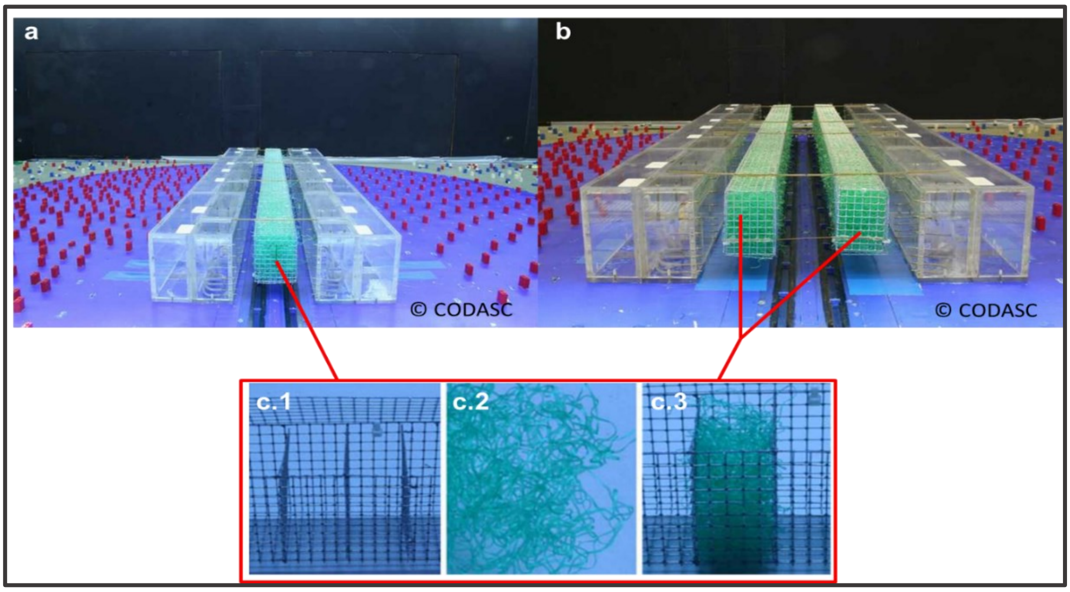
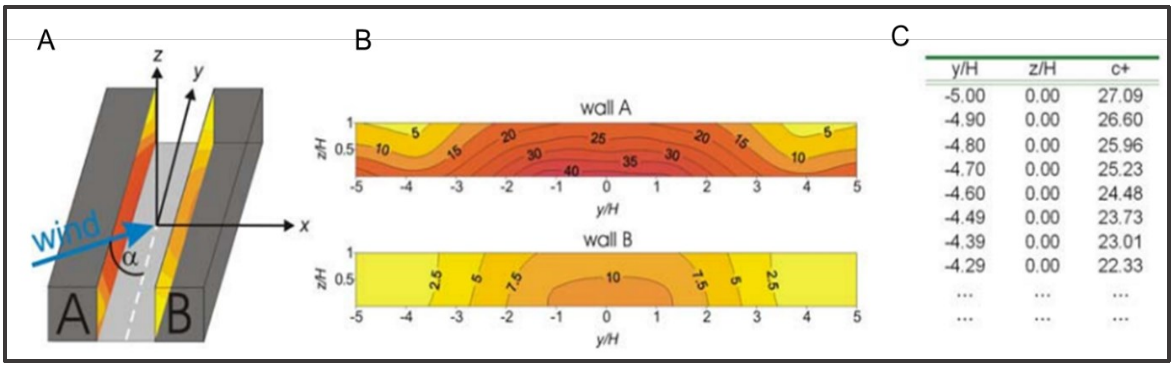


Figure 47. Wind tunnel images.
a) representation of a narrow street canyon with tree planting (H/W=1), b) representation of a wide street canyon with tree planting (H/W=0.5), c) images of the model of a porous fake crown tree. C1 empty lattice cage, C2 filament/fibre-like synthetic wadding material, and C3 filled lattice cage. Source: Adapted from © CODASC and Gromke and Ruck (2008b)

The database includes concentration data for tree-avenue configurations of different tree arrangements, tree stand densities and crown porosities (Gromke & Ruck, 2008b; Gromke, 2013). Each concentration data file contains the concentration data on a regular grid consisting of 700 nodes. Each file consists of three columns: 1) measured points along the street-axis coordinate (y/H), 2) measured points along the vertical coordinate (z/H), and 3) the normalised concentration c+ for those points (coordinates) (Figure 48) (Gromke, 2013).



y/H	z/H	c+
-5.00	0.00	27.09
-4.90	0.00	26.60
-4.80	0.00	25.96
-4.70	0.00	25.23
-4.60	0.00	24.48
-4.49	0.00	23.73
-4.39	0.00	23.01
-4.29	0.00	22.33
...	...	...
...	...	...

Figure 48. Data presentation in CODASC.
A. Location of the coordinate system, B. Sample-contour plot of normalised concentrations c+, and C. Spreadsheet format structure of the concentration data files. Source: Adapted from Gromke (2013)

Table 18. Modelling studies that validated their model results using CODASC data. The reference highlighted shows a validation performed for ENVI-met.

Reference	CFD code	Computational domain			Wind direction	W/H	Description of the model canyon street	Validation results (3)				
		Δx	Δy	Δz				Scenario (1)	NMSE	R	FAC2	FB
Gromke et al. (2008)	FLUENT	H/20	H/2	H/20	90˚	1	Tree-free + one row of tree-avenue	Tree-free	0.23	0.91	0.71	0.07
								Non-porous crown	0.06	0.98	0.83	-0.004
								Porous crown	0.09	0.97	0.53	-0.14
Balczó et al. (2009)	MISCAM	H/180	H/90	H/180	90˚	1	tree-free + one row of tree-avenue	Tree-free	0.98	0.92	0.63	-0.35
Buccolieri et al. (2009)	FLUENT	H/25	H/5	H/25	90˚	2	tree-free + two rows tree-avenues	Tree-free	0.06	0.96	0.97	0.15
								Non-porous crown	0.13	0.98	1.00	0.21
								Porous crown	0.09	0.99	1.00	0.14
Salim et al. (2011a)	FLUENT	H/13	H/13	H/13	90˚	1	One row of tree-avenue	No statistical results were presented.				
Buccolieri et al. (2011)	FLUENT	H/25	H/25	H/25	45˚	2	tree-free + two rows of tree-avenues	Tree-free (L)	0.25	NIA	0.80	0.39
								Tree-free (W)	0.15	NIA	0.82	-0.05
								Tree case (L)	0.15	NIA	0.59	0.31
								Tree case (W)	0.42	NIA	0.51	-0.33
Moonen et al. (2013)	FLUENT	H/24	H/24	H/24	90˚	1	tree-free + one row of tree-avenue	Tree-free (L)	NIA	0.93	1.00	-0.21
								Tree-free (W)	NIA	0.95	0.59	-0.56
								Dense crown (L)	NIA	0.88	0.85	-0.04
								Dense crown (W)	NIA	0.91	0.26	-1.16
Vranckx et al. (2015)	SIMPLE FOAM	H/20	H/20	H/35	90˚, 45˚, 0˚	1,2	tree-free + one row of tree-avenue	Tree-free (L)	0.15	NIA	0.83	0.32
								Tree-free (W)	1.25	NIA	0.62	-0.46
								Tree case (L)	0.07	NIA	0.99	0.07
								Tree case (W)	0.81	NIA	0.83	-0.52
Jeanjean et al. (2015)	OpenFOAM	H/16	H/16	H/20	90˚, 45˚, 0˚	1	tree-free + one row of tree-avenue	Graphical statistical results were presented.				
Abhijith and Gokhale (2015)	FLUENT	H/24	H/24	H/24	90˚	2	tree-free	Tree-free	NIA	0.90	0.87	0.16
(Morakinyo & Lam, 2016b)	ENVI-met	H/2	H/2	2H/5	90˚	1	tree-free + one row of tree-avenue	Tree-free (L)	0.09	0.86	0.87	0.14
								Tree-free (W)	2.47	0.81	0.12	1.13
								Tree case (L)	0.44	0.83	0.70	0.47
								Tree case (W)	9.12	0.80	0.05	1.75
Moradpour et al. (2017)	CFD model	H/20	H/20	H/20	No mention	1	tree-free	Graphical statistical results were presented.				
Merlier et al. (2018)	LBM	H/96	H/96	H/96	90˚	1	tree-free + one row of tree-avenue	Tree-free	NIA	0.9	0.90	-0.1

NIA = No Information Available (1) L = leeward wall, W = windward wall; HSD = high stand density; (3) Metric range: MNSE <4; R >0.8; FAC2 >0.5; FB [-0.3, 0.3]

2 Validation method

The CODASC dataset for a *regular* street canyon and perpendicular wind for with and without trees scenarios was used to validate the pollutant dispersion capability of the ENVI-met model (CODASC, n.d.). First, the CODASC setup is introduced, and then the ENVI-met setup is described in Section 2.2. After that, in Section 2.3, the assumptions are explained along with the ENVI-met input values to replicate the WT experiment.

2.1 Configuration of CODASC: Wind tunnel experiment to validate ENVI-met

The wind tunnel was formed by two parallel aligned blocks of acrylic glass representing two buildings in an isolated street canyon. The length of the block and the street canyon was 180m and 18m in width, with two parallel buildings of 18m height and 18m weight at a scale of 1:150.

In order to validate the pollutant dispersion capability of the ENVI-met model, the concentration data for a street canyon with an aspect ratio equal to one (H/W = 1) with and without trees and with a perpendicular wind was used (CODASC, n.d.) (Figure 49).

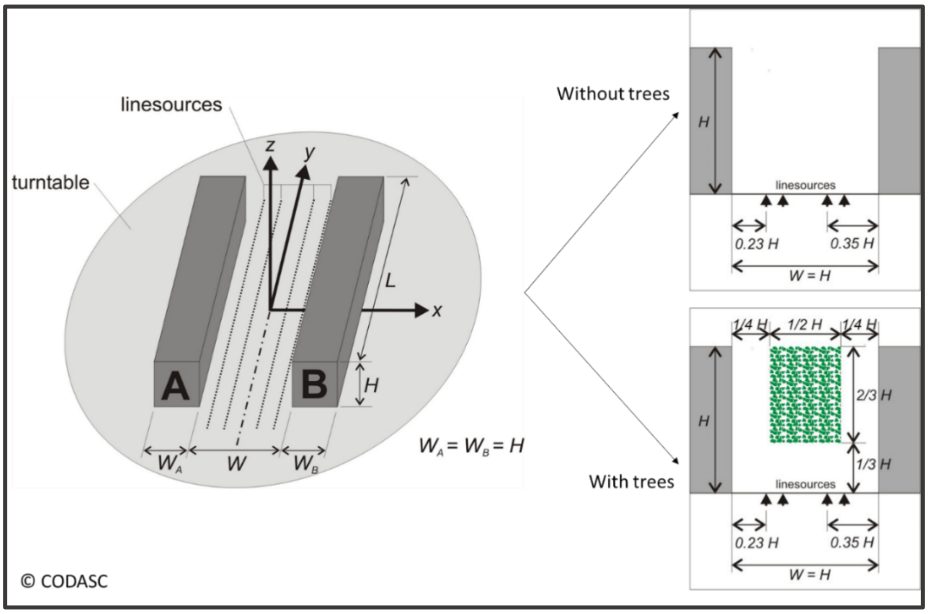


Figure 49. Schematic view of street canyon (H/W=1) in the wind tunnel.
Source: © CODASC webpage.

2.1.1 Tree configuration

A row of trees in the middle of the street canyon (H/W=1) was used. Trees were represented by lattice cages filled homogeneously in each cell; as a result, a pore volume of 97.5% (high crown porosity) was reported, representing a pressure loss coefficient of $\lambda=80m^{-1}$ (CODASC, n.d.). See Appendix F for more explanation about the pore volume and vegetation representation in CODASC.

2.2 Configuration of the ENVI-met model

2.2.1 Computational and grid domain

The street canyon domain is proportionally equal to the dimensions of the wind tunnel experiment (Figure 50 and Figure 51). A regular aspect ratio (H/W = 1) was chosen to analyse the pollutant dispersion of a perpendicular wind flow in two scenarios: 1) without trees and 2) with a row of trees in the middle of the canyon. This was the exact configuration that CODASC has in its dataset.

The computational domain covers 291m x 361m and has a vertical height of 72m. The size of the grid cells was set to 1m x 1m x 1m. The first scenario was an isolated street canyon of 180m length (L), and 18m width (W) with buildings of 18m height (H) and 18 m width (W) that was modelled without vegetation (Figure 50). The domain dimensions followed the best practices guidelines suggested by COST Action 732[21] (Schatzmann et al., 2010).

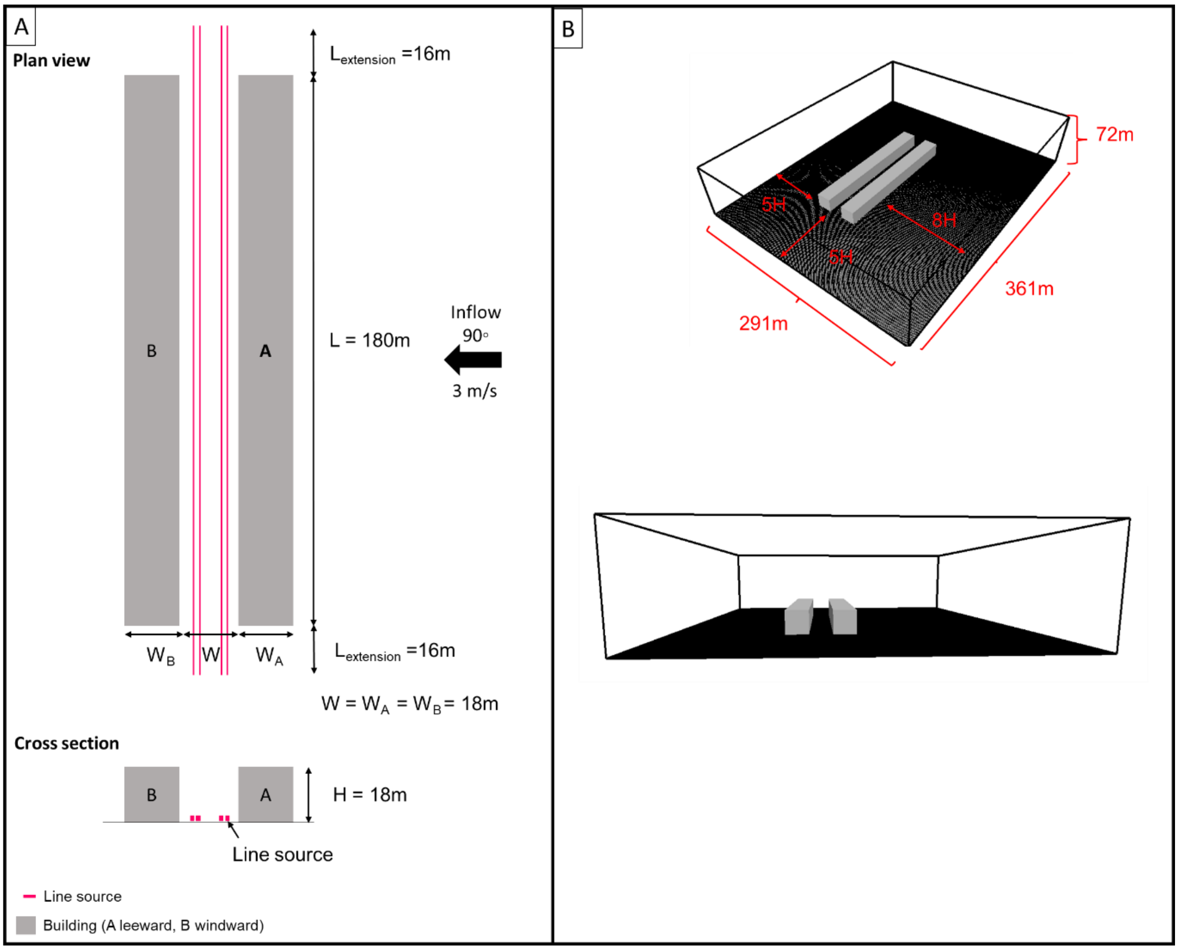


Figure 50. Schematic representation of treeless scenario performed in ENVI-met.
A) plan view of the treeless scenario, and B) 3-D visualisation of the model area in ENVI-met

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[21] COST Action 732 is a model evaluation guide which aims to improve and ensure the quality of micro-scale models and their application for the prediction of flow and transport processes in urban environments.

The second scenario contained a row of trees in the middle of the street canyon (Figure 51 and Figure 52), maintaining the same computational domain described above.

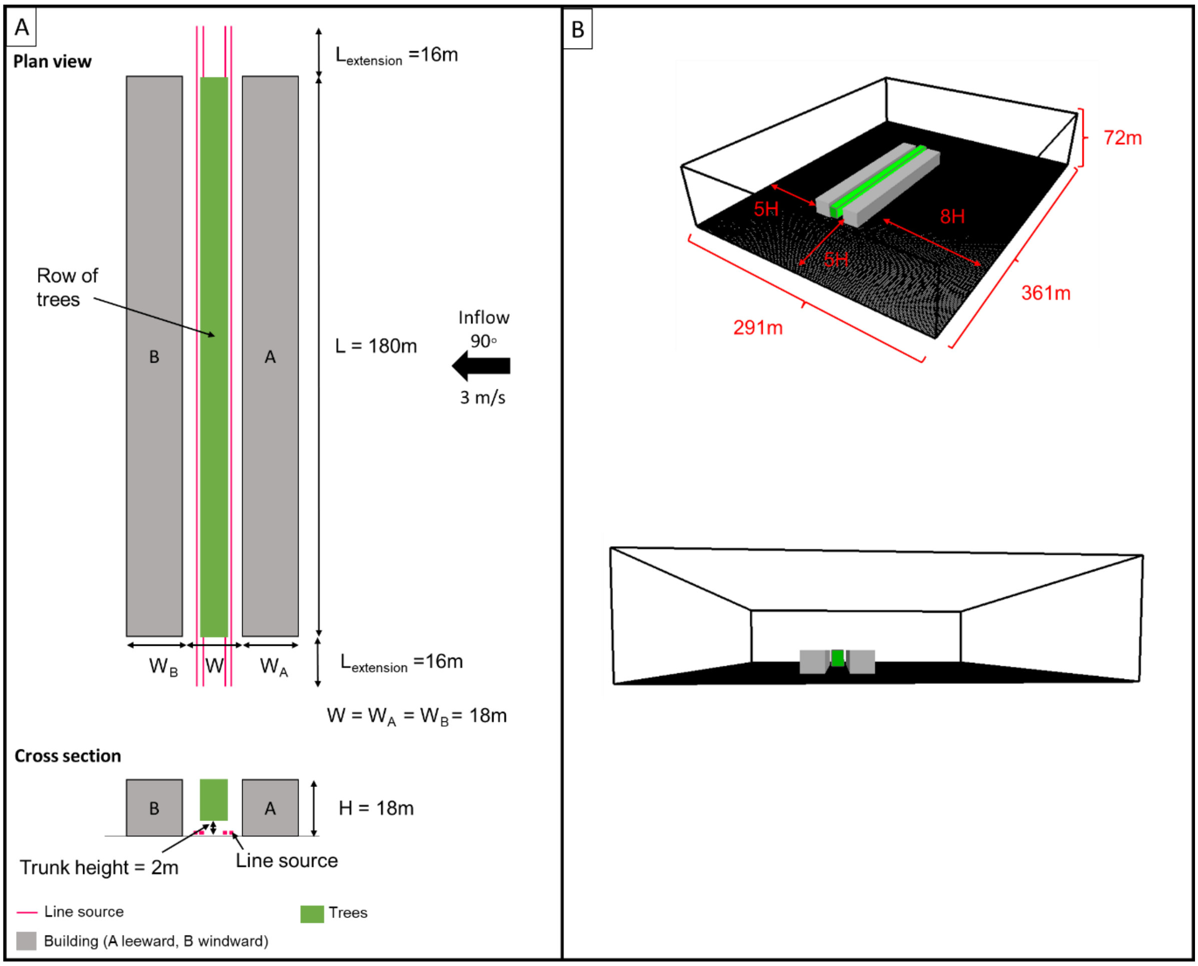

Figure 51. Schematic representation of the row of foliated tree scenario performed in ENVI-met. A) plan view of the scenario with a row of trees and B) 3-D visualisation of the model area in ENVI-met

Although ENVI-met can simulate different leaf area densities (LAD) along the canopy to simulate realistic tree porosity, it was developed to be maintain consistency across the whole canopy to precisely replicate the WT experiment. More detail about the LAD values used in ENVI-met is provided in Section 2.3.

The model simulations ran for five hours, starting at 2 am to avoid the influence of radiation in the simulated scenario during the first hours. The model was initialised according to the parameter values provided in Table 19.

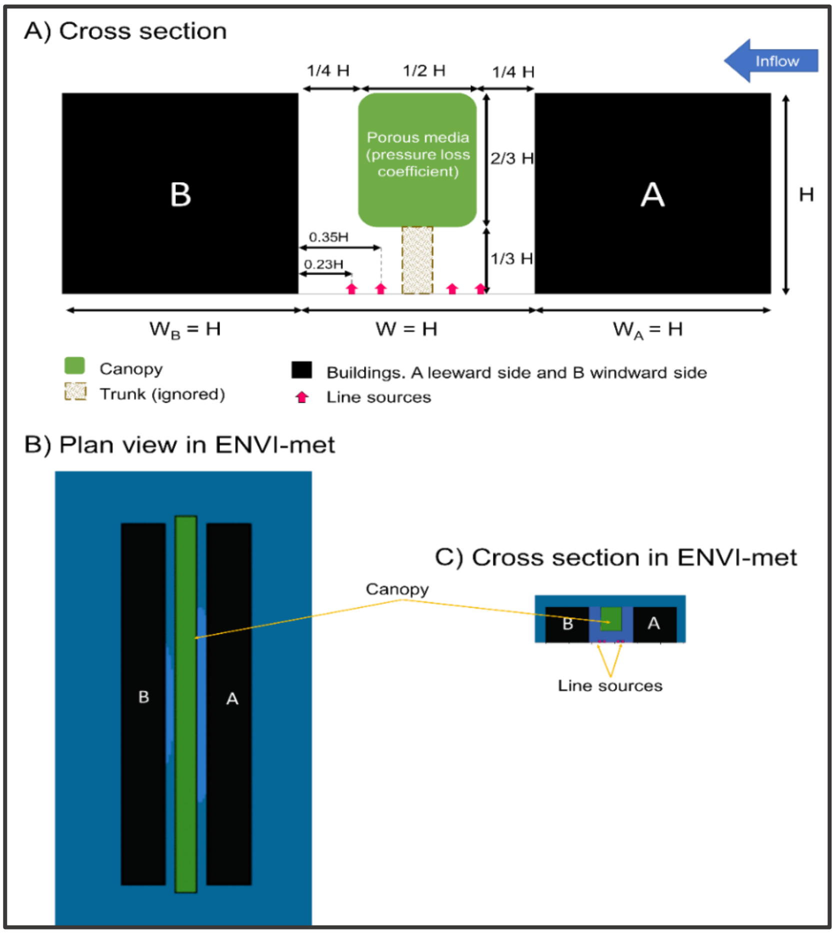

Figure 52. Cross-section of the modelled tree in ENVI-met.
A) cross-section of a schematic representation of trees, B) visual examples of the plan view (top view) in ENVI-met (z=17.5m), and C) cross-section of an ENVI-met scenario with trees

2.2.2 Meteorological conditions

Temperature and relativity humidity were set up as room conditions, simulating the same conditions as the WT experiment (Personal Communication Gromke C., 2020). Wind velocity at reference height (10 m above the ground level) was set to 3 ms^{-1}, and the wind direction was set to 90˚ (direction from East to West).

2.2.3 Pollution source

Four lines of traffic emissions (12.7 µg s^{-1} m^{-1}) were embedded in the model between the buildings at a height of 0.3m (simulating exhaust pipe height) (Wania et al., 2012; Morakinyo & Lam, 2016b). The four traffic release lines were extended to 16m on each side of the canyon to account for traffic exhaust fumes released on the sidewise street intersections (Moonen et al., 2013; Personal Communication Gromke C., 2020). Thus, the lines of traffic measure in total 34m each (18m canyon long measure + 16m extension) (represented by red lines within the buildings in Figure 50 and Figure 51).

The pollution source was set to emit fine particulate matter (PM$_{2.5}$).

2.3 ENVI-met practises and other validation test cases

More than 150 test scenarios were modelled in ENVI-met. At the beginning of this research, ENVI-met was practised using published scenarios, such as those by Wannia (2007) and Morakinyo and Lam (2016b). The results of these test scenarios demonstrated a good understanding of the model concerning parameter settings and building model area. In addition, the ENVI-met website has several tutorials that teach users how to build model areas from scratch, provide useful information, and answer challenges that users may face.

Once the behaviour of the model under different parameters was understood, several test scenarios results were compared to the wind tunnel. Different computational domains, grid sizes, roughness, street configurations, and pollutant, such as gases (CO_2 and NO_2) and particles ($PM_{2.5}$ and PM_{10}), were tested. The most common test scenarios studied were similar to the isolated street in the wind tunnel. However, different street lengths and widths and two buildings of different heights and widths were modelled, as well as different meteorological parameters were chosen to identify under which configuration and parameters the model best replicated the wind tunnel data.

Airflow and pollutant concentrations outcomes from each test scenario were studied and compared to CODASC. All this work was done to justify the input values to configure the ENVI-met model (Table 19). See Appendix F, Table 1 for the additional work carried out. The table summarises the different model domains, street configurations, pollutants and statistical analysis of some test scenarios.

2.4 Assumptions

The parameters used to run the ENVI-met scenarios were as similar as possible to the WT experiment (Table 19). Despite tutorial sessions, forum questions, and personal communication with the owner of ENVI-met (Personal Communication ENVI-met, 2020) and CODASC (Personal Communication Gromke C., 2020) and the different test scenarios studied, the model input values could not be entirely equal to those of the WT. Thus, some assumptions were made:

1) *Roughness length:* Previous test scenarios were simulated in this research to select specific values of roughness length. This parameter is part of the vertical wind profile equation that models the wind velocity near the ground in ENVI-met. Although different roughness length values were tested, the model works adequately using the default value of 0.01m, with lower values ENVI-met stopped working.
2) *Leaf Area Density (LAD):* ENVI-met does not include pressure loss coefficient (See Section 2.1.1.) as and input, but includes a similar term, which is the momentum sink induced by trees (Vranckx et al., 2015; Jeanjean et al., 2017). The momentum sink

(Cx) (same as pressure loss coefficient in CODASC, λ_{WT}= 80m^{-1} ⇒ $\lambda_{\text{full scale}}$ = 0.53m^{-1}) is uniformly assigned to the cells in the computational domain occupied by the tree crowns, expressed as

$$Cx = C_d \times LAD \tag{4}$$

C_d is the leaf drag coefficient, and LAD is the leaf area density. The leaf drag coefficient depends on the species and literature values ranging between 0.1 and 0.3 (Gromke & Blocken, 2015). For this study, C_d = 0.25 was used, representing a common tree in the summer season (leaves fully developed) (Jeanjean et al., 2017). Finally, the LAD value was calculated and used as an input in ENVI-met equal to 2.12 m^2/m^3. The values for the LAD of full-grown deciduous trees range from 0.2 to 2.2 m^2/m^3 (Lalic & Mihailovic, 2004). See Appendix F for calculations of LAD.

3) *Pollution source:* Emission rate, traffic flow and traffic composition (type and number of vehicles) were not found in the CODASC dataset, but they were input values required in ENVI-met. So, the values were set to be the same as those of Morakinyo and Lam (2016b) used to perform a validation of ENVI-met against CODASC (Table 18).

The parameters enlisted in Table 19 were consulted with ENVI-met to confirm good practice and use of the model.

Table 19. Overview of the main parameters required for the configuration of the ENVI-met model and identification of the CODASC parameters used.

Parameter	Definition	Value in ENVI-met	Value in CODASC
Street canyon	H/W	1	1
	Width (W)	18m	0.12m
	Length (L)	180m	1.2m
	Height (H)	18m	0.12m
	Roughness length	0.01m (default ENVI-met value)	0.0037m (full scale 0.555m)
Meteorological conditions	Wind speed	3 ms^{-1}	4.65ms^{-1}
	Wind direction	90˚	90˚
	Initial air temperature	20˚C – 25˚C	20˚C – 25˚C
	Relative humidity at 2m	40% - 60%	40% - 60%
Pollution source	Species	Particulate matter of 2.5 µg diameter	Gas (sulphur hexafluoride SF_6)
	Source geometry (1)	A linear source at 0.3m height (the minimum ground level reached in ENVI-met)	A linear source at ground level
	Number of line sources	Four	Four
	Emission rate	12.7 µg s^{-1} m^{-1}	No information
	Traffic flow (No cars)	8,000	No information
	Light-duty vehicles	5.0%	No information
	Heavy-duty vehicles	2.5%	No information

Parameter	Definition	Value in ENVI-met	Value in CODASC
	Motorcycles, urban public transport, and coaches	4.5%	No information
Vegetation cover: Street trees	Height	12m (2/3 Height)	2/3 Height
	Trunk height	6m (1/3 Height)	1/3 Height
	Leaf Area Density	2.1 m^2/m^3	Not applicable (CODASC does not use LAD values, use pore volume)
	Momentum sink term	0.53 m^{-1}	80 m^{-1}

(1) 0.3m is the minimum distance from the ground in ENVI-met.

2.5 Data analysis

As was explained in Section 1.3 of this **Chapter**, the CODASC concentration dataset is presented along the canyon (y-axis) and at seven heights (z-axis) (Figure 48 and Figure 53). The same coordinates (points) that CODASC uses to present its data were used in ENVI-met to compare.

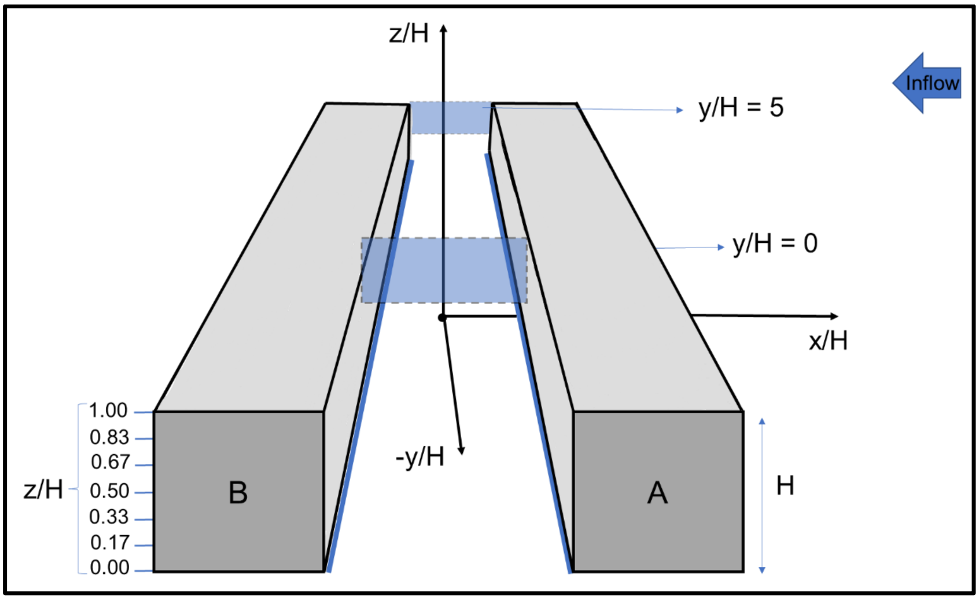

Figure 53. Representation of an isolated street canyon (image is not to scale).
A Cartesian coordinate system is in the middle of the canyon (x, y, z). The blue line on the ground next to each building wall (A and B) represents the grid (location) where ENVI-met concentrations were extracted. H is the height of the building (18m). z/H represents the different heights (z-y plane). At seven heights (z/H), the normalised concentration data set is provided by CODASC (N=7). Source: Own elaboration

The results are presented into three parts.

1) Part 1: General airflow and vertical velocity in the ENVI-met model

A general study of the model's behaviour against theoretical air flows was performed. The ENVI-met normalised vertical velocity was calculated to compare the theoretical flow in the model with the wind velocity of the CODASC dataset.

Normalised vertical velocities (w+)

The wind flow in the ENVI-met treeless scenario was compared to the theoretical wind flow in a treeless street canyon to understand how the model works. Wind velocity data was not available in the published database but was obtained directly from the WT author Dr Christof Gromke after personal contact with him (Gromke, 2021). In a vertical plane perpendicular to the street axis in the middle of the canyon (y/H=0), the velocity component (w) was measured in ENVI-met and CODASC. The ENVI-met velocities were normalised by the velocity of the undisturbed flow U_H at building height H =18m (U_{ref}), according to (5) (personal communication Gromke C. & Ruck B., 2008; Gromke, 2021). These ENVI-met velocities were normalised to facilitate comparison with CODASC.

$$w^+ = \frac{w}{U_H} \tag{5}$$

The reference velocity (U_{ref}), which is the x-component velocity at z=H (18m in ENVI-met), was used to graph the profiles of normalized vertical velocity (U/U_{ref}) for the inflow in ENVI-met and CODASC.

2) Part 2: Effect of trees in ENVI-met

The effect of trees in the model was assessed. The ENVI-met concentrations with and without trees were studied individually. After that, a comparison was made between both scenarios to study the effect of vegetation in the model. Here, no comparison was made with CODASC concentrations, that was done in the third part of this work (see below).

Effect of trees in ENVI-met

For both scenarios without (reference case) and with trees, the ENVI-met concentrations were studied at three heights, along the y-axis in front of the leeward and windward wall of the street canyon. Three plan views (x/y plane) z=0.5m, z=2.5m, and z=17.5m were cut to study ENVI-met concentrations. The first two (z=0.5 and 2.5 m) represented the pedestrian level (the focus level of this research), and the final height (z=17.5m) represented the top of the building or canopy for the scenario with trees.

In addition, to study the effect of trees in both scenarios, the absolute differences in concentrations between the two scenarios were compared at two heights: 1) 0.5m to reflect the pollutant exposure at a pedestrian level, and 2) 6.5m to reflect the effect of the tree canopy (where the canopy appears after the trunk). At the beginning of the crown tree, this last height was selected to study the influence of "vegetative material" in the model. These absolute differences were made directly in ENVI-met. Hence, the treeless scenario (reference case) was compared to the tree scenario, and a comparative figure with the absolute differences in concentrations was created.

3) Part 3: Model validation

CODASC reports normalised concentrations (c^+) along the canyon (y-axis) in front of the leeward and windward walls at seven heights (z/H) (Figure 48 and Figure 53). The validation was done by extracting ENVI-met concentrations in the middle of the canyon (y/H = 0) at similar heights (z/H) to CODASC. These were not exactly the same because in ENVI-met the first point close to the ground is 0.5m.

Comparing ENVI-met concentrations and CODASC experimental concentrations requires data normalisation due to the difference in scale between the WT and the full-scale model ($C^+_{WT} = C^+_{full\ scale}$) (University of Hamburg, 2013). So, the ENVI-met pollutant concentrations were normalised according to (6)

$$C^+ = \frac{C_m \, H \, U_H}{Q_I} \tag{6}$$

Where, C^+ is the normalised concentration (dimensionless), C_m is the concentration (µg m^{-3}) modelled by ENVI-met, H is building height (m), U_H is wind velocity at height H (m s^{-1}), Q_l is the emission rate of the line source (µg s^{-1} m^{-1}).

Effect of trees in ENVI-met

Using the normalised ENVI-met concentrations (c+), the relative difference in concentration (RDC) (7) between with and without trees scenarios was calculated

$$RDC = \left(\frac{C^+_{veg} - C^+_{ref}}{C^+_{ref}} \right) \times 100\% \tag{7}$$

RDC is the effect of trees on $PM_{2.5}$ concentrations inside the canyon (%), C^+_{veg} is the $PM_{2.5}$ concentration inside the canyon with trees (ug m^{-3}), and C^+_{ref} is the $PM_{2.5}$ concentration inside the canyon without trees (µg m^{-3}). Negative values imply lower $PM_{2.5}$ concentration (air quality improvement).

The comparison was made at two heights for the windward and leeward sides in the middle of the canyon. Two plan views (x/y plane) z=0.5m and z=6.5m were cut to study ENVI-met normalised concentrations against CODASC data. As was explained before, the first height evaluates the effect of trees at the pedestrian level, and the second is the height at the beginning of the crown, representing the effect of trees inside the street canyon.

2.6 Statistical evaluation

The model performance evaluation was conducted using the standard metrics suggested in the COST Action 732 (Schatzmann et al., 2010) and Chang and Hanna (2004). For the normalised ENVI-met concentrations, the normalised mean square error (NMSE), correlation coefficient (R), fraction of the model predictions within a factor 2 (FAC2), and fractional bias (FB) were calculated. All statistical measures within the accepted values for satisfactory model performance were obtained from the COST Action 732 and Chang & Hanna, 2004 and 2005 (Chang & Hanna, 2004, 2005; Schatzmann et al., 2010) (Table 20).

The most common metric is FAC2, which is the most robust measure because it is not influenced by high or low outliers (Chang & Hanna, 2004). The FB refers to the arithmetic difference between the model's predictions and its observations. This value provides information on under (positive values) and overestimation (negative values). The R reflects the linear relationship between two variables, the most frequently used measure to identify the robustness between the WT data and the model (Taleghani et al., 2020; Xing & Brimblecombe, 2020b). This correlation, however, only confirms a reasonable agreement if the relationship is linear, avoiding non-linear interactions (e.g., parabolic or sigmoid relations). The NMSE assumes that the mean observed concentration equals the mean of the model concentrations. If NMSE becomes much larger than 1.0, it can be inferred that the distribution is not normal but is closer to log-normal (Chang & Hanna, 2004).

The statistical evaluation presented by Chang and Hanna (2004) is widely used to evaluate the performance of a model against a WT experiment. This evaluation, however, is for mesoscale models (Chang & Hanna, 2004), and despite various efforts, no statistical evaluation at microscale was found. In fact, several microscale studies used Chang and Hanna (2004) statistical analysis (Table 18) with acceptable agreement on the statistical criteria. Thus, it was adopted for the evaluation of ENVI-met.

Table 20. Statistical model performance.

Metric	Acceptable range	Formula
NMSE	<4	$\boldsymbol{NMSE} = \dfrac{\overline{(C_o - C_p)^2}}{\overline{C_o}\,\overline{C_p}}$
R	>0.8	$\boldsymbol{R} = \dfrac{\overline{(C_o - \overline{C_o})(C_p - \overline{C_p})}}{\sigma_{C_p}\ \sigma_{C_o}}$
FAC2	>0.5	$\boldsymbol{FAC2} \Rightarrow 0.5 \leq \dfrac{C_p}{C_o} \leq 2.0$
FB	[−0.3, 0.3]	$\boldsymbol{FB} = \dfrac{(\overline{C_o} - \overline{C_p})}{0.5\,(\overline{C_o} + \overline{C_p})}$

C_p model prediction; C_o observation; $\overline{C_o}$ and $\overline{C_p}$ average over the dataset, σ_{C_p} and σ_{C_o} standard deviation over the dataset.

3 Results

3.1 Part 1: General airflow and vertical velocity in the ENVI-met model

Theoretically, in a street canyon a vortex in the middle of the canyon and corner eddies are expected to appear (**Chapter 2**). The airflow profile in the treeless scenario in ENVI-met was correct. The ENVI-met airflow showed the expected theoretical canyon vortex in the middle of the street. However, the normalised velocities (w+) did not match the WT. The ENVI-met flow velocity at the middle of the canyon is lower than the WT (below 0.29 m s^{-1})[22], resulting in a visible but weak vortex in the middle of the canyon (See Appendix F, Figure 3 for a plan view of ENVI-met wind speed patterns at 0.5m). The corner eddies at the ends of the street did not show a visible formation (See Appendix F, Figure 4 and Figure 5 for the horizontal flow pattern). Probably, the corner eddies were not visible because the ENVI-met velocity magnitudes were much lower than those observed in the WT (-46.3% average difference in the vertical flow w+), resulting in the formation of weak vortices (Figure 54).

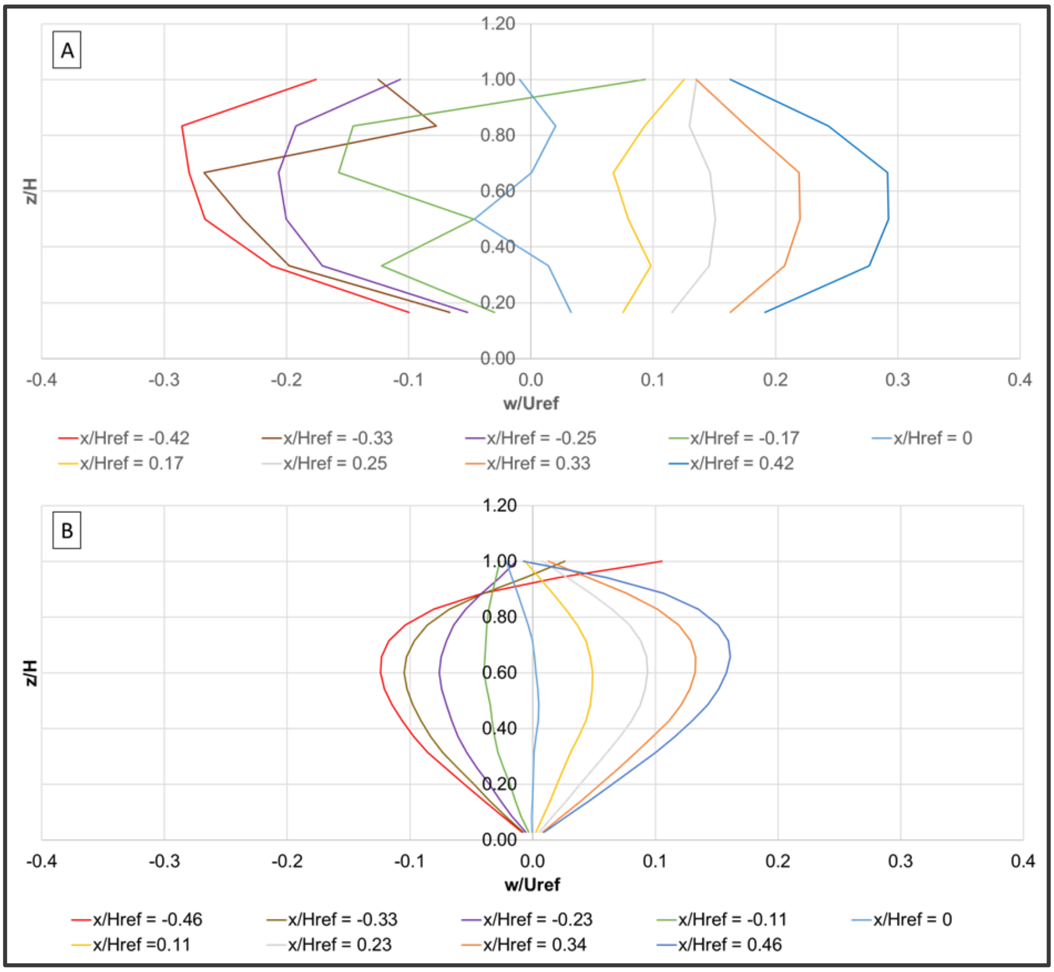

Figure 54. Normalised vertical velocities (w) at the centre of the street canyon.
Figure A normalised vertical velocity (w+) in the wind tunnel, Figure B normalised velocity (w+) in ENVI-met treeless scenario.

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[22] The ENVI-met wind flow could not be compared to that of the wind tunnel due to the absence of such online data.

The low velocity in the middle of the canyon also was modelled by the other test scenarios studied, see Appendix F, from Figure 6 to 8. All these scenarios revealed weak formation of canyon vortex in the and no visible formation of corner eddies. This demonstrated and confirmed that ENVI-met velocity magnitudes are much lower than those seen in the WT, with an average wind speed in the middle of the canyon below of 0.37 m s^{-1}.

3.2 Part 2: Effect of trees in the ENVI-met model

3.2.1 $PM_{2.5}$ dispersion in street canyon without trees

Pollutant dispersion inside a street canyon with a perpendicular wind direction has a particular and well-known behaviour. Generally, low pollutant concentrations can be found on the windward side, close to the windward wall. On the other hand, high pollutant concentrations in the street canyon are observed on the leeward side. The reason for this difference in concentrations across the street is due to the vortex in the street which means that the airflow at street level is in the opposite direction of the prevailing wind direction. This flow disperses the traffic emissions to the leeward side, producing higher concentrations there (Baik & Kim, 1999; Gromke & Ruck, 2012). This pollutant dispersion pattern was simulated correctly by ENVI-met; Higher $PM_{2.5}$ concentrations at all heights were observed on the leeward side, while lower concentrations were found on the windward side (Figure 55 and Figure 56).

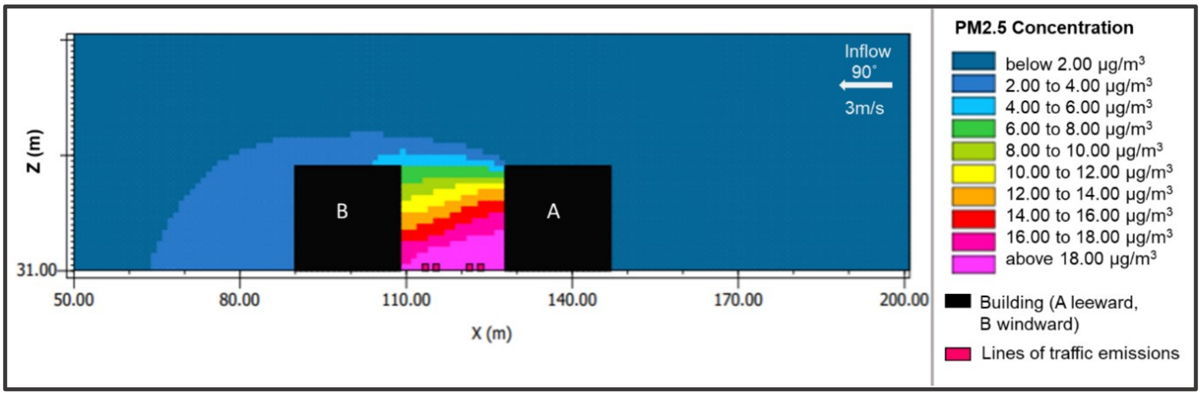


Figure 55. Vertical particle concentrations in strong wind (3 m/s) with a perpendicular inflow. A cross-section was made in the middle of the canyon; x/z cut at j=180 (y=180.5m). The model domain was cut, leaving 50 m on both sides of the canyon to have a better visualisation of the concentrations of pollutants in the canyon

The ENVI-met concentration gradient demonstrated higher concentrations of pollutants in the ground compared to the top of the building, which was theoretically expected. Once the pollutants reach the roof level, some pollutants enter the street canyon again, and some escape from the street, decreasing concentrations as height increases (Zhu & Hinds, 2005; Wu et al., 2014). The maximum average of $PM_{2.5}$ concentrations found at heights of 0.5m, 2.5m, and 17.5m was 23.02 µg m^{-3}, 20.59 µg m^{-3}, and 6.56 µg m^{-3}, respectively (Figure 56).

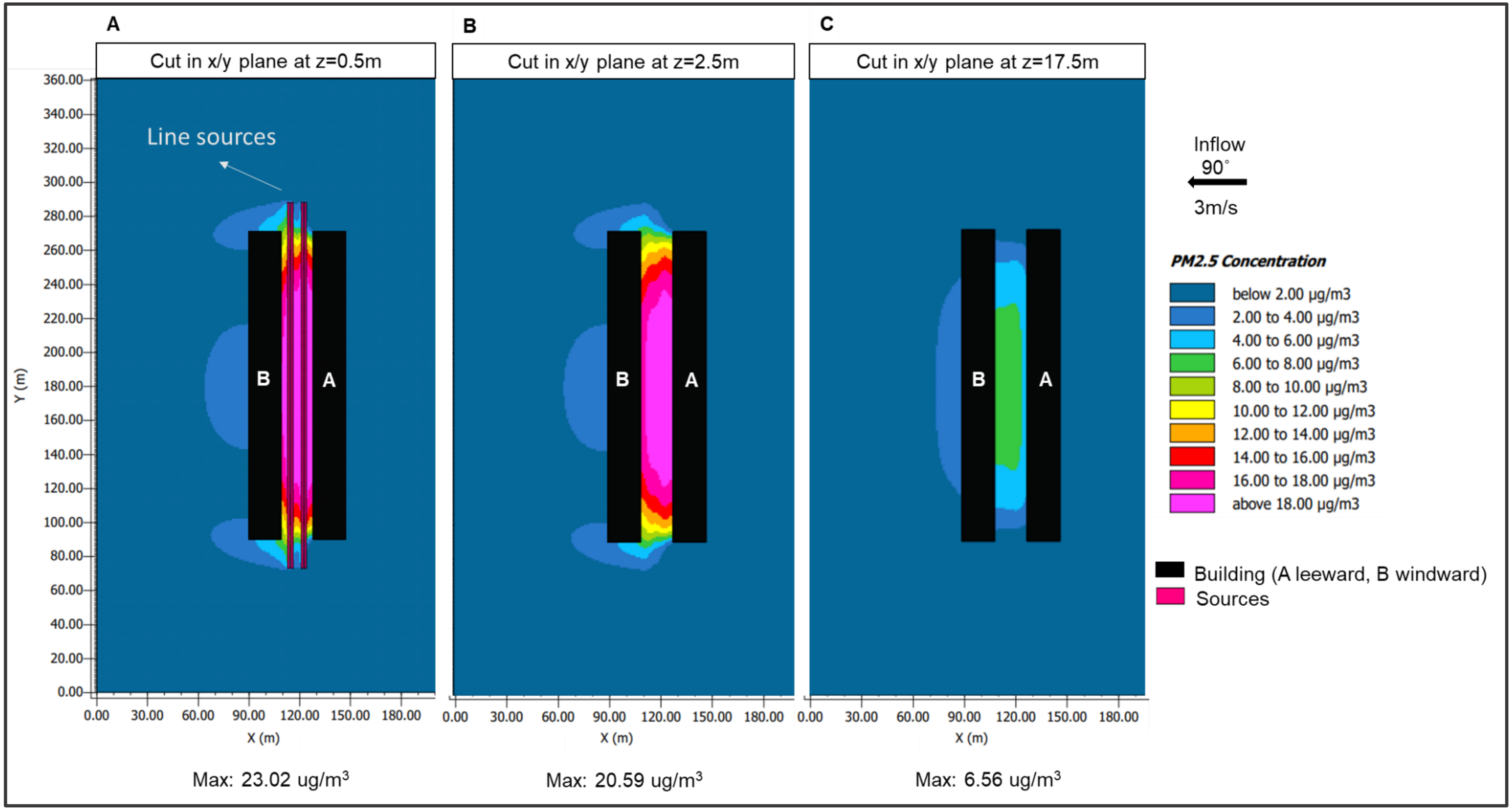


Figure 56. Plan view of $PM_{2.5}$ concentrations inside the street canyon in strong wind (3 m s^{-1}) with perpendicular (90˚) inflow at three different heights. 0.5m (A), 2.5m (B) and 17.5m (C) from the ground. The horizontal model domain (x-axis) was cut at 200m. These figures do not represent the entire computational domain of this study

3.2.2 $PM_{2.5}$ dispersion in street canyon with trees

The row of trees increases the concentrations of pollutants under its canopy, displaying a high level of $PM_{2.5}$ along the canyon, especially at pedestrian level (from 0.5 to 2m) (Figure 57). The maximum $PM_{2.5}$ concentration at pedestrian level was between 100.24 μgm^{-3} (0.5 m) and 88.81 μgm^{-3} (2.5 m), four times more than the treeless scenario. At building height (17.5m), $PM_{2.5}$ concentrations decreased, reaching a maximum of 14.24 μgm^{-3} next to leeward side (wall A), indicating an accumulation of $PM_{2.5}$ (Figure 58).

The ENVI-met concentrations showed a slight reduction in concentrations at the end of the streets, possibly attributable to the presence of trees. Balczó et al. (2009), using a model to study the tree planting arrangement, found the same result. At the end of the leeward wall, the concentration decreased with the presence of trees (LAD) (Balczó et al., 2009).

As the height increases, ENVI-met concentrations ($PM_{2.5}$) increase on the leeward side (A) and decrease on the windward side (B). This accumulation on the leeward side is more evident when the canopy appears at 6 m, accumulating a large concentration of $PM_{2.5}$ on this side of the wall (Figure 57). These findings correspond with the results of previous studies that have shown that the aerodynamic effect of trees ends up trapping road emissions due to the porosity of the trees, inducing a reduction in wind speed and accumulating pollutants below the canopy (Gromke & Ruck, 2008b; Buccolieri et al., 2009; Bitog et al., 2011; Buccolieri et al., 2011; Rafael et al., 2018).

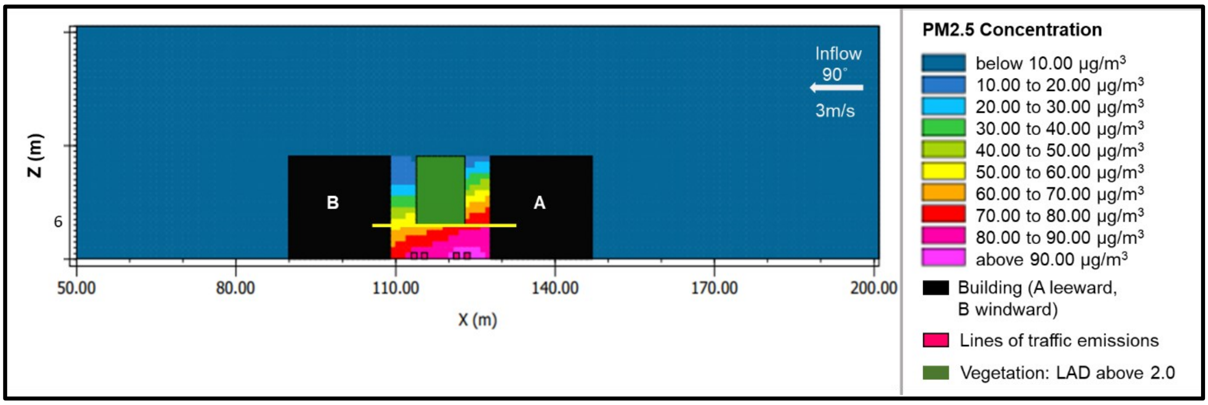


Figure 57. The vertical particulate concentrations profile is influenced by a row of trees in the middle of the canyon (x/z cut at y=130m) in strong wind (3 m/s) with a perpendicular inflow.

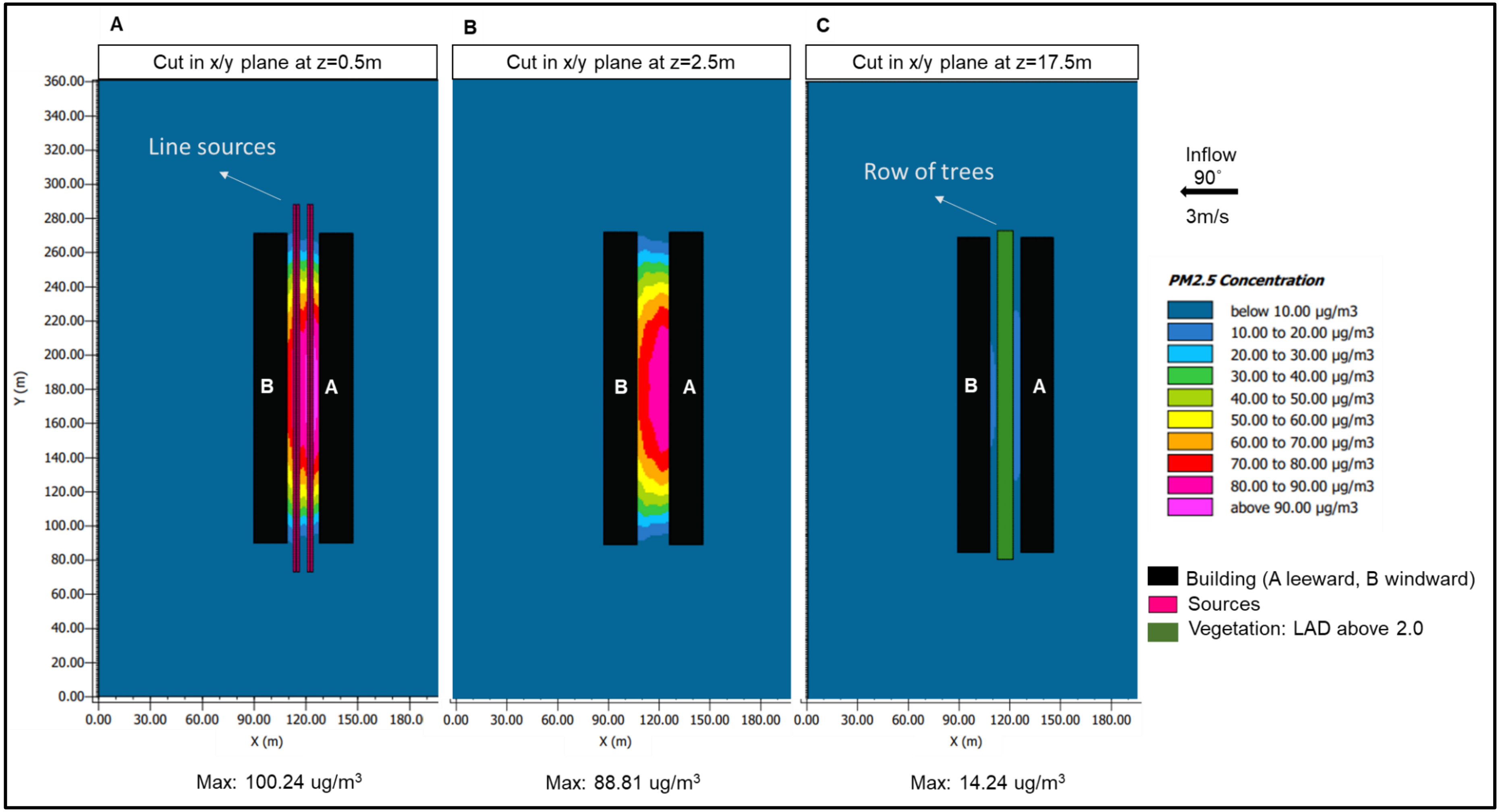


Figure 58. Influence of a row of sparsely foliated trees on PM$_{2.5}$ concentrations inside the street canyon in strong wind (3 ms^{-1}) with perpendicular (90˚) inflow at three different heights.

0.5m (A), 2.5m (B) and 18.5m (C) from the ground. The horizontal model domain (x-axis) was cut at 200m. These figures do not represent the entire computational domain of this study

3.2.3 Influence of trees on $PM_{2.5}$ dispersion

The treeless scenario was compared with the tree scenario to evaluate the $PM_{2.5}$ concentration changes induced by a row of trees at two different heights (Figure 59). The continuous row of trees induces higher concentrations in the middle of the canyon, accumulating $PM_{2.5}$ on the leeward side (wall A). Concentrations were slightly reduced at the ends of the canyon street compared to the treeless scenario.

The greatest changes in concentration were found at the height of 6.5 m, where the canopy appears (Figure 59B). Although the ENVI-met concentrations remained high at this height, there was a slight improvement on the windward side (wall B) with a difference of 10 μgm^{-3} compared to 0.5m height. However, in comparison with the ENVI-met concentrations of the treeless scenario, incorporating street trees into the street canyon does not improve air quality.

The effect of a row of trees in the middle of the street canyon was detrimental (above 52 μgm^{-3} at 0.5m) and is of particular concern at the pedestrian level. This result is similar to that of Jeanjean et al. (2017), who found that trees exacerbate trapping pollutants when winds blow perpendicular to the street canyon (Jeanjean et al., 2017).

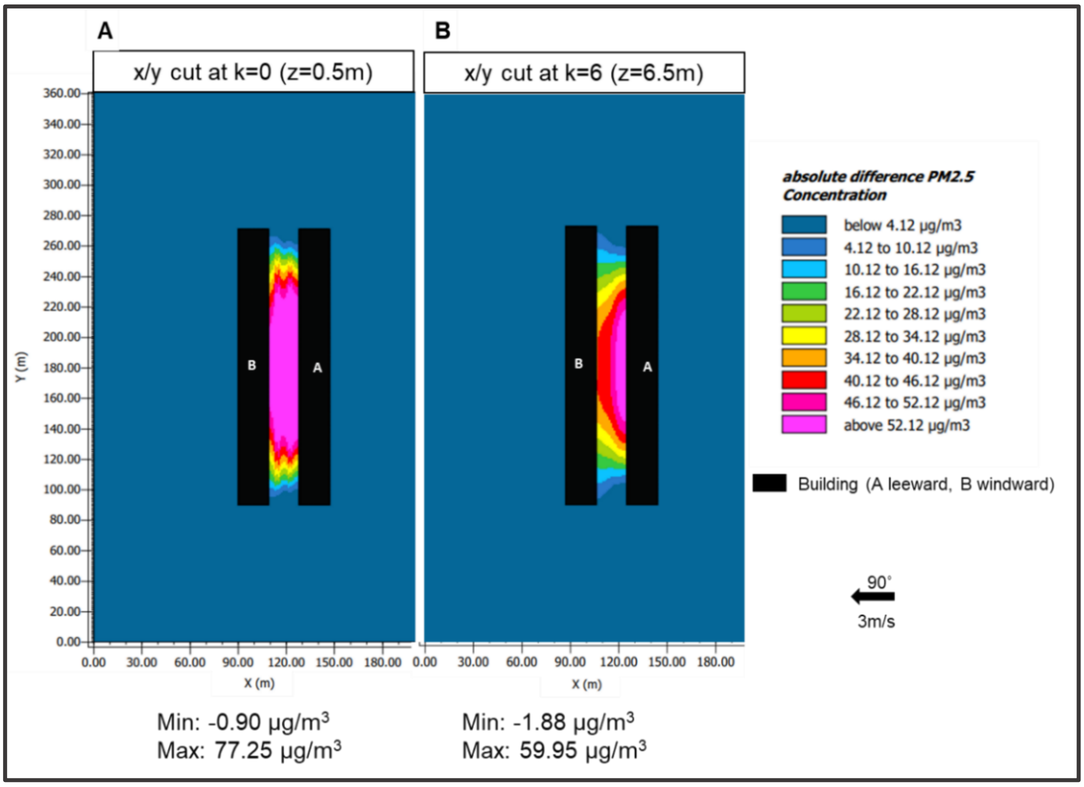


Figure 59. Influence of a row of foliated trees on $PM_{2.5}$ concentrations in a strong wind (3 ms^{-1}) with perpendicular flow.
Comparison between the simulation without trees (Reference case) with the row of trees simulation at two heights, A. 0.5m and B. 6.5m. The warm colours represent an increase, and the cold colours represent a decrease in $PM_{2.5}$ concentrations

3.3 Part 3: Model validation

A statistical validation test was carried out on normalised concentrations from the ENVI-met model against the wind tunnel data for the windward (wall B) and leeward sides (wall A) (Chang & Hanna, 2004, 2005) in the scenarios with and without trees (Table 21).

The statistical validation for the treeless scenario showed an acceptable agreement with the WT data only for the windward wall (B). By contrast, only one criterion was met at the leeward wall, reflecting a poor agreement between the model results and the WT data. The normalised concentrations in ENVI-met were quite similar on both sides of the canyon street, masking the notorious differences between the leeward and windward sides, as is shown in the WT (See Appendix F, Figure 9).

The statistical validation for the tree scenario also did not provide an acceptable agreement between the model concentrations and WT data. The WT predicted that concentrations on the leeward side would increase by about 35% and decrease by about 40% on the windward side compared to the scenario without trees at pedestrian level. In total, in the WT, the pollutant concentrations increased by 28% compared to the treeless scenario (Gromke & Ruck, 2008b), whereas in ENVI-met, the pollutant concentrations increased by over 800% compared to the treeless scenario (Table 22). ENVI-met overpredicted the concentrations when trees were present in the street canyon, thus no improvement in air quality was observed (See Appendix F, Figure 10).

Table 21. Results of the statistical evaluation for the street canyon (H/W=1). Normalised mean square error (NMSE), the fraction of the model predictions within a factor 2 (FAC2), fractional bias (FB), and correlation coefficient (R) (N=7). Highlighted cells represent unacceptable values.

Statistical evaluation	Without trees				With trees			
	NMSE	FAC2	FB	R	NMSE	FAC2	FB	R
Criterion	**< 4**	**>0.5**	**[-0.3, 0.3]**	**>0.8**	**< 4**	**>0.5**	**[-0.3, 0.3]**	**>0.8**
Leeward side (wall A)	0.63	0.43	0.72	0.77	0.15	0.86	-0.18	0.82
Windward side (wall B)	0.08	1.00	-0.15	0.86	6.85	0.14	-1.48	0.84

The relative difference in concentrations (RDC) for the normalised CODASC and ENVI-met results showed that the ENVI-met concentrations did not match the concentrations found in the WT (Table 22). In the treeless scenario, ENVI-met underpredicted the leeward side concentrations and overpredicted the windward side concentrations, without showing any air improvement on this side. In the scenario with trees, ENVI-met concentrations were overpredicted at the two studied heights. Thus, no air improvement was observed with trees, especially on the windward side of the street (Table 22).

Table 22. Comparing the normalised concentrations (c+, dimensionless) in walls A and B inside the street canyon with and without trees at two different heights.
Presented ENVI-met results versus WT data. For each height, the relative difference between the simulation and WT data is included

Wall	Height (m)	Scenarios without trees			Scenarios with trees			RDC [(1)]	
		WT	ENVI-met	Diff.	WT	ENVI-met	Diff.	WT	ENVI-met
Leeward (A)	0.5	42.6	19.1	-55%	59.2	83.3	41%	39%	337%
	6.5	33.3	17.3	-48%	51.7	75.2	45%	55%	334%
Windward (B)	0.5	11.8	16.8	42%	6.1	67.6	1008%	-49%	303%
	6.5	10.9	14.3	30%	6.0	55.0	816.6%	-45%	286%

(1) RDC is the relative difference in concentration between scenarios with and without trees (effect of trees in both wind tunnel and ENVI-met models). Negative values imply lower $PM_{2.5}$ concentrations (air quality improvement).

4 Discussions

A study of ENVI-met airflow and pollutant dispersion was conducted. Different approaches were analysed, firstly to understand the model performance, such as airflow profile and ENVI-met concentrations with and without a row of trees. Statistical validation was then carried out on normalised concentrations from the ENVI-met model against the WT data for leeward and windward walls.

ENVI-met modelled an expected airflow profile and vertical concentration gradient, however, inside the canyon, the wind velocity was reduced in comparison to the WT, creating a weak vortex leading to lower normalised concentrations at the leeward side as compared to the WT. The same results were found by Paas and Schneider (2016), who compared the local meteorological measurement data with the ENVI-met simulations, with the wind speed in ENVI-met found to be lower than the real measurements (Paas & Schneider, 2016).

The validation of CFD models against wind tunnels has been practised on for decades, and the influence of different scales across the two domains is well-understood in scientific research (Ahmad et al., 2005; Bitog et al., 2011). So, validating the ENVI-met results against the WT is a helpful tool for model evaluation. Morakinyo and Lam (2016b), for example, validated ENVI-met using the same WT dataset. The authors concluded that the comparison with the WT was satisfactory for their purposes. However, the comparison is not satisfactory for our purposes, which require resolving the velocity and concentration fields at high resolution and accuracy (see Table 17) (Morakinyo & Lam, 2016b). Another CFD model (FLUENT) managed to replicate the WT results with high accuracy using a comparable mesh resolution, with the study concluding that, although there were differences of ± 60% between WT and model results, all statistical measures (NMSE, R, FAC2 and FB) were within the accepted values for satisfactory model performance for their purposes (see Table 18) (Buccolieri et al., 2009). Despite the good agreement of the FLUENT model against WT, the model was not used in this study because it is not as easy-to-use as ENVI-met. The model is not designed to be used by general practitioners and an advanced understanding of CFD is needed to set it up correctly.

Other ENVI-met air pollution studies have validated their results using field measuring data, also showing poor or a lack of agreement between ENVI-met performance and observable data. For example, Deng et al. (2019) compared field monitoring and ENVI-met model simulation for $PM_{2.5}$ concentrations in different green spaces, showing that ENVI-met concentrations were lower than the measurement's data (no data was found) (Deng et al., 2019). Hofman et al. (2016), who calculated the PM_{10} deposited on real leaves and compared their results with an ENVI-met simulation, found that the leaf-deposited PM_{10} mass differed by two orders of magnitude between the modelled and calculated leaf concentrations (Hofman et al., 2016). The authors of both studies justified the lack of agreement with ENVI-met, claiming that there were possible measurement errors during the campaigns and the ideal representation of the model, which only included local traffic sources (Hofman et al., 2016; Deng et al., 2019). In a more similar WT context, where the effect of vegetation along a motorway was modelled, De Maerschalck et al. (2008) showed a good agreement between the measurement data and ENVI-met simulations for nitrogen oxides (NOx), though for PM the model concentrations did not agree with the measurement data (no data was found) (De Maerschalck et al., 2008).

Following our validation study and a review of the available literature on the validation of ENVI-met, we concluded that the model could not represent the wind flow and pollution concentrations at a microscale (i.e., the flow within a single street) with a sufficient degree of accuracy to be useful for our purposes.

It could be argued that an additional type of validation is needed to validate ENVI-met, but the problem is that there is no other adequate validation data set available for comparison. For example, a randomised control trial with a before and after evaluation and a control group to evaluate the impact of real GI on streets does not exist. To the author's knowledge, there is no published or openly accessible real-life measurement campaign dataset for GI. Thereby, to validate the modelling studies with GI, there are currently only two options: 1) an individual measurement campaign and 2) the wind tunnel experiment of Gromke and Ruck (2007, 2008b, 2012).

Using the WT to validate the ENVI-met tree model is problematic, because the WT tree is a model in itself and does not include some of the important GI characteristics that influence air quality. However, the WT is an appropriate tool to validate ENVI-met's ability to simulate the dispersion of pollutants around buildings. The treeless scenario indicates that ENVI-met struggles to do this. Adding trees increases the complexity of the problem, but if the model is unable to simulate the simpler scenario (the treeless scenario) correctly, then it is unlikely to be successful with a more complex scenario.

From the author's perspective, further validation of air pollution concentrations is required for this model – and the field in general – but only for air pollution, since the model has been validated for microclimate, thermal comfort, and the urban heat island effect (UHI). According to a literature review of ENVI-met validation on microclimate studies, 55% (52 out of 92 selected studies) have reported the evaluation and validation of results (Tsoka et al., 2018). Validation for thermal comfort and urban air temperature has been run with ENVI-met results presenting an excellent agreement against measured data (Elnabawi et al., 2013; Jamei et al., 2017; Morakinyo et al., 2017; Perini et al., 2017).

4.1 Limitations and uncertainties of the validation

It is important to recognise the different degrees of uncertainty associated with WT data and to understand how ENVI-met results are compared to this data. Uncertainty assessments provide a better understanding of model error, input data, and the overall accuracy and applicability of the model. Some limitations and uncertainties of this validation are mentioned below:

- **Wind flow**. The wind profiles may be correct, however, the magnitude of the normalised velocity in the ENVI-met did not match with that of the WT. Lower wind velocities were presented in the ENVI-met, leading to air stagnation, reduced air circulation, and the eventual trapping of more pollutants in the canyon. This result was discussed in consultation with ENVI-met, who noted that the modelled airflow is correct, and that a wind speed decrease, due to the blocking effect of the leeward building, is expected in the middle of the canyon (Personal Communication ENVI-met, 2020). This airflow regime also occurs in the WT but to a lesser degree. So, the lower wind velocities that ENVI-met presented in the middle of the street could be due to a difference in the parameterisation. The surface roughness (0.01m) in the model was much lower than the full-scale equivalent of the WT. However, the main driving force for the flow in the canyon is the roof height velocity (U_{ref}), and to validate the wind flow of the model, normalised values were used.

  The lack of agreement between the model and the wind tunnel experiment could be attributable to the lower wind velocity circulating in the middle of the street canyon. This influences a weak vortex, consequently, low dispersion of $PM_{2.5}$ along the street. Probably, the problem is that the model does not have sufficient resolution for modelling at the microscale, and it uses a fast method for solving the Navier–Stokes equations, which is known to add additional diffusivity to the flow and give less accurate results

(Zuo & Chen, 2009). Practitioners should be aware of this problem. They may be more inclined to use a fast-running model; however, even a user-friendly model requires some understanding of model simulation. The result of a CFD simulation largely depends on user choices, inputs, grid size, simplifications, and model design in order to get (fast)results. Users will make assumptions, which might lead to additional uncertainties, affecting the final results significantly. The experience, skills and abilities of users and the possibility to validate CFD models by comparison with experiments will determine the reliability of the model for a specific need.

- **Measured heights.** The WT data only has seven points (heights) to compare in the vertical dimension, while ENVI-met was able to reproduce 18 points along the cross-section of the building. The minimum number of recommended observation-prediction points to increase confidence is around 20 (Chang & Hanna, 2004), so comparing only seven values is likely not the best option for estimating the model's performance in this case.
- **Pollutant source size**. The size and height of pollutant sources might influence particle distributions. The smaller source size is close to the ground, and hence the particles are emitted into the edge of the vortex sweeping around the canyon, leading to high concentrations on the leeward wall. Larger sources are centred further away from the ground and emit particles nearer to the centre of the vortex, leading to higher concentrations away from the leeward wall (Kumar et al., 2009). Both ENVI-met and the WT utilise small traffic emission sources. So, a better representation of the size of a pollutant source is needed to improve dispersion at the pedestrian level. It should be noted that the effect of traffic-produced turbulence is not considered in ENVI-met simulations which can produce a well-mixed area close to pedestrian level.
- **Vegetation representation**. The inaccurate representation of trees in WT could interfere with the results and produce misleading conclusions about different canopies that ENVI-met is able to reproduce. Wind tunnels are widely accepted as producing realistic simulations of flows around buildings and street configurations, but adding GI, and all the GI characteristics that influence air quality, requires further study. Both WTs and models have missed the real effect of trees (GI) in the streets. In the WT, trees are depicted in rectangular lattice cages filled with a synthetic material without considering important species-specific information, such as crown dimensions and LAD. By contrast, tree representation in ENVI-met considers real values of LAD to reflect a real-world scenario. Tree crown morphology and LAD are key factors influencing the local distribution of atmospheric particles (Hofman et al., 2016). Thus, different parameters to represent trees might lead to different quantitative results.

4.2 When does a good enough approach become an acceptable model?

Validation establishes the accuracy and overall performance of the computational model, comparing predictions to real-world conditions, thus proper model evaluation ensures fidelity in simulations. (Chang & Hanna, 2004) create statistical methods to evaluate the air quality model's performance. Although this statistical evaluation considers evaluating models at a mesoscale and observables values from measuring data (Chang et al., 2003; Chang & Hanna, 2004), no statistical evaluation at the microscale was found. Therefore, their performance criteria are not necessarily suitable for this study, but their statistical evaluation is widely accepted for comparing model results (Balczó et al., 2009; Buccolieri et al., 2011; Amorim et al., 2013; Morakinyo & Lam, 2016b).

A perfect model performance would have R and FAC2= 1.0 and FB and NMSE = 0. Of course, there is no perfect model, but acceptably performing models have to follow typical performance values. Therefore, the model acceptance criteria and the objective of evaluating a model are necessary to decide whether or not to accept it (Chang & Hanna, 2004).

There is no single statistical measure universally applicable to all model situations. Even though the model should be able to replicate the WT with a certain degree of accuracy independent of any real-world/field study considerations or WT data, in this research, given the purpose of studying traffic-related PM dispersion from a street canyon with trees, the model ENVI-met did not fulfil the validation criteria established as indicators of adequacy.

In the WT, tree planting increases the traffic-induced pollutant concentrations inside the street canyon compared to the treeless scenario. The same is concluded in ENVI-met, however, the model overpredicted the concentrations (FB_{leeward} = -0.18, FB_{windward} = -1.48). Gromke and Ruck (2008b), in their WT experiment, found considerable increases in concentrations at the leeward wall and moderate decreases at the windward wall in the tree scenario (Gromke & Ruck, 2008b). In ENVI-met the leeward side met acceptable criteria (NMSE = 0.15, FAC2 = 0.86, FB = -0.18, R=0.82). However, on the windward side, the concentrations did not decrease, showing unacceptable criteria for three metrics (NMSE = 6.85, FAC2 = 0.14, FB = -1.48). ENVI-met failed to replicate the effect of street trees for a microscale study proposed by the WT experiment (CODASC).

Finally, addressing the question posed in the title of this section, when is good enough approach depends on the context of the problem, but currently there is no tool available that can be used easily by practitioners to evaluate the impact on air quality of planting GI in specific locations.

5 Conclusion

Airflow and dispersion of $PM_{2.5}$ in an isolated urban street canyon of aspect ratio H/W=1 with and without a tree planting in a row were investigated and validated against WT data (CODASC).

ENVI-met is, thus far, the only microscale model capable of simulating different GI, such as coniferous trees, deciduous trees, shrubs, hedges, green walls, and green roofs, using dispersion and deposition approaches, and including isoprene emissions (BVOC) and stomatal resistance. This makes it a unique model in the field, involving almost all the four mechanisms described in the previous chapters. **According to the validation, however, ENVI-met is not an acceptable model for our purpose of studying the effect of trees on air dispersion at a microscale**. The model overpredicted $PM_{2.5}$ concentrations, especially when trees are presented in the street. The WT experiment also concluded that trees increase pollutants on streets, however, there is a slight improvement on the windward side that ENVI-met was not able to simulate.

Implementing green infrastructure in urban areas requires an evaluation of its effectiveness. The effect of GI (primarily trees) on air quality is highly dependent on urban design (H/W), weather parameters and GI characteristics. Due to this complex relationship, general guidelines cannot be provided to practitioners about where to plant GI (other than a few specific pointers, see **Chapter 5**), and must be addressed on a case-by-case basis. A modelling approach could resolve site-specific questions. Easy-to-use models are recommended for practitioners to assess the effect of trees (or GI) in specific scenarios and conditions, provided there is adequate validation of the model.

The findings emphasise the need for continuous validation efforts of modelled results against experimental data. It is a challenge to compare the model GI outcomes against what actually happens on real streets. Therefore, further efforts should be made to develop robust validation data sets to measure the influence of GI in streets on air pollution.

Chapter 8. Conclusions, recommendations and looking forward

1 Introduction

This thesis contributes to the growing literature on using green infrastructure (GI) to improve urban air quality by investigating GI mitigation mechanisms that influence urban air quality. The extensive literature review on GI revealed the four mechanisms by which GI influences air quality: deposition, absorption, biogenic emissions, and dispersion **(Objective 1)**. All the mechanisms are themselves influenced by local context, site- and species-specific characteristics as discussed from Chapters 3 to 5 **(Objective 2)**.

A survey of 87 urban planting-related practitioners in the United Kingdom showed that GI is mainly used in street-side plantings to improve the aesthetics of streetscapes, improve the health and well-being of citizens, and to increase biodiversity, falling into fourth preference air pollution mitigation. Prioritising the well-known benefits, along with uncertainties surrounding the current evidence on the impact of GI characteristics in the contexts of air quality could be the reasons for this position. Survey respondents would also like to have access to easy-to-use modelling tools to improve their planting decisions **(Objective 3)**. Despite all the GI characteristics identified, reviewed and considered with practitioners, it is impossible to provide clear and unambiguous advice on the most important GI characteristics for improving air quality nor to offer a clear quantification of their effects either separately or combined. The impact of GI on air quality in streets depends on the spatio-temporal context, species characteristics, and the multi-dimensional suitability of the species to the urban environment. Therefore, a holistic framework encompassing the GI characteristics and spatio-temporal context that guides consideration of the benefits and trade-offs of planting decisions for air pollution mitigation was created **(Objective 4)**. In addition, with the aid of numerical simulation and wind tunnel experimental data, an easy-to-use computational model (the ENVI-met model) was explored as a tool for non-expert users to investigate the effect of GI on street air quality. The model shows promise but is not yet tractable for microscale studies (practical scale), which is the necessary level for practitioners planting street-side **(Objective 5)**.

This final discussion now synthesises the work and offers advice for policymaking and further research. The limitations of the research are reviewed, urban planting recommendations for practitioners are made, and five research directions that build on the knowledge generated in this thesis are outlined.

2 Limitations and strengths of this research

2.1 Limitations

Despite substantial exploration and review of the existing literature, some of the inferences are limited by biases and an imbalance in the underpinning works. These biases lie in several areas and may affect the robustness of some conclusions. For example, the number of studies related to the influence of green roofs and green walls on air quality is limited, representing around 10% of the literature reviewed. The lack of literature surrounding these GIs and their effect on air quality may affect the overall results of the identified GI characteristics.

The results of this research is restricted to a few geographical areas: Europe and China. Despite extensive inclusion criteria, most of the information on urban GI came from China, especially with regard to pollutant deposition. The other mechanisms, such as absorption and biogenic emissions, were more widely spread, but the core is concentrated in Europe. Absorption research is focused mainly on carbon storage and sequestration, absorption of other gases and particles and the effect on air quality is limited. The geographical bias also influences the species studied as there are clear local planting preferences. In China, for example, some of the most common species in urban planting are *Ginkgo biloba*, *Sophora japonica,* and *Salix matsudana* (Liu & Slik, 2022), and none of these species is common in the UK (See Table 15, **Chapter 6**).

Unlike the other mechanisms, dispersion is typically estimated and studied using computational modelling tools, simulating typical (European) streets. As this mechanism is dependent on the spatio-temporal context of any planting, individual and local GI measurement dispersion could be time-consuming, expensive, and inefficient. Therefore, the investigation of dispersion is typically subject to the use and level of sophistication of mathematical or computational fluid dynamic (CFD) models.

An easy-to-use computational model such as ENVI-met also represented a limitation. This easy-to-use model for non-expert users did not achieve the expected accuracy for microscale study. It is likely that with a more sophisticated CFD model, the results of this research would have been different since it would have included GI scenarios instead of validation. Easy-to-use models for practical use outside of academia to study the effect of GI are still required. From the experience with ENVI-met, even if CFD models can be designed to be "easy-to-use", they still currently require an understanding of the underlying mathematics (and GI characteristics) to ensure reliable results. Maybe in the future an established and well validated methods to model GI in regard to air pollution mitigation will be published, in which case CFD models for use by non-expert practitioners could work, but there is still much to be done. Even more, models that including micro and macro-GI morphologies in their inputs, are still missing from the field.

The methodological heterogeneity across and within studies increased the breadth of information identified but reduced the comparability between individual GI characteristics. For example, the different study designs and metrics used prevented a quantitative meta-analysis of deposition capacity and thus air pollution mitigation potential. In addition, many articles did not provide the information required to conduct a meta-analysis, such as background concentrations, location of the species (GI), and weather parameters. In particular, limited precision on temporal and spatial scales and a lack of standardisation for studying GI in urban areas combine to prevent robust comparisons between GI mechanisms.

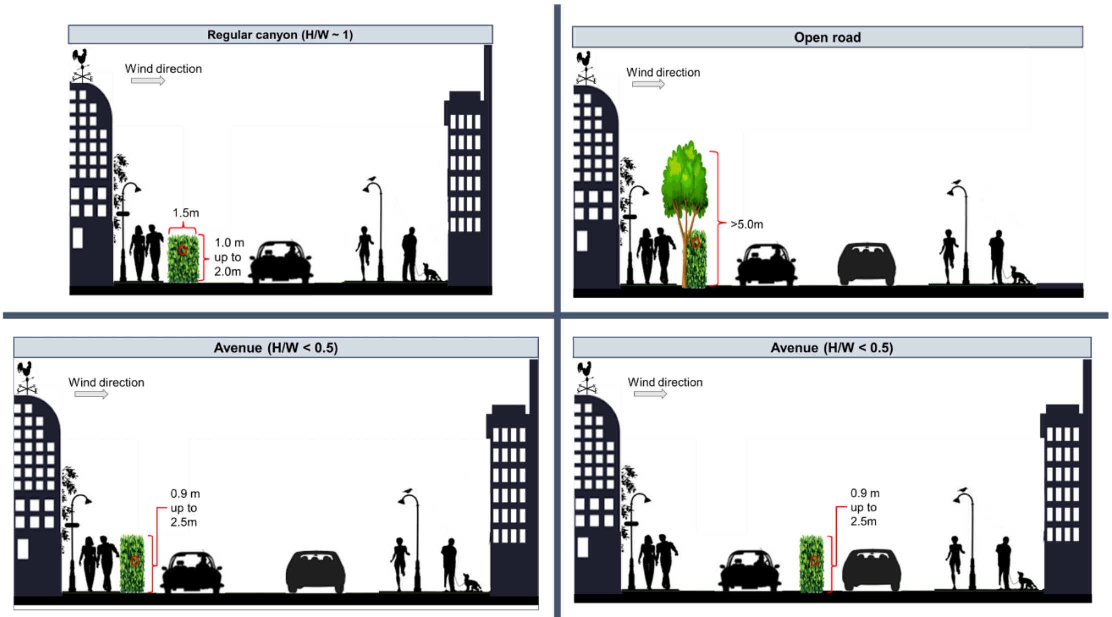
Due to the different methodologies, approaches and parameters that have been used, the quantification of influence of GI on air quality is still uncertain. Field experiments have reported a wide range of air improvements in the air quality due to GI interventions, attributing between 7% and 63%, while computational models report between 2.5% and 10% of improvement in the local air quality (See Table 1, **Chapter 2**). Further observations and experiments on real conditions/streets are needed to evaluate the impact of GI on air quality. Computational models will help understand this impact once the main GI characteristics are included, such as micro- and macro-morphologies, seasons, type of GI and spatio-temporal context, as essential parameters in the study of GI and its relationship with air quality. Perhaps too much simplification has been used in computational models for these to be truly inferential given such a complex relationship. There is great uncertainty surrounding the quantification of the effectiveness of GI for improving air quality. Being able to judge the compromises benefits and trade-offs between this ES, depends on a more accurate understanding of plan-mediated air pollution attenuation than we have currently.

The information gathered by using the survey is geographically and culturally limited as it arises from urban planting practitioners in the United Kingdom. Several other actors (e.g., highway engineers, property developers, and contractors) influence planting decisions, but the work reported here only reflects the decision-making processes of tree officers (or related urban street-side planting practitioners) with internet access. Additionally, the completion of the questionnaire was highly sensitive to the respondent's experience and knowledge (Andrade, 2020), therefore, may have been incomplete or false answers due to these influences. Just over half of the total respondents did not complete the entire questionnaire, possibly due to a lack of knowledge, interest, or time (note that the questionnaire was kept short to avoid lack of completion due to lack of time). The lack of respondent incentives could also have reduced some participation (Van Selm & Jankowski, 2006).

2.2 Strengths

This research is the first to bring synthesise and examine the four mechanisms through which street-side GI influences air quality. This research explained these mechanisms, summarised, and evaluated the level and strength of evidence of the GI characteristics that affect air quality on streets. Additionally, the mechanisms were studied jointly, providing a framework that highlights mutual GI characteristics and spatio-temporal context that might improve air quality. These characteristics were consulted with urban street-side planting practitioners. The results of this, indicated that the information available in the academic field on the effectiveness of GI on air pollution in streets is not important in GI urban planting decision-making in the UK. Little evidence on tangible and quantifiable effect on air quality by specific site and characteristics of GI makes its application doubtful, which might restrict its use. Direct this effort to computational model studies is not recommendable unless some of GI characteristics per mechanisms will be added to the model and field campaigns validate the model outcomes. This is one of the novelties of this work and differs from previous similar studies, that investigates the air pollutant removal by GI.

Through the **Chapters** of this thesis, a promising GI design for streets was suggested to reduce pedestrian exposure to air pollution (Figure 60). As it was mentioned previously, it is not recommendable offer specific guidance, however, some GI locations have demonstrated successful pedestrian protection.



○ Ideally, rough, hairy, wax-coated, sticky-surfaced leaves with large and dense stomas, native, low BVOC emitting and entomophilous plant species should be privileged during the species selection process for improving air quality.

Figure 60. Promising Green Infrastructure design in different street designs.
Source: Own elaboration

The mixed-method approach that was used strengthened both quantitative and qualitative methods to provide an innovative approach for addressing the use of GI for air quality improvements. Combining both methods helped to overcome limitations and deliver the holistic view of GI that mono-method research has failed to deliver. Using only one methodology – literature review, questionnaire, or modelling – may easily exclude one of the GI characteristics or mechanisms influencing air quality.

3 Comparison to previous research

Similar research to this thesis has been published in recent years, for example, the studies by Barwise and Kumar (2020), Diener and Mudu (2021) and Tomson et al. (2021). These reviews investigate the air pollutant removal potential of GI in urban environments (Barwise & Kumar, 2020; Diener & Mudu, 2021; Tomson et al., 2021).

The mentioned reviews confirm some of the findings of this thesis. They agree that at a local scale, GI can reduce pollution exposure by considering the collective impacts of mechanisms, especially deposition and dispersion, and the context where GI is planted. There is an agreement about some leaf traits that can maximise particle deposition, such as micro-roughness, grooves, and epicuticular wax, as well as the importance of morphological plant traits (e.g., porosity and size), to improve dispersion. Furthermore, one of them concluded that the different metrics (and scales) used in the published GI studies did not allow a quantitative meta-analysis of air pollution mitigation (Diener & Mudu, 2021), as this thesis also concluded. A similar discussion in this regard is provided by Tomson et al. (2021).

The three mentioned reviews noted the importance of GI characteristics and spatio-temporal context with improvement in air quality. However, none of them warned about the uncertainties surrounding the effectiveness of GI in improving air quality and the multiple characteristics and context linked to that benefit. Additionally the information provided by ENVI-met model was widely used in GI studies because it integrates dispersion-deposition approaches to assess air quality improvement, which makes it attractive to provide a more holistic view of GI in streets (Barwise & Kumar, 2020; Diener & Mudu, 2021; Tomson et al., 2021). As a result of the work of this thesis, researchers and practitioners are cautioned to consider the results of modelling studies, especially those models that have not been validated for street-level studies.

These reviews also synthesise the findings of previous works around GI characteristics that can improve air quality, however, none of them synthesises, evaluates separately and together four mechanisms for a comprehensively understanding of the impact of GI on air quality, joining all mechanisms and its GI characteristics in a comprehensive framework (See Table 16 and Figure 44).

4 Recommendations for urban planting practitioners

Some recommendations can be provided for practitioners when planning street-side plantings, as follows:

1) Design and management of street-side urban planting

Design, placement, and management of GI to achieve air quality improvement is not an easy task. Some approaches, however, can be recommended to maximise the air quality control benefit as part of planning for holistic benefits (Figure 61). Street planting design should be context-based, thus, location, GI intervention and the particular species should be considered strategically in order to enhance air quality improvement. Design with a purpose, maximising Ecosystem Services and reducing Disservices and constraints should be the aim of planting decisions in order to improving the pedestrian air quality. It is recommended that practitioners first consider the spatio-temporal context location of GI (e.g., street uses/type), along with local site conditions (weather parameters, street design and air pollutant concentrations). In the final instance, practitioners can then evaluate the selection of species according to the selected mechanism(s), although always in the context of other planting constraints or benefits they aim to achieve, along with the suitability of the species to survive in a stressed urban environment (See also Figure 44Figure 44. A holistic framework to outline the mechanisms by which green infrastructure may influence air quality and the associated characteristics that should be considered in urban planting., **Chapter 6**).

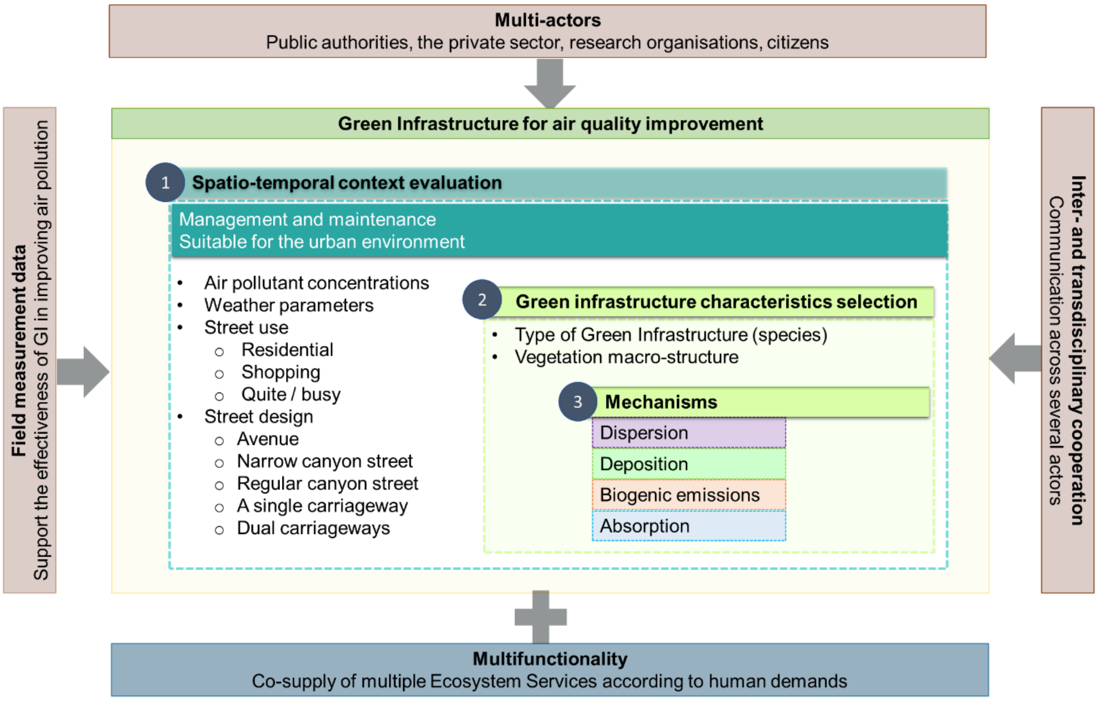


Figure 61. Framework for planning and managing urban planting decision-making for air pollution.

For pedestrian-level protection, GI barriers should be placed close to pollutant sources (e.g., roads) to ensure maximum benefit (Baldauf et al., 2013; Abhijith & Kumar, 2019). In a narrow, confined street, smaller barrier shrubs and hedges are the recommended planting options for reducing pavement-side pollutant accumulation, but along wider open roads, trees can play their part.

2) Inter- and transdisciplinary cooperation supports the multifunctionality of green infrastructure

With increases in urbanisation, the demand for more sustainable, liveable and green cities will require the participation of many actors for effective management and delivery of the multiples functions of GI. Greater connection, communication, collaboration, and engagement with other actors, such as stakeholders, policymakers, landscape architects, and highway engineers, should be encouraged in urban planting decision-making. Similarly, effective communication of academic research to update the guidelines and documents available to practitioners would promote and ensure improved multifunctionality in GI implementation.

The involvement of diverse groups taking collective action for more liveable cities could assure a balanced distribution of benefits and thus change the paradigm from top-down public urban planting administration to the lateral inclusion of multiple stakeholders, locals and practitioners (Pretzsch, 2016). Integrating communities, private and public sectors into collective action-driven GI planning may increase understanding about the necessities of planting GI on the streets.

3) Maintenance of the plantings

The strong demand for GI in cities and the lack of a guaranteed future budget destined for its maintenance can hinder the survival and health of plantings, reducing the desired GI benefits, including ameliorated air quality. Appropriate GI maintenance (e.g., pruning, trimming, watering) can control flowering and thereby decrease pollen emissions. In addition, GI pest management could prevent/reduce BVOC emissions in response to leaf, trunk, or branch damage caused by insect pests. Furthermore, GI maintenance enhances aesthetics, promotes density, reduces pest and disease risks, improves clear sightlines in streets, brings vegetation stability and improves safety (i.e., removing dead branches). All the benefits that GI can provide to citizens are threatened by poor management, and this is a serious issue that should be addressed by ring-fenced central funding. Urban planting needs to consider management and maintenance budget and capable tree officers to ensure reaching the maximum of ES in cities.

5 Recommendations for further research

The literature reviews indicate that research nexus of GI and air quality has gradually grown over the past 20 years, with the last decade producing most of the work that determines our current academic knowledge (Xing & Brimblecombe, 2020a; Ying et al., 2021). Yet to take this research field to the next level, field experiments to measure the real impact of GI on air quality are required to provide robust evidence of the interactions between GI, air pollution and human health. In addition, developing an easy-to-use model, but genuinely informative computer modelling tool for practitioner use could improve planting decisions to maximise air quality benefits. The following section provides five suggestions for future research pathways as a direct outcome of the work presented in this thesis.

1) Increase the number of field experiments

There is often contrasting information between many predictive modelling studies and the few field experimental studies that evaluate the effect of GI on streets. It is, therefore, not possible to conclude that the modelled predictions of the effects of GI in streets are accurate given this lack of experimental studies confirming the modelling findings. In addition, where measurements are made, there is a lack of experimental data on pollution levels before and after planting to estimate the real impact of the GI on air quality.

Further research is required to measure and validate the real impact of GI on the streets. Wind tunnel experiments have a role in computational model validation, but given the complexity of GI and the multiple variables that influence pollution removal by GI, real measurement data is essential to provide genuine validation of modelling studies. Field measurements of pollutant concentrations at different aspect ratios (street canyons), weather parameters, and types and configurations of GI can provide quantification of GI influences on air quality, thereby confirming the real impact of GI in streets and validating computational model results.

Future research should be directed to field experimental demonstration of whether GI (plants) can exert effect on pollutant concentrations under real-world conditions. More studies need to be conducted to properly address the effectiveness of GI in the real-world to understand about how GI can improve air quality and, consequently, promote GI configurations that can maximise that benefit.

2) Increase the number of studies on the impacts of green infrastructure on air quality

Most of the published studies on the impact of GI on air quality in street canyons focus on trees and/or hedges (Tomson et al., 2021). There is a lack of research on the quantifiable air quality influence by other GI, such as green roofs and walls. Only a few studies have reported the effect of green roofs on air pollution mitigation (Currie & Bass, 2008; Speak et al., 2012; Jayasooriya et al., 2017), and these have preferentially used the i-Tree software to quantify these benefits. Green roofs modify the shape and texture of a roof, affecting the wind behaviour inside streets, which could alter pollutant concentrations (Kastner-Klein et al., 2004; Baik et al., 2012). As so few studies exist, further work is required to investigate the effect of green roof configurations on street-level air pollution mitigation. A similar situation occurs for green walls; this GI can be beneficial in a polluted street canyon or where open space is scarce and limits the planting of trees or shrubs (a recurrent problem in crowded cities). In addition, adding green walls to streets can bring about other benefits, such as aesthetic improvement and noise pollution attenuation.

Other GI alternatives are also recommended for study, such as alleys covered by a dense canopy of tall trees could be a promising design to avoid pollutant exposure in streets (if the pollution source is not below them), pergola system, and green parking or parklet[23] might also add diversity and multifunctionality to urban settings.

3) Longitudinal and international studies

As the effectiveness of GI on air quality is dependent on the local temporal context and GI characteristics, so duplicating or comparing research results from one sampling site to another could be inappropriate. It is recommended that each site earmarked for urban planting evaluates its local context and GI species in relation to air pollution. This, however, could prove impractical and expensive in many councils. Therefore, more research in different sampling sites, countries and spatial scales would improve the knowledge and understanding of the complex processes of GI and its nexus with air quality improvements.

Different temporal scale is also required for future research. A longer sampling period would cover the effect of different seasons on leaves and, thus the effect of evergreen and deciduous tree species on street air quality. More extended study periods might reveal important insights into the long-term effect of GI on health improvements. Future investigations should focus on the relationship between GI and the climatic zone and its impact on air quality over a more extended period.

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[23] Parklets is an expansion of the sidewalk with plants and rest areas that are located in a car parking space.

4) Develop an easy-to-use validated computational tool for practitioners

Given the development of sophisticated computational models and the complexity of this field, it might be difficult for practitioners, urban planners, policymakers, and stakeholders to follow the outcomes of current research and put these into practice locally. In addition, this research could not provide specific guidance for GI planting in relation to air quality improvement because of the dependency on spatio-temporal context. A site-specific evaluation would be needed to decide where and what GI to plant. A practitioner accessible validated modelling tool would facilitate this for urban planting decision-making. An easy-to-use model capable of predicting air quality at the relevant scale and which can include sufficient GI characteristics and local contexts, such as different street designs, surrounding buildings, weather, pollutant chemistry, source-induced turbulence, and flow alternation, could facilitate these decision-making processes and ensure optimal of GI for air quality.

The complexity of urban systems and GI characteristics are challenging to constructing, validating, and using environmental computational models at a relevant scale; however, increases in data availability and computing power will advance how environmental models are developed and used.

5) Investigate the effect of GI in reducing the prolonged exposure of pedestrians

This investigation focused on the effectiveness of GI in the pedestrian walking zone and the activities that take place in it. Street pollution exposure, however, changes according to the activities that are held on streets. People waiting at bus stops, sitting in cafes, restaurants or benches near the road, for example, expend more time exposed to air pollution. Recent research demonstrated that even short-term exposure to air pollution increases the risk of myocardial infarction mortality (Liu et al., 2021). Therefore, further studies to evaluate the effectiveness of GI to minimise short- and long-term exposure to air pollutants in street are needed. Likewise, further studies are needed to investigate the effectiveness of GI in reducing indoor environments where people spend more time than in streets (Han et al., 2022), especially nowadays when many companies have implemented remote work after COVID-19 (Jain et al., 2022).

6 Concluding remarks

Green infrastructure has a wide range of documented benefits (Ecosystem Services), providing aesthetic value, shade, opportunities for socialising, improved mental and physical health, reductions in flooding, and improvements in air quality by directly absorbing gaseous pollutants, capturing particles and indirectly blocking air pollutants, having a local and short-term controlling effects on pollutant concentrations.

At the beginning of the thesis, the following questions were posed: *what is the full range of GI characteristics that can influence urban air quality? Can a comprehensive framework of GI characteristics influencing air quality be established with a view to helping practitioners make improved GI planting decisions? How is air pollution mitigation included in the design of urban green infrastructure in urban plantings?* Through the Chapters and through the application of a mixed-method approach using literature reviews, a survey, and a computational model, the different mechanisms and GI characteristics that influence air quality have been explored, and the broad answer to these questions is:

> The potential of GI to positively influence urban air quality depends on several species-specific characteristics, its shaping and management, and on the local context. Species types, leaf surface microstructures, stomatal form, and macrostructural features influence the deposition and absorption of pollutants. Vegetation form, height, and density all influence the dispersion of pollutants. Local characteristics, such as street design, meteorological parameters, and proximity to pollutant sources, also influence the rate of pollution deposition and dispersion. This underlines that the closer GI is to the pollution sources, the greater its blocking effect. Planting closer to the pollutant sources, however, must be tolerant to the urban stresses and suitable for urban survival. The potential allergenic biogenic emissions, BVOC and pollen, should be minimised by appropriate species selection. Therefore, species selection, GI management and maintenance also influence the balance between air quality improvement and biogenic emissions by reducing BVOC and pollen release in response to pruning, mowing or cutting.
>
> Generally, air pollution mitigation is a minor consideration in the decision-making processes of practitioners in the United Kingdom. Perhaps, the lack of quantification and confidence in how site- and species-specific characteristics might improve air quality makes other more tractable factors dominate urban planting decisions. There are synergies and trade-offs between these various characteristics, compounded by much uncertainty and site- specificity; this highlights the need for holistic thinking but also makes generalised planting

guidance difficult. A comprehensive framework of GI characteristics influencing air quality may help practitioners make better-informed decisions about GI solutions to improve air quality in urban planting practices. Nevertheless, there are still uncertainties surrounding the quantification of pollutant mitigation by effect of GI on streets. To be able to judge the compromises between trade-offs and benefits delivered by GI depends on a more accurate understanding of plant(GI)–mediated air pollution attenuation that we have currently.

Green infrastructure should be implemented strategically through a comprehensive understanding of the Ecosystem Services and Disservices, and the particularities of streets should be considered. This research contributes to informing decision-making about health-promoting urban environments by optimising the benefits expected of GI through a holistic understanding of the positive and negative impacts of GI on air pollution in streets. The potential for GI to appreciably mitigate air pollution over a wide array of sites and environmental conditions is limited.

Air pollution threatens our health and quality of life and affects wildlife and ecosystems. Short- and long-term solutions are urgently required. Adding GI, however, in a busy street will not solve the air pollution problem, and relying on the idea that more GI is better is clearly simplistic. Effective air quality interventions should focus on reducing primary pollutant emissions, such as cars, rather than on increasing green areas or introducing more GI. Unless they go together and simultaneously, cars and road space are replaced by GI or green areas might be an interesting proposal for improving urbanisation.

Additionally, GI can play its part in urban planning as a blocker of pollutants, protecting and reducing pedestrian exposure. Using different GI configurations can extend the distance between sources and receptors and block pedestrian zone exposure to street air pollutants. Further GI experimental studies with inter and transdisciplinary cooperation identifying the site- and species-specific characteristics that mitigate poor air quality will help a successful urban planning process. And ultimately, further research and international transdisciplinary collaboration are needed to contribute to a better conceptual understanding and implementation of green infrastructure to deliver the greatest public health benefits through air pollution mitigation.

References

Abhijith, K. V., & Gokhale, S. (2015). Passive control potentials of trees and on-street parked cars in reduction of air pollution exposure in urban street canyons. *Environmental Pollution, 204*, 99 - 108.

Abhijith, K. V., & Kumar, P. (2019). Field investigations for evaluating green infrastructure effects on air quality in open-road conditions. *Atmospheric Environment, 201*, 132-147.

Abhijith, K. V., & Kumar, P. (2020). Quantifying particulate matter reduction and their deposition on the leaves of green infrastructure. *Environmental Pollution, 265*(Part B), 114884. doi:10.1016/j.envpol.2020.114884

Abhijith, K. V., Kumar, P., Gallagher, J., McNabola, A., Baldauf, R., Pilla, F., Broderick, B., Di Sabatino, S., & Pulvirenti, B. (2017). Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments – A review. *Atmospheric Environment, 162*, 71-86. doi:10.1016/j.atmosenv.2017.05.014

Adam, M. G., Tran, P. T. M., & Balasubramanian, R. (2021). Air quality changes in cities during the COVID-19 lockdown: A critical review. *Atmospheric Research, 264*, 105823. doi:10.1016/j.atmosres.2021.105823

Ahmad, K., Khare, M., & Chaudhry, K. K. (2005). Wind tunnel simulation studies on dispersion at urban street canyons and intersections—a review. *Journal of Wind Engineering and Industrial Aerodynamics, 93*, 697–717. doi:10.1016/j.jweia.2005.04.002

Al-Dabbous, A. N., & Kumar, P. (2014). The influence of roadside vegetation barriers on airborne nanoparticles and pedestrians exposure under varying wind conditions. *Atmospheric Environment, 90*, 113-124. doi:10.1016/j.atmosenv.2014.03.040

Ameye, M., Allmann, S., Verwaeren, J., Smagghe, G., Haesaert, G., Schuurink, R. C., & Audenaert, K. (2018). Green leaf volatile production by plants: a meta-analysis. *New Phytologist 220*(3), 666-683. doi:10.1111/nph.14671

Amorim, J. H., Rodrigues, V., Tavares, R., Valente, J., & Borrego, C. (2013). CFD modelling of the aerodynamic effect of trees on urban air pollution dispersion. *Science of The Total Environment, 461-462*, 541-551. doi:10.1016/j.scitotenv.2013.05.031

Andrade, C. (2020). The Limitations of Online Surveys. *Indian J Psychol Med, 42*(6), 575-576. doi:10.1177/0253717620957496

Aram, F., Higueras Garcia, E., Solgi, E., & Mansournia, S. (2019). Urban green space cooling effect in cities. *Heliyon, 5*(4), e01339. doi:10.1016/j.heliyon.2019.e01339

Aristodemou, E., Boganegra, L. M., Mottet, L., Pavlidis, D., Constantinou, A., Pain, C., Robins, A., & ApSimon, H. (2018). How tall buildings affect turbulent air flows and dispersion of pollution within a neighbourhood. *Environmental Pollution, 233*, 782-796. doi:10.1016/j.envpol.2017.10.041

Atkinson, L. Z., & Cipriani, A. (2018). How to carry out a literature search for a systematic review: a practical guide. *BJPsych Advances, 24*(2), 74-82. doi:10.1192/bja.2017.3

Austin, G. (2014). Green Infrastructure for Landscape Planning: Integrating Human and Natural Systems. In *Chapter one: Introduction* (pp. 1-14): Abingdon, Oxon ; New York, New York : Routledge.

Aydin, Y. M., Yaman, B., Koca, H., Altiok, H., Dumanoglu, Y., Kara, M., Bayram, A., Tolunay, D., Odabasi, M., & Elbir, T. (2014). *Comparison of biogenic volatile organic compound emissions from broad leaved and coniferous trees in Turkey*. Paper presented at the Environmental Impact II.

Ayuntamiento de Madrid. (2021). Bosque Metropolitano. January 2021 https://www.madrid.es/portales/munimadrid/es/Inicio/Vivienda-urbanismo-y-obras/Urbanismo/Bosque-Metropolitano/?vgnextfmt=default&vgnextoid=effb3c0a55e16710VgnVCM1000001d4a900aRCRD&vgnextchannel=2af331d3b28fe410VgnVCM1000000b205a0aRCRD.

Baik, J.-J., & Kim, J.-J. (1999). A Numerical Study of Thermal Effects on Flow and Pollutant Dispersion in Urban Street Canyons. *Journal of Applied Meteorology, 38*(9), 1249-1261. doi:10.1175/1520-0450(1999)038<1249:Ansote>2.0.Co;2

Baik, J.-J., Kwak, K.-H., Park, S.-B., & Ryu, Y.-H. (2012). Effects of building roof greening on air quality in street canyons. *Atmospheric Environment, 61*, 48-55. doi:10.1016/j.atmosenv.2012.06.076

Balczó, M., Gromke, C., & Ruck, B. (2009). Numerical modeling of flow and pollutant dispersion in street canyons with tree planting. *Meteorologische Zeitschrift, 18*(2), 197-206. doi:10.1127/0941-2948/2009/0361

Baldauf, R. (2017). Roadside Vegetation Design to Improve Local, Near-Road Air Quality. *Transportation Research Part D 52*(11), 354-361. doi:10.1016/j.trd.2017.03.013

Baldauf, R., McPherson, E. G., Wheaton, L., Zhang, M., Cahill, T., Bailey, C., Hemphill Fuller, C., Withycombe, E., & Titus, K. (2013). Integrating vegetation and green infrastructure into sustainable transportation planning. *Environmental Sustainability in Transportation, 288*, 14-18.

Baraldi, R., Chieco, C., Neri, L., Facini, O., Rapparini, F., Morrone, L., Rotondi, A., & Carriero, G. (2019). An integrated study on air mitigation potential of urban vegetation: From a multi-trait approach to modeling. *Urban Forestry & Urban Greening, 41*, 127-138. doi:10.1016/j.ufug.2019.03.020

Baraldi, R., Neri, L., Costa, F., Facini, O., Rapparini, F., & Carriero, G. (2018). Ecophysiological and micromorphological characterization of green roof vegetation for urban mitigation. *Urban Forestry & Urban Greening*. doi:10.1016/j.ufug.2018.03.002

Barcham. (2021). *Time for trees. A guide to species selection for the UK*. Retrieved from UK: https://www.barcham.co.uk/guides-advice/time-for-trees-edition-04/

Barcham. (n.d.). Species selection. A guide to informed decision-making. 23. Retrieved from https://www.barchampro.co.uk/wp-content/uploads/2019/05/Species-Selection-FINAL.pdf

Barima, Y. S., Angaman, D. M., N'Gouran K, P., Koffi, N. A., Kardel, F., De Canniere, C., & Samson, R. (2014). Assessing atmospheric particulate matter distribution based on Saturation Isothermal Remanent Magnetization of herbaceous and tree leaves in a tropical urban environment. *Science of The Total Environment, 470-471*, 975-982. doi:10.1016/j.scitotenv.2013.10.082

Barrie, L. A., & Schemenauer, R. S. (1986). Pollutant wet deposition mechanisms in precipitation and fog water. *Water, Air, & Soil Pollution, 30*, 91-104.

Barwise, Y., & Kumar, P. (2020). Designing vegetation barriers for urban air pollution abatement: a practical review for appropriate plant species selection. *Climate and Atmospheric Science, 3*(1). doi:10.1038/s41612-020-0115-3

Beckett, K. P., Freer-Smith, P. H., & Taylor, G. (2000). Particulate pollution capture by urban trees Effect of species and windspeed. *Global Change Biology, 6*, 995-1003.

Bell, N., & Treshow, M. (2002). *Air Pollution and Plant Life* (2nd ed.). UK.465 pp

Berardi, U., GhaffarianHoseini, A., & GhaffarianHoseini, A. (2014). State-of-the-art analysis of the environmental benefits of green roofs. *Applied Energy, 115*, 411-428. doi:10.1016/j.apenergy.2013.10.047

Besir, A. B., & Cuce, E. (2018). Green roofs and facades: A comprehensive review. *Renewable and Sustainable Energy Reviews, 82*, 915–939.

Bettiol, A., Gelain, E., Milanesio, E., Asta, F., & Rusconi, F. (2021). The first 1000 days of life: traffic-related air pollution and development of wheezing and asthma in childhood. A systematic review of birth cohort studies. *Environmental Health, 20*(1), 46. doi:10.1186/s12940-021-00728-9

Birke, M., Rauch, U., & Hofmann, F. (2018). Tree bark as a bioindicator of air pollution in the city of Stassfurt, Saxony-Anhalt, Germany. *Journal of Geochemical Exploration, 187*, 97-117. doi:10.1016/j.gexplo.2017.09.007

Bitog, J. P., Lee, I. B., Hwang, H. S., Shin, M. H., Hong, S. W., Seo, I. H., Mostafa, E., & Pang, Z. (2011). A wind tunnel study on aerodynamic porosity and windbreak drag. *Forest Science and Technology, 7*(1), 8-16. doi:10.1080/21580103.2011.559939

Blanco, J., Dendoncker, N., Barnaud, C., & Sirami, C. (2019). Ecosystem disservices matter: Towards their systematic integration within ecosystem service research and policy. *Ecosystem Services, 36*. doi:10.1016/j.ecoser.2019.100913

Blanusa, T., Fantozzi, F., Monaci, F., & Bargagli, R. (2015). Leaf trapping and retention of particles by holm oak and other common tree species in Mediterranean urban environments. *Urban Forestry & Urban Greening, 14*(4), 1095-1101. doi:10.1016/j.ufug.2015.10.004

Blanusa, T., & Hunt, L. (2013). Urban vegetation: truths, uncertainties and misconceptions. *Horticulatural Science*(231 - 235).

Bogawski, P., Grewling, Ł., Dziób, K., Sobieraj, K., Dalc, M., Dylawerska, B., Pupkowski, D., Nalej, A., Nowak, M., Szymańska, A., Kostecki, Ł., Nowak, M. M., & Jackowiak, B. (2019). Lidar-Derived Tree Crown Parameters: Are They New Variables Explaining Local Birch (Betula sp.) Pollen Concentrations? *Forests, 10*(12). doi:10.3390/f10121154

Bolund, P., & Hunhammar, S. (1999). Ecosystem services in urban areas. *Ecological Economics, 29*, 293-301.

Bonn, B., von Schneidemesser, E., Andrich, D., Quedenau, J., Gerwig, H., Lüdecke, A., Kura, J., Pietsch, A., Ehlers, C., Klemp, D., Kofahl, C., Nothard, R., Kerschbaumer, A., Junkermann, W., Grote, R., Pohl, T., Weber, K., Lode, B., Schönberger, P., Churkina, G., Butler, T. M., & Lawrence, M. G. (2016). BAERLIN2014 – the influence of land surface types on and the horizontal heterogeneity of air pollutant levels in Berlin. *Atmospheric Chemistry and Physics, 16*(12), 7785-7811. doi:10.5194/acp-16-7785-2016

Boogaard, H., Patton, A. P., Atkinson, R. W., Brook, J. R., Chang, H. H., Crouse, D. L., Fussell, J. C., Hoek, G., Hoffmann, B., Kappeler, R., Kutlar Joss, M., Ondras, M., Sagiv, S. K., Samoli, E., Shaikh, R., Smargiassi, A., Szpiro, A. A., Van Vliet, E. D. S., Vienneau, D., Weuve, J., Lurmann, F. W., & Forastiere, F. (2022). Long-term exposure to traffic-related air pollution and selected health outcomes: A systematic review and meta-analysis. *Environ Int, 164*, 107262. doi:10.1016/j.envint.2022.107262

Borough, K. (2015). Tree Strategy 2015 - 2021. Retrieved February 2022 https://moderngov.kingston.gov.uk/documents/s57941/DxGreenSpacesAnnex2Tree%20Strategy.pdf, from The Royal Borough of Kingston Upon Thames

Bottalico, F., Chirici, G., Giannetti, F., De Marco, A., Nocentini, S., Paoletti, E., Salbitano, F., Sanesi, G., Serenelli, C., & D., T. (2016). Air pollution removal by green infrastructures and urban forest in the city of Florence. *Agriculture and Agricultural Science Procedia, 8*, 243 - 251.

Bracho-Nunez, A., Welter, S., Staudt, M., & Kesselmeier, J. (2011). Plant-specific volatile organic compound emission rates from young and mature leaves of Mediterranean vegetation. *Journal of Geophysical Research, 116*(D16). doi:10.1029/2010jd015521

Brancher, M. (2021). Increased ozone pollution alongside reduced nitrogen dioxide concentrations during Vienna's first COVID-19 lockdown: Significance for air quality management. *Environmental Pollution, 284*, 117153. doi:10.1016/j.envpol.2021.117153

Brantley, H. L., Hagler, G. S., Deshmukh, P. J., & Baldauf, R. W. (2014). Field assessment of the effects of roadside vegetation on near-road black carbon and particulate matter. *Science of The Total Environment, 468-469*, 120-129. doi:10.1016/j.scitotenv.2013.08.001

Bristol Council. (n.d.). Tree Design Guide_Bristol. Retrieved February 2022 https://www.bristol.gov.uk/documents/20182/34488/TreeDesignGuideNotesdraft2.pdf/, from Bristo; Council

Britt, C., & Johnston, M. (2008). Trees in Town II. 36 pp.

Bruse, M. (2007). Particle filtering capacity of urban vegetation A microscale numerical approach. *Berliner Geographische Arbeiten, 109*, 61-70.

Bruse, M., & Fleer, H. (1998). Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model. *Environmental Modelling & Software, 13*, 373 - 384.

Brussels, A. C. (2021, 21/10/2021). 2020-2030 Tree Plan. 17/01/2022*.* Retrieved from https://www.brussels.be/2020-2030-tree-plan

BS 8545:2014. (2014). *Trees: from nursery to independence in the landscape. Recommendations.* British Standard Institute: ISBN 978 0 580 71317 0

Buccolieri, R., Gromke, C., Di Sabatino, S., & Ruck, B. (2009). Aerodynamic effects of trees on pollutant concentration in street canyons. *Science of The Total Environment, 407*(19), 5247-5256. doi:10.1016/j.scitotenv.2009.06.016

Buccolieri, R., Jeanjean, A. P. R., Gatto, E., & Leigh, R. J. (2018a). The impact of trees on street ventilation, NOx and PM2.5 concentrations across heights in Marylebone Rd street canyon, central London. *Sustainable Cities and Society, 41*, 227-241.

Buccolieri, R., Salim, S. M., Leo, L. S., Di Sabatino, S., Chan, A., Ielpo, P., de Gennaro, G., & Gromke, C. (2011). Analysis of local scale tree–atmosphere interaction on pollutant concentration in idealized street canyons and application to a real urban junction. *Atmospheric Environment, 45*(9), 1702-1713. doi:10.1016/j.atmosenv.2010.12.058

Buccolieri, R., Santiago, J. L., Rivas, E., & Sanchez, B. (2018b). Review on urban tree modelling in CFD simulations Aerodynamic, deposition and thermal effects. *Urban Forestry & Urban Greening, 31*, 212 - 220.

Buccolieri, R., Santiago, J. L., Rivas, E., & Sanchez, B. (2019). Reprint of: Review on urban tree modelling in CFD simulations: Aerodynamic, deposition and thermal effects. *Urban Forestry & Urban Greening, 37*, 56-64.

Burgess, S. (2015). Multifunctional green infrastructure: a typology. In D. Sinnett, N. Smith, & S. Burgess (Eds.), *Handbook on Green Infrastructure* (pp. 227-240). UK: Edward Elgar Publishing Limited.

Burhan, O., & Karaca, E. (2013). Vertical Gardens. In M. Özyavuz (Ed.), *Advances in Landscape Architecture* (pp. 940): IntechOpen.

Burkhardt, J., & Pariyar, S. (2014). Particulate pollutants are capable to 'degrade' epicuticular waxes and to decrease the drought tolerance of Scots pine (Pinus sylvestris L.). *Environmental Pollution, 184*, 659-667. doi:10.1016/j.envpol.2013.04.041

Buters, J. T., Kasche, A., Weichenmeier, I., Schober, W., Klaus, S., Traidl-Hoffmann, C., Menzel, A., Huss-Marp, J., Kramer, U., & Behrendt, H. (2008). Year-to-year variation in release of Bet v 1 allergen from birch pollen: evidence for geographical differences between West and South Germany. *Int Arch Allergy Immunol, 145*(2), 122-130. doi:10.1159/000108137

BwN, B. w. N. (2022). Training. March 2022. Retrieved from https://www.buildingwithnature.org.uk/training

Calfapietra, C., Fares, S., Manes, F., Morani, A., Sgrigna, G., & Loreto, F. (2013). Role of Biogenic Volatile Organic Compounds (BVOC) emitted by urban trees on ozone concentration in cities: a review. *Environmental Pollution, 183*, 71-80. doi:10.1016/j.envpol.2013.03.012

Camden Council. (2020). Camden Tree Planting Strategy 2020-2025. Retrieved February 2022 https://www.camden.gov.uk/documents/20142/5268201/Camden+Tree+Planting+Strategy.pdf

Campbell, L., Monaco, M., Falxa-Raymond, N., Lu, J., Newman, A., Rae, R. A., & Svendsen, E. S. (2014). *Million TreesNYC: the integration of research and practice*. Scientific Journal (JRNL)

Camuffo, D. (2014). Chapter 8. Dry Deposition of Airborne Particulate Matter: Mechanisms and Effects. In *Microclimate for cultural heritage* (pp. 283-346): Amsterdam: Oxford: Elsevier, 1998.

Cariñanos, P., Calaza-Martínez, P., O'Brien, L., & Calfapietra, C. (2017). The Cost of Greening: Disservices of Urban Trees. *7*, 79-87. doi:10.1007/978-3-319-50280-9_9

Cariñanos, P., & Casares-Porcel, M. (2011). Urban green zones and related pollen allergy: A review. Some guidelines for designing spaces with low allergy impact. *Landscape and Urban Planning, 101*(3), 205-214. doi:10.1016/j.landurbplan.2011.03.006

Cariñanos, P., Casares-Porcel, M., & Quesada-Rubio, J.-M. (2014). Estimating the allergenic potential of urban green spaces: A case-study in Granada, Spain. *Landscape and Urban Planning, 123*, 134-144. doi:10.1016/j.landurbplan.2013.12.009

Cariñanos, P., Foyo-Moreno, I., Alados, I., Guerrero-Rascado, J. L., Ruiz-Penuela, S., Titos, G., Cazorla, A., Alados-Arboledas, L., & Diaz de la Guardia, C. (2021). Bioaerosols in urban environments: Trends and interactions with pollutants and meteorological variables based on quasi-climatological series. *J Environ Manage, 282*, 111963. doi:10.1016/j.jenvman.2021.111963

Cariñanos, P., Grilo, F., Pinho, P., Casares-Porcel, M., Branquinho, C., Acil, N., Andreucci, M. B., Anjos, A., Bianco, P. M., Brini, S., Calaza-Martinez, P., Calvo, E., Carrari, E., Castro, J., Chiesura, A., Correia, O., Goncalves, A., Goncalves, P., Mexia, T., Mirabile, M., Paoletti, E., Santos-Reis, M., Semenzato, P., & Vilhar, U. (2019). Estimation of the Allergenic Potential of Urban Trees and Urban Parks: Towards the Healthy Design of Urban Green Spaces of the Future.

International Journal of Environmental Research and Public Health, 16(8). doi:10.3390/ijerph16081357

Cariñanos, P., Ruiz-Penuela, S., Valle, A. M., & de la Guardia, C. D. (2020). Assessing pollination disservices of urban street-trees: The case of London-plane tree (Platanus x hispanica Mill. ex Munchh). *Science of The Total Environment, 737*, 139722. doi:10.1016/j.scitotenv.2020.139722

Carne, R. J. (1994). *Urban vegetation Ecological and social value*. Paper presented at the National Greening Australia Conference, Australia.

Chang, J., Franzese, P., Chayantrakom, K., & Hanna, S. (2003). Evaluations of CALPUFF, HPAC, and VLSTRACK with Two Mesoscale Field Datasets. *Journal of Applied Meteorology, 42*(4), 453 - 466.

Chang, J. C., & Hanna, S. R. (2004). Air quality model performance evaluation. *Meteorology and Atmospheric Physics, 87*(1-3), 167–196 doi:10.1007/s00703-003-0070-7

Chang, J. C., & Hanna, S. R. (2005). *Technical Descriptions and User's Guide for the BOOT Statistical Model Evaluation Software Package, Version 2.0*. Retrieved from https://www.harmo.org/Kit/Download/BOOT_UG.pdf

Chaparro, M. A. E., Chaparro, M. A. E., Castaneda-Miranda, A. G., Marie, D. C., Gargiulo, J. D., Lavornia, J. M., Natal, M., & Bohnel, H. N. (2020). Fine air pollution particles trapped by street tree barks: In situ magnetic biomonitoring. *Environmental Pollution, 266*(Pt 1), 115229. doi:10.1016/j.envpol.2020.115229

Chaudhary, I. J., & Rathore, D. (2018). Suspended particulate matter deposition and its impact on urban trees. *Atmospheric Pollution Research, 9*(6), 1072-1082. doi:10.1016/j.apr.2018.04.006

Chen, J., Tang, J., & Yu, X. (2020). Environmental and physiological controls on diurnal and seasonal patterns of biogenic volatile organic compound emissions from five dominant woody species under field conditions. *Environmental Pollution, 259*, 113955. doi:10.1016/j.envpol.2020.113955

Chen L., L. C., Zou R., Yang M., Zhang Z. (2017). Variation in Tree Species Ability to Capture and Retain Airborne Fine Particulate Matter (PM2.5). *Scientific Reports, 7*(1), 3206. doi:10.1038/s41598-017-03360-1

Chen, X., Pei, T., Zhou, Z., Teng, M., He, L., Luo, M., & Liu, X. (2015). Efficiency differences of roadside greenbelts with three configurations in removing coarse particles (PM10): A street scale investigation in Wuhan, China. *Urban Forestry & Urban Greening, 14*(2), 354-360. doi:10.1016/j.ufug.2015.02.013

Chen, X., Wang, X., Wu, X., Guo, J., & Zhou, Z. (2021a). Influence of roadside vegetation barriers on air quality inside urban street canyons. *Urban Forestry & Urban Greening, 63*, 127219. doi:10.1016/j.ufug.2021.127219

Chen X., Zhou Z., Teng M., Wang P., & Zhou L. (2015). Accumulation of three different size of particulate matter on plant leaf surface: effect on leaf traits. *Arch. Biol. Sci., 67*(4), 1257 - 1267.

Chen, Y., Wang, Y., Liew, J. H., & Wang, P. L. (2021b). Development of a methodological framework for evaluating biodiversity of built urban green infrastructures by practitioners. *Journal of Cleaner Production, 303*. doi:10.1016/j.jclepro.2021.127009

Churkina, G., Grote, R., Butler, T. M., & Lawrence, M. (2015). Natural selection? Picking the right trees for urban greening. *Environmental Science & Policy, 47*, 12-17. doi:10.1016/j.envsci.2014.10.014

Cieslik, S., Omasa, K., & Paoletti, E. (2009). Why and how terrestrial plants exchange gases with air. *Plant Biol (Stuttg), 11 Suppl 1*, 24-34. doi:10.1111/j.1438-8677.2009.00262.x

City of Copenhagen. (2015). Urban Nature in Copenhagen - Strategy 2015-2025. Retrieved June 2020 https://kk.sites.itera.dk/apps/kk_pub2/index.asp?mode=detalje&id=1653

City of Vancouver. (2015). Greenest City. 2020 Action Plan, Part two: 2015 - 2020. Retrieved June 2020 https://vancouver.ca/files/cov/greenest-city-2020-action-plan-2015-2020.pdf

CODASC. (2008). CODASC: Laboratory of Building- and Environmental Aerodynamics. Retrieved from https://www.windforschung.de/CODASC.htm

CODASC. (n.d.). CODASC data base (Data base containing concentration measurement data of street canyons with avenue-like tree planting). Retrieved 2019-2022 https://www.umweltaerodynamik.de/bilder-originale/CODA/CODASC.html

Cohen, G., Steinberg, D. M., Keinan-Boker, L., Yuval, Levy, I., Chen, S., Shafran-Nathan, R., Levin, N., Shimony, T., Witberg, G., Bental, T., Shohat, T., Broday, D. M., Kornowski, R., & Gerber, Y. (2020). Preexisting coronary heart disease and susceptibility to long-term effects of traffic-related air pollution: A matched cohort analysis. *European Journal of Preventive Cardiology*, 2047487320921987. doi:10.1177/2047487320921987

Collins, K., Onwuegbuzie, A., & Sutton, I. (2006). A Model Incorporating the Rationale and Purpose for Conducting Mixed-Methods Research in Special Education and beyond. *Learning Disabilities: A Contemporary Journal 4*(1), 67–100

Cooper, C., Booth, A., Varley-Campbell, J., Britten, N., & Garside, R. (2018). Defining the process to literature searching in systematic reviews: a literature review of guidance and supporting studies. *BMC Medical Research Methodology, 18*(1), 85. doi:10.1186/s12874-018-0545-3

Cooper, N., Brady, E., Steen, H., & Bryce, R. (2016). Aesthetic and spiritual values of ecosystems: Recognising the ontological and axiological plurality of cultural ecosystem ‘services’. *Ecosystem Services, 21*, 218-229. doi:10.1016/j.ecoser.2016.07.014

Corada, K., Woodward, H., Alaraj, H., Collins, C. M., & de Nazelle, A. (2021). A systematic review of the leaf traits considered to contribute to removal of airborne particulate matter pollution in urban areas. *Environmental Pollution, 269*, 116104. doi:10.1016/j.envpol.2020.116104

Coskun Hepcan, C., & Hepcan, S. (2018). Assessing regulating ecosystem services provided by the Ege University Rectorship Garden. *Urban Forestry & Urban Greening, 34*, 10-16. doi:10.1016/j.ufug.2018.05.011

Coutts, C., & Hahn, M. (2015). Green Infrastructure, Ecosystem Services, and Human Health. *International Journal of Environmental Research and Public Health, 12*(8), 9768-9798. doi:10.3390/ijerph120809768

Cui, E., Weng, E., Yan, E., & Xia, J. (2020). Robust leaf trait relationships across species under global environmental changes. *Nature Communications, 11*(1), 2999. doi:10.1038/s41467-020-16839-9

Currie, B. A., & Bass, B. (2008). Estimates of air pollution mitigation with green plants and green roofs using the UFORE model. *Urban Ecosystems, 11*(4), 409-422. doi:10.1007/s11252-008-0054-y

D'Amato, G., Cecchi, L., Bonini, S., Nunes, C., Annesi-Maesano, I., Behrendt, H., Liccardi, G., Popov, T., & van Cauwenberge, P. (2007). Allergenic pollen and pollen allergy in Europe. *Allergy, 62*(9), 976-990. doi:10.1111/j.1398-9995.2007.01393.x

Damialis, A., Gioulekas, D., Lazopoulou, C., Balafoutis, C., & Vokou, D. (2005). Transport of airborne pollen into the city of Thessaloniki: the effects of wind direction, speed and persistence. *Int J Biometeorol 49*(3), 139-145. doi:10.1007/s00484-004-0229-z

Dandy, N. (2010). Climate Change & street trees project. The social and cultural values, and governance of street trees. Retrieved March 2019 https://www.forestresearch.gov.uk/documents/763/CCST_Social_Report_March2010.pdf, from The Research Agency of the Forestry Commission

Dang, N., Zhang, H., Abdus Salam, M. M., Li, H., & Chen, G. (2022). Foliar dust particle retention and metal accumulation of five garden tree species in Hangzhou: Seasonal changes. *Environmental Pollution, 306*, 119472. doi:10.1016/j.envpol.2022.119472

Daussy, J., & Staudt, M. (2020). Do future climate conditions change volatile organic compound emissions from Artemisia annua? Elevated CO2 and temperature modulate actual VOC emission rate but not its emission capacity. *Atmospheric Environment: X, 7*, 100082. doi:10.1016/j.aeaoa.2020.100082

Davies, H., Doick, K., Handley, P., O'Brien, L., & Wilson, J. (2017). Delivery of ecosystem services by urban forest. Retrieved April 2019 https://forestry.gov.scot/publications/98-delivery-of-ecosystem-services-by-urban-forests, from Forestry Commission: Edinburgh

Davies, J. M. (2019). Pollen Allergens. In *Encyclopedia of Environmental Health* (pp. 300-322).

de la Concha, H., Roche, M. L., & García, A. (2015). Inventario del Arbolado Urbano de la Ciudad de Mérida. Retrieved June 2020 https://www.itreetools.org/documents/207/Inventario_Urbano_Merida_imprmir_en_dos_caras.pdf

De Maerschalck, B., Janssen S., Vankerkom J., Mensink C., van de Burg A., & P., F. (2008). *CFD simulations of the impact of a line vegetation element along a motorway on local air quality*. Paper presented at the 12th conference on "Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes", Cavtat, Croatia.

de Ridder, K., Bañuelos A., Dufek J., Damsgaard O., Briuse M., Weber C., Baños de Guisasola E., & Beckroege W. (2004). *Benefit of Urban Green Spaces (BUGS) Research Summary*.

de Vries, S., van Dillen, S. M., Groenewegen, P. P., & Spreeuwenberg, P. (2013). Streetscape greenery and health: stress, social cohesion and physical activity as mediators. *Social Science & Medicine, 94*, 26-33. doi:10.1016/j.socscimed.2013.06.030

DEFRA. (2020a). *Air Pollution in the UK 2019*. Department for Environment, Food & Rural Affairs Retrieved from https://uk-air.defra.gov.uk/assets/documents/annualreport/air_pollution_uk_2019_issue_1.pdf

DEFRA. (2020b). Estimation of changes in air pollution emissions, concentrations and exposure during the COVID-19 outbreak in the UK. Retrieved July 2020 https://uk-air.defra.gov.uk/library/reports.php?report_id=1005, from Department for Environment, Food & Rural Affairs

DEFRA. (2022). UK AIR, Air Information Resource. Site environment types. 24/06/2022 https://uk-air.defra.gov.uk/networks/site-types.

Delian, E. (2020). Stomata-A key factor with multiple fuctions in the conditions of global climate change A brief overview. *Management, Economic Engineering in Agriculture and Rural Development, 20*(1), 151 - 160.

Deng, S., Ma, J., Zhang, L., Jia, Z., & Ma, L. (2019). Microclimate simulation and model optimization of the effect of roadway green space on atmospheric particulate matter. *Environmental Pollution, 246*, 932-944. doi:10.1016/j.envpol.2018.12.026

DeWees, T. A., Mazza, G. L., Golafshar, M. A., & Dueck, A. C. (2020). Investigation Into the Effects of Using Normal Distribution Theory Methodology for Likert Scale Patient-Reported Outcome Data From Varying Underlying Distributions Including Floor/Ceiling Effects. *Value Health, 23*(5), 625-631. doi:10.1016/j.jval.2020.01.007

Diener, A., & Mudu, P. (2021). How can vegetation protect us from air pollution? A critical review on green spaces' mitigation abilities for air-borne particles from a public health perspective - with implications for urban planning. *Science of The Total Environment, 796*, 148605. doi:10.1016/j.scitotenv.2021.148605

Doiron, D., de Hoogh, K., Probst-Hensch, N., Fortier, I., Cai, Y., De Matteis, S., & Hansell, A. L. (2019). Air pollution, lung function and COPD: results from the population-based UK Biobank study. *Eur Respir J, 54*(1). doi:10.1183/13993003.02140-2018

Donovan, R., Stewart, H., Owen, S. M., MacKenzie, A. R., & Hewitt, C. N. (2005). Development and Application of an Urban Tree Air Quality Score for Photochemical Pollution Episodes Using the Birmingham, United Kingdom, Area as a Case Study. *Environmental Science & Technology, 39*(17), 6730-6738.

Dore, A. J., Choularton, T. W., & Fowler, D. (1992). An improved wet deposition map of the United Kingdom incorporating the seeder—feeder effect over mountainous terrain. *Atmospheric Environment, 26A*(8), 1375-1381.

Dover, J. (2015). *Green Infrastructure. Incorporating plants and enhancing biodiversity in buildings and urban environments*: Routledge.337 pp

Duan, G., & Ngan, K. (2017). Effects of Time-Dependent Inflow Perturbations on Turbulent Flow in a Street Canyon. *Boundary-Layer Meteorology, 167*, 257–284. doi:10.1007/s10546-017-0327-1

Dublin City Council. (2016). Dublin City Tree Strategy 2016-2020. Retrieved March 2022 https://www.dublincity.ie/sites/default/files/media/file-uploads/2018-08/Dublin_City_Tree_Strategy_2016-2020.pdf

Dzierzanowski, K., & Gawronski, S. (2011). Use of trees for reducing particulate matter pollution in air. *Challenges of Modern Technology, 1*, 69-73.

Dzierzanowski, K., Popek, R., Gawronska, H., Saebo, A., & Gawronski, S. W. (2011). Deposition of Particulate Matter of Different Size Fractions on Leaf Surfaces and in Waxes of Urban Forest Species. *International Journal of Phytoremediation, 13*, 1037–1046. doi:doi.org/10.1080/15226514.2011.552929

Ealing Council. (2013). Ealing Tree Strategy 2013-2018. Retrieved June 2020 https://www.ealing.gov.uk/downloads/file/10138/ealing_councils_tree_strategy

Eisenman, T. S. (2013). Frederick Law Olmsted, Green Infrastructure, and the Evolving City. *Journal of Planning History, 12*(4), 287-311. doi:10.1177/1538513212474227

Elnabawi, M., Hamza N., & S., D. (2013). *Use and evaluation of the ENVI-met mode for two different urban forms in Cairo, Egypt Measurements and model simulations*. Paper presented at the 13th Conference of International Building Performance Simulation Association, Chambéry, France.

Emberlin, J., Smith, M., Close, R., & Adams-Groom, B. (2007). Changes in the pollen seasons of the early flowering trees Alnus spp. and Corylus spp. in Worcester, United Kingdom, 1996-2005. *Int J Biometeorol, 51*(3), 181-191. doi:10.1007/s00484-006-0059-2

ENVI-met. (2020). ENVI-met web page. Retrieved from https://www.envi-met.com/

ENVI-met. (2022). ENVI-met - Decode urban nature with Microclimate simulations. 2019 - 2022 https://www.envi-met.com. Retrieved from https://www.envi-met.com/

EPA. (2017). What is Open Space/Green Space? October 2021 https://www3.epa.gov/region1/eco/uep/openspace.html.

EPA. (2021). What is Green Infrastructure? October 2021 https://www.epa.gov/green-infrastructure/what-green-infrastructure.

Escobedo, F. J., Kroeger, T., & Wagner, J. E. (2011). Urban forests and pollution mitigation: analyzing ecosystem services and disservices. *Environmental Pollution, 159*(8-9), 2078-2087. doi:10.1016/j.envpol.2011.01.010

Escobedo, F. J., & Nowak, D. J. (2009). Spatial heterogeneity and air pollution removal by an urban forest. *Landscape and Urban Planning, 90*(3-4), 102-110. doi:10.1016/j.landurbplan.2008.10.021

Escobedo, F. J., Wagner, J. E., Nowak, D. J., De la Maza, C. L., Rodriguez, M., & Crane, D. E. (2008). Analyzing the cost effectiveness of Santiago, Chile's policy of using urban forests to improve air quality. *Journal of Environmental Management, 86*(1), 148-157. doi:10.1016/j.jenvman.2006.11.029

Etyemezian, V., Ahonen, S., Nikolic, D., Gillies, J., Kuhns, H., Gillette, D., & Veranth, J. (2004). Deposition and removal of fugitive dust in the arid southwestern United States: measurements and model results. *Journal of the Air & Waste Management Association, 54*(9), 1099-1111. doi:10.1080/10473289.2004.10470977

EU. (2005). Benefits of urban green space (BUGS), European Commission, CORDIS EU research results. November 2020 https://cordis.europa.eu/project/id/EVK4-CT-2000-00041.

European Commission. (n.d.). The forms and functions of green infrastructure. 15/11/2020 https://ec.europa.eu/environment/nature/ecosystems/benefits/index_en.htm#:~:text=Green%20infrastructure%20is%20a%20strategically,and%20climate%20mitigation%20and%20adaptation.

FAO. (2021). Food and Agriculture Organization of the United Nations, Urban and Peri-urban Forestry - Definition. 8/10/2021.

Farías, I., Préndez, M., & Bown, H. E. (2022). Leaf Fluxes of Carbon Dioxide, Methane and Biogenic Volatile Organic Compounds of the Urban Trees Platanus × acerifolia and Schinus molle in Santiago, Chile. *Atmosphere, 13*(2). doi:10.3390/atmos13020298

Feng, L., Yang, S., Zhou, Y., & Shuai, L. (2021). Exploring the effects of the spatial arrangement and leaf area density of trees on building wall temperature. *Building and Environment, 205*. doi:10.1016/j.buildenv.2021.108295

Fernández-Rodríguez, S., Tormo-Molina, R., Maya-Manzano, J. M., Silva-Palacios, I., & Gonzalo-Garijo, Á. (2014). A comparative study on the effects of altitude on daily and hourly airborne pollen counts. *Aerobiologia, 30*(3), 257-268. doi:10.1007/s10453-014-9325-7

Filazzola, A., Shrestha, N., MacIvor, J. S., & Stanley, M. (2019). The contribution of constructed green infrastructure to urban biodiversity: A synthesis and meta-analysis. *Journal of Applied Ecology, 56*(9), 2131-2143. doi:10.1111/1365-2664.13475

Finkel, I. (1988). The Hanging Gardens of Babylon. In P. Clayton & M. Price (Eds.), *Seven Wonders Ancient World* (pp. 38). London and New York: Routledge.

Fisher, J. C., Rankin, E., Irvine, K. N., Goddard, M. A., Davies, Z. G., & Dallimer, M. (2022). Can biodiverse streetscapes mitigate the effects of noise and air pollution on human wellbeing? *Environ Res, 212*(Pt A), 113154. doi:10.1016/j.envres.2022.113154

Fogli, J., & Herkenhoff, L. (2018). Survey Administration. In D. Stengel (Ed.), *Conducting survey research. A practical guide* (2nd ed.). 222 East 46th Street, New York, NY 10017: Business Expert Press.

Forest Research. (2010). *Benefit of green infrastructure. Report by Forest Research*. Farnham, Surrey

Forest Research. (2021). What is greenspace/green infrastructure (GI)? November 2021 https://www.forestresearch.gov.uk/tools-and-resources/fthr/urban-regeneration-and-greenspace-partnership/greenspace-in-practice/what-is-greenspacegreen-infrastructure-gi/.

Forest Research. (n.d.). The Right Tree in the Right Place for a Resilient Future. Retrieved September 2019 https://www.forestresearch.gov.uk/documents/5318/7111_FC_Urban_Tree_Manual_V15.pdf

Foster, D., & Duinker, P. (2017). The HRM Urban Forest in 2016. Retrieved August 2020 file:///C:/Users/karin/Downloads/FosterDuinker_2017_iTreeEcoForHalifax_Feb2017.pdf, from School for Resource and Environmental Studies, Dalhousie University February 2017

Fowler, D., Pilegaard, K., Sutton, M. A., Ambus, P., Raivonen, M., Duyzer, J., Simpson, D., Fagerli, H., Fuzzi, S., Schjoerring, J. K., Granier, C., Neftel, A., Isaksen, I. S. A., Laj, P., Maione, M., Monks, P. S., Burkhardt, J., Daemmgen, U., Neirynck, J., Personne, E., Wichink-Kruit, R., Butterbach-Bahl, K., Flechard, C., Tuovinen, J. P., Coyle, M., Gerosa, G., Loubet, B., Altimir, N., Gruenhage, L., Ammann, C., Cieslik, S., Paoletti, E., Mikkelsen, T. N., Ro-Poulsen, H., Cellier, P., Cape, J. N., Horváth, L., Loreto, F., Niinemets, Ü., Palmer, P. I., Rinne, J., Misztal, P., Nemitz, E., Nilsson, D., Pryor, S., Gallagher, M. W., Vesala, T., Skiba, U., Brüggemann, N., Zechmeister-Boltenstern, S., Williams, J., O'Dowd, C., Facchini, M. C., de Leeuw, G., Flossman, A., Chaumerliac, N., & Erisman, J. W. (2009). Atmospheric composition change: Ecosystems–Atmosphere interactions. *Atmospheric Environment, 43*(33), 5193-5267. doi:10.1016/j.atmosenv.2009.07.068

Francis, L. F. M., & Jensen, M. B. (2017). Benefits of green roofs: A systematic review of the evidence for three ecosystem services. *Urban Forestry & Urban Greening, 28*, 167-176. doi:10.1016/j.ufug.2017.10.015

Freer-Smith, P. H., Beckett, K. P., & Taylor, G. (2005). Deposition velocities to Sorbus aria, Acer campestre, Populus deltoides X trichocarpa 'Beaupre', Pinus nigra and X Cupressocyparis leylandii for coarse, fine and ultra-fine particles in the urban environment. *Environmental Pollution 133*(1), 157-167. doi:10.1016/j.envpol.2004.03.031

Freer-Smith, P. H., El-Khatib, A., & Taylor, G. (2004). Capture of particulate pollution by trees: a comparison of species typical of semi-arid areas (Ficus nitida and Eucalyptus globulus) with European and North American species *Water, Air, and Soil Pollution, 155*(1-4), 173-187 doi:10.1023/B:WATE.0000026521.99552.fd

Freer-Smith, P. H., Holloway S., & Goodman A. (1997). The uptake of particulates by an urban woodland: Site description and particulate composition. *Environmental Pollution, 95*(1), 27-35. doi:10.1016/s0269-7491(96)00119-4

Fu, P., & Yung, K. K. L. (2020). Air Pollution and Alzheimer's Disease: A Systematic Review and Meta-Analysis. *Journal of Alzheimer’s Disease 77*(2), 701-714. doi:10.3233/JAD-200483

Fujii, S., Cha, H., Kagi, N., Miyamura, H., & Kim, Y.-S. (2005). Effects on air pollutant removal by plant absorption and adsorption. *Building and Environment, 40*(1), 105-112. doi:10.1016/j.buildenv.2004.04.015

Fusaro, L., Salvatori, E., Winkler, A., Frezzini, M. A., De Santis, E., Sagnotti, L., Canepari, S., & Manes, F. (2021). Urban trees for biomonitoring atmospheric particulate matter: An integrated approach combining plant functional traits, magnetic and chemical properties. *Ecological Indicators, 126*, 107707. doi:10.1016/j.ecolind.2021.107707

Gallagher, J., Baldauf, R., Fuller, C. H., Kumar, P., Gill, L. W., & McNabola, A. (2015). Passive methods for improving air quality in the built environment: A review of porous and solid barriers. *Atmospheric Environment, 120*, 61-70. doi:10.1016/j.atmosenv.2015.08.075

Gao, G., Sun, F., Thanh, T., Nguyen, T., Lun, X., & Yu, X. (2015). Different Concentrations of TSP, PM10, PM2.5, and PM1 of Several Urban Forest Types in Different Seasons. *Polish Journal of Environmental Studies, 24*(6), 2387-2395. doi:10.15244/pjoes/59501

Gardner, J., McDuie, M., & Boyle, E. (2017). Valuing the Waite Arboretum, South Australia. An i-Tree Ecosystem Analysis. Retrieved August 2020 https://www.itreetools.org/documents/378/WaiteArb_iTree_2017.pdf

Gatto, E., Buccolieri, R., Perronace, L., & Santiago, J. L. (2021). The Challenge in the Management of Historic Trees in Urban Environments during Climate Change: The Case of Corso Trieste (Rome, Italy). *Atmosphere, 12*(4). doi:10.3390/atmos12040500

Ghasemian, M., Amini, S., & Princevac, M. (2017). The influence of roadside solid and vegetation barriers on near-road air quality. *Atmospheric Environment, 170*, 108-117. doi:10.1016/j.atmosenv.2017.09.028

Gheorghe, I. F., & Ion, B. (2011). The Effects of Air Pollutants on Vegetation and the Role of Vegetation in Reducing Atmospheric Pollution. In M. K. Khallaf (Ed.), *The Impact of Air Pollution on Health, Economy, Environment and Agricultural Sources* (pp. 43).

GLA. (2021). The London Plan. The Spatial Development Strategy for Greater London. Retrieved March 2021 https://www.london.gov.uk/sites/default/files/the_london_plan_2021.pdf, from Greater London Authority. ISBN 978-1-84781-739-6

Gong, C., Xian, C., Cui, B., He, G., Wei, M., Zhang, Z., & Ouyang, Z. (2021). Estimating NOx removal capacity of urban trees using stable isotope method: A case study of Beijing, China. *Environmental Pollution, 290*, 118004. doi:10.1016/j.envpol.2021.118004

Gonzalez, F., & Candau, P. (1997). Olea europaea Airborne Pollen in Southern Spain. *Annals of Allergy, Asthma & Immunology 78*, 278-284.

Goodwin, D. (2017). *The Urban Tree*. New York: Taylor & Francis. 282 pp. ISBN 9780415702461

Gostin, I. (2016). Air Pollution Stress and Plant Response In U. Kulshrestha & P. Saxena (Eds.), *Plant Responses to Air Pollution* (pp. 99 - 117): Springer.

Government Office for Science. (2018). Computational modelling: Technological Futures. Retrieved January 2020 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/682579/computational-modelling-blackett-review.pdf

Grant, M. J., & Booth, A. (2009). A typology of reviews: an analysis of 14 review types and associated methodologies. *Health Info Libr J, 26*(2), 91-108. doi:10.1111/j.1471-1842.2009.00848.x

GreenBlue Urban. (n.d.-a). The 7 fundamentals of tree planting in paved surrounds. March 2022 https://www.greenblue.com/wp-content/uploads/2016/05/Tree-Planting-in-Paved-Surrounds.pdf.

GreenBlue Urban. (n.d.-b). Health Benefits of Urban Trees. Retrieved March 2022 https://www.greenblue.com/wp-content/uploads/2016/05/Health-Benefits-of-Urban-Trees.pdf

Gromke, C. (2011). A vegetation modeling concept for Building and Environmental Aerodynamics wind tunnel tests and its application in pollutant dispersion studies. *Environmental Pollution, 159*(8-9), 2094-2099. doi:10.1016/j.envpol.2010.11.012

Gromke, C. (2013). *CODASC : a database for the validation of street canyon dispersion models*. Paper presented at the 15th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes (HARMO), Madrid, Spain.

Gromke, C. (2021, 16/02/2021). [Personal communicacion. More information about CODASC, Wind velocity in the street canyon].

Gromke, C., & Blocken, B. (2015). Influence of avenue-trees on air quality at the urban neighborhood scale. Part I: quality assurance studies and turbulent Schmidt number analysis for RANS CFD simulations. *Environmental Pollution, 196*, 214-223. doi:10.1016/j.envpol.2014.10.016

Gromke, C., Buccolieri, R., Di Sabatino, S., & Ruck, B. (2008). Dispersion study in a street canyon with tree planting by means of wind tunnel and numerical investigations – Evaluation of CFD data with experimental data. *Atmospheric Environment, 42*(37), 8640-8650. doi:10.1016/j.atmosenv.2008.08.019

Gromke, C., Jamarkattel N., & B., R. (2016). Influence of roadside hedgerows on air quality in urban street canyons. *Atmospheric Environment, 139*, 75-86.

Gromke, C., & Ruck, B. (2007). Influence of trees on the dispersion of pollutants in an urban street canyon - Experimental investigation of the flow and concentration field. *Atmospheric Environment, 41*, 3287-3302.

Gromke, C., & Ruck, B. (2008a). Aerodynamic modelling of trees for small-scale wind tunnel studies. *Forestry, 81*(3), 243-258. doi:10.1093/forestry/cpn027

Gromke, C., & Ruck, B. (2008b). On the Impact of Trees on Dispersion Processes of Traffic Emissions in Street Canyons. *Boundary-Layer Meteorology, 131*(1), 19-34. doi:10.1007/s10546-008-9301-2

Gromke, C., & Ruck, B. (2012). Pollutant Concentrations in Street Canyons of Different Aspect Ratio with Avenues of Trees for Various Wind Directions. *Boundary-Layer Meteorology, 144*(1), 41-64. doi:10.1007/s10546-012-9703-z

Grote, R., Samson, R., Alonso, R., Amorim, J. H., Cariñanos, P., Churkina, G., Fares, S., Le Thiec, D., Niinemets, U., Norgaard Mikkelsen, T., Paoletti, E., Tiwary, A., & Calfapietra, C. (2016). Functional traits of urban trees: air pollution mitigation potential. *Frontiers in Ecology and the Environment, 14*(10), 543-550.

Guenther, A., Karl, T., Harley, P., Wiedinmyer, C., Palmer P., & Geron, C. (2006). Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature). *Atmospheric Chemistry and Physics, 6*, 3181–3210.

Guo, L., & Maghirang, R. G. (2012). Numerical Simulation of Airflow and Particle Collection by Vegetative Barriers. *Engineering Applications of Computational Fluid Mechanics, 6*(1), 110-122. doi:10.1080/19942060.2012.11015407

Gupta, A. (2016). Effect of Air Pollutants on Plant Gaseous Exchange Process: Effect on Stomata and Respiration In P. S. U. Kulshrestha (Ed.), *Plant Responses to Air Pollution* (pp. 85 - 92).

Gupta, G. P., & Kulshrestha, U. (2016). Chapter 11: Biomonitoring and Remediation by Plants In P. S. U. Kulshrestha (Ed.), *Plant Responses to Air Pollution* (pp. 198).

Gupta, G. P., Kumar, B., Singh, S., & Kulshrestha, U. (2015). Urban climate and its effect on biochemical and morphological characteristics of Arjun (Terminalia arjuna) plant in National Capital Region Delhi. *Chemistry and Ecology, 31*(6), 524-538. doi:10.1080/02757540.2015.1043286

Hagler, G. S., Lin, M. Y., Khlystov, A., Baldauf, R. W., Isakov, V., Faircloth, J., & Jackson, L. E. (2012). Field investigation of roadside vegetative and structural barrier impact on near-road ultrafine particle concentrations under a variety of wind conditions. *Science of The Total Environment, 419*, 7-15. doi:10.1016/j.scitotenv.2011.12.002

Hagler, G. S. W., Tang, W., Freeman, M. J., Heist, D. K., Perry, S. G., & Vette, A. F. (2011). Model evaluation of roadside barrier impact on near-road air pollution. *Atmospheric Environment, 45*, 2522-2530.

Han, Y., Hu, Y., & Qian, F. (2011). Effects of air temperature and humidity on particle deposition. *Chemical Engineering Research and Design, 89*(10), 2063-2069. doi:10.1016/j.cherd.2011.02.001

Han, Y., Lee, J., Haiping, G., Kim, K. H., Wanxi, P., Bhardwaj, N., Oh, J. M., & Brown, R. J. C. (2022). Plant-based remediation of air pollution: A review. *J Environ Manage, 301*, 113860. doi:10.1016/j.jenvman.2021.113860

Harley, P., Monson, R. K., & Lerdau, M. T. (1999). Ecological and evolutionary aspects of isoprene emission from plants. *Oecologia, 118*, 109-123.

Harris, T. B., & Manning, W. J. (2010). Nitrogen dioxide and ozone levels in urban tree canopies. *Environmental Pollution, 158*(7), 2384-2386. doi:10.1016/j.envpol.2010.04.007

Harrison, R. M., Vu, T. V., Jafar, H., & Shi, Z. (2021). More mileage in reducing urban air pollution from road traffic. *Environment International, 149*, 106329. doi:10.1016/j.envint.2020.106329

He, C., Qiu, K., Alahmad, A., & Pott, R. (2020a). Particulate matter capturing capacity of roadside evergreen vegetation during the winter season. *Urban Forestry & Urban Greening, 48*. doi:10.1016/j.ufug.2019.126510

He, C., Qiu K., & R., P. (2020b). Reduction of traffic-related particulate matter by roadside plants: effect of traffic pressure and sampling height. *Int J Phytoremediation, 22*(2), 184-200. doi:10.1080/15226514.2019.1652565

He, F., Tang, J., Zhang, T., Lin, J., Li, F., Gu, X., Chen, A., Nevill, A., & Chen, R. (2021). Impact of air pollution exposure on the risk of Alzheimer's disease in China: A community-based cohort study. *Environmental Research*, 112318. doi:10.1016/j.envres.2021.112318

HEI. (2010). Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects. A Special Report of the HEI Panel on the Health Effects of Traffic-Related Air Pollution. Executive Summary. *Health Effects Institute, Special Report 17*, 12 pp.

Hewitt, C. N., Ashworth, K., & MacKenzie, A. R. (2020). Using green infrastructure to improve urban air quality (GI4AQ). *Ambio, 49*(1), 62-73. doi:10.1007/s13280-019-01164-3

Heydari, S., Tainio, M., Woodcock, J., & de Nazelle, A. (2020). Estimating traffic contribution to particulate matter concentration in urban areas using a multilevel Bayesian meta-regression approach. *Environment International, 141*, 105800. doi:10.1016/j.envint.2020.105800

Hillier Nurseries, & RHS. (2019). *The Hillier Manual of Trees & Shrubs: Revised & updated with 1,500 new plants* (R. L. Dawn Edwards & Rosalyn Marshall, Richard Sandford Ed. 9th ed.). London: Royal Horticultural Society

Hirabayashi, S., Kroll, C. N., & Nowak, D. (2015). *iTree Eco Dry Deposition Model Descriptions*. Retrieved from The Davey Tree Expert Company, Syracuse, New York 13210, USA:

Hirons, A., & Sjöman, H. (2019). Tree species selection for green ingrastructure. A guide for specifiers. *Trees & Desing Action Group*(13), 375.

Hirons, A. D., & Thomas, P. (2018). Leaves and Crowns. In *Applied tree biology* (pp. 64): Hoboken, NJ : John Wiley & Sons, Inc.

HM Government. (2018). A Green Future: Our 25 Year Plant to Improve the Enviroment. Retrieved November 2020 www.gov.uk/government/publications., from DEFRA

Hofman, J., Bartholomeus, H., Janssen, S., Calders, K., Wuyts, K., Van Wittenberghe, S., & Samson, R. (2016). Influence of tree crown characteristics on the local PM 10 distribution inside an urban street canyon in Antwerp (Belgium): A model and experimental approach. *Urban Forestry & Urban Greening, 20*, 265-276. doi:10.1016/j.ufug.2016.09.013

Hofman, J., & Samson, R. (2014). Biomagnetic monitoring as a validation tool for local air quality models: a case study for an urban street canyon. *Environment International, 70*, 50-61. doi:10.1016/j.envint.2014.05.007

Hofman, J., Stokkaer, I., Snauwaert, L., & Samson, R. (2013). Spatial distribution assessment of particulate matter in an urban street canyon using biomagnetic leaf monitoring of tree crown deposited particles. *Environmental Pollution, 183*, 123-132. doi:10.1016/j.envpol.2012.09.015

Hofman, J., Wuyts, K., Van Wittenberghe, S., & Samson, R. (2014). On the temporal variation of leaf magnetic parameters: seasonal accumulation of leaf-deposited and leaf-encapsulated particles of a roadside tree crown. *Science of The Total Environment, 493*, 766-772. doi:10.1016/j.scitotenv.2014.06.074

Holopainen, J. K., & Gershenzon, J. (2010). Multiple stress factors and the emission of plant VOCs. *Trends Plant Sci, 15*(3), 176-184. doi:10.1016/j.tplants.2010.01.006

Holton, J. R. (2004). *An introduction to dynamic meteorology* (4th ed. ed.). Amsterdam ; London: Elsevier Academic Press

Hong, B., Lin, B., & Qin, H. (2017). Numerical Investigation on the Effect of Avenue Trees on PM2.5 Dispersion in Urban Street Canyons. *Atmosphere, 8*(12), 129. doi:10.3390/atmos8070129

Honour, S. L., Bell, J. N., Ashenden, T. W., Cape, J. N., & Power, S. A. (2009). Responses of herbaceous plants to urban air pollution: effects on growth, phenology and leaf surface characteristics. *Environmental Pollution, 157*(4), 1279-1286. doi:10.1016/j.envpol.2008.11.049

Hortipedia. (2022). Plant database. 2/06/22 https://en.hortipedia.com/Main_page.

Hosker, R. P., & Lindberg, S. (1982). Review: Atmospheric deposition and plant assimilation of gases and particles. *Atmospheric Environment, 16*(5), 889-910.

House of Parlament. (2013). *Urban Green Infrastructure*. London

Hulshof, C. M., & Swenson, N. G. (2010). Variation in leaf functional trait values within and across individuals and species: an example from a Costa Rican dry forest. *Functional Ecology, 24*(1), 217-223. doi:10.1111/j.1365-2435.2009.01614.x

IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. & T. K. M. Matthews, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (Eds.). Cambridge University Press.

IPCC, A. W. (2022). Chapter 8: Urban Systems and Other Settlements, Climate Change 2022 Mitigation of Climate Change. Retrieved April 2022 https://www.ipcc.ch/report/ar6/wg3/

Islam, M. N., Rahman, K.-S., Bahar, M. M., Habib, M. A., Ando, K., & Hattori, N. (2012). Pollution attenuation by roadside greenbelt in and around urban areas. *Urban Forestry & Urban Greening, 11*(4), 460-464. doi:10.1016/j.ufug.2012.06.004

Jain, T., Currie, G., & Aston, L. (2022). COVID and working from home: Long-term impacts and psycho-social determinants. *Transportation Research Part A: Policy and Practice, 156*, 52-68. doi:10.1016/j.tra.2021.12.007

Jamei, E., Ossen, D. R., & Rajagopalan, P. (2017). Investigating the effect of urban configurations on the variation of air temperature. *International Journal of Sustainable Built Environment, 6*(2), 389-399. doi:10.1016/j.ijsbe.2017.07.001

Janhäll, S. (2015). Review on urban vegetation and particle air pollution – Deposition and dispersion. *Atmospheric Environment, 105*, 130-137. doi:10.1016/j.atmosenv.2015.01.052

Jayasooriya, V. M., Muthukumaran, A. W. M., Ng, S., & Perera, B. J. C. (2017). Green infrastructure practices for improvement of urban air quality. *Urban Forestry & Urban Greening, 21*, 34–47.

Jeanjean, A. P. R., Buccolieri, R., J., E., Monks, P. S., & Leigh, R. J. (2017). Air quality affected by trees in real street canyons: The case of Marylebone neighbourhood in central London. *Urban Forestry & Urban Greening, 22*, 41–53.

Jeanjean, A. P. R., Hinchliffe, G., McMullan, W. A., Monks, P. S., & Leigh, R. J. (2015). A CFD study on the effectiveness of trees to disperse road traffic emissions at a city scale. *Atmospheric Environment, 120*, 1-14. doi:10.1016/j.atmosenv.2015.08.003

Jeanjean, A. P. R., Monks, P. S., & Leigh, R. J. (2016). Modelling the effectiveness of urban trees and grass on PM2.5 reduction via dispersion and deposition at a city scale. *Atmospheric Environment, 147*, 1-10.

Ji, W., & Zhao, B. (2018). A wind tunnel study on the effect of trees on PM2.5 distribution around buildings. *J Hazard Mater, 346*, 36-41. doi:10.1016/j.jhazmat.2017.11.043

Jia, C., Li, W., Wu, T., & He, M. (2021a). Road traffic and air pollution: Evidence from a nationwide traffic control during coronavirus disease 2019 outbreak. *Science of The Total Environment, 781*, 146618. doi:10.1016/j.scitotenv.2021.146618

Jia, M., Zhou, D., Lu, S., & Yu, J. (2021b). Assessment of foliar dust particle retention and toxic metal accumulation ability of fifteen roadside tree species: Relationship and mechanism. *Atmospheric Pollution Research, 12*(1), 36-45. doi:10.1016/j.apr.2020.08.003

Jianan, X., Zhiyun, O., Hua, Z., Xiaoke, W., & Hong, M. (2007). Allergenic pollen plants and their influential factors in urban areas. *Acta Ecologica Sinica, 27*(9), 3820-3827. doi:10.1016/s1872-2032(07)60082-1

Jim, C. Y., & Chen, W. Y. (2008). Assessing the ecosystem service of air pollutant removal by urban trees in Guangzhou (China). *Journal of Environmental Management, 88*(4), 665-676. doi:10.1016/j.jenvman.2007.03.035

Jin S., G. J., Wheeler S., Kan L., Che S. (2014). Evaluation of impacts of trees on PM2.5 dispersion in urban streets. *Atmospheric Environment, 99*, 277-287.

Jo, H.-K., Kim, J.-Y., & Park, H.-M. (2020). Carbon and PM2.5 Reduction and Design Guidelines for Street Trees in Korea. *Sustainability, 12*(24), 10414. doi:10.3390/su122410414

Jones, S., & Somper, C. (2014). The role of green infrastructure in climate change adaptation in London. *The Geographical Journal, 180*(2), 191-196. doi:10.1111/geoj.12059

Kampa, M., & Castanas, E. (2008). Human health effects of air pollution. *Environmental Pollution, 151*, 362 - 367.

Kardel, F., Wuyts, K., Maher, B. A., Hansard, R., & Samson, R. (2011). Leaf saturation isothermal remanent magnetization (SIRM) as a proxy for particulate matter monitoring: Inter-species differences and in-season variation. *Atmospheric Environment, 45*(29), 5164-5171. doi:10.1016/j.atmosenv.2011.06.025

Karim, A. A., & Nolan, P. F. (2011). Modelling reacting localized air pollution using Computational Fluid Dynamics (CFD). *Atmospheric Environment, 45*, 889-895.

Kastner-Klein, P., Berkowicz, R., & Britter, R. (2004). The influence of street architecture on flow and dispersion in street canyons. *Meteorology and Atmospheric Physics, 87*(1-3). doi:10.1007/s00703-003-0065-4

Kaur, S., Nieuwenhuijsen, M., & Colvile, R. (2005). Pedestrian exposure to air pollution along a major road in Central London, UK. *Atmospheric Environment, 39*(38), 7307-7320. doi:10.1016/j.atmosenv.2005.09.008

Kenney, W. A. (2000). Leaf Area Density as an urban forestry planning and management tool. *The Forestry Chronicle, 76*, 235 - 239.

Kesselmeier, J., & Staudt, M. (1999). Biogenic Volatile Organic Compounds (VOC) An overview on emission, physiology and ecology.pdf>. *Journal of Atmospheric Chemistry, 33*, 23-88.

Kessler, A. (2018). Introduction to a special feature issue - New insights into plant volatiles. *New Phytologist, 220*, 655 - 658.

Khan, A., & Abbasi, S. A. (2000). Attenuation of gaseous pollutants. *Environmental Monitoring and Assessment 64*, 457–475.

Kilian, J., & Kitazawa, M. (2018). The emerging risk of exposure to air pollution on cognitive decline and Alzheimer's disease - Evidence from epidemiological and animal studies. *Biomedical Journal, 41*(3), 141-162. doi:10.1016/j.bj.2018.06.001

Kim, J. C. (2001). Factors controlling natural VOC emissions in a southeastern US pine forest. *Atmospheric Environment, 35*(19), 3279-3292.

Kim, J. C., Kim, K. J., Kim, D. S., & Han, J. S. (2005). Seasonal variations of monoterpene emissions from coniferous trees of different ages in Korea. *Chemosphere, 59*(11), 1685-1696. doi:10.1016/j.chemosphere.2004.10.048

Kim, K. R., Oh, J. W., Woo, S. Y., Seo, Y. A., Choi, Y. J., Kim, H. S., Lee, W. Y., & Kim, B. J. (2018). Does the increase in ambient CO2 concentration elevate allergy risks posed by oak pollen? *International Journal of Biometeorology, 62*(9), 1587-1594. doi:10.1007/s00484-018-1558-7

Koch, K., & Barthlott, W. (2006). Plant epicuticular waxes: Chemistry, form, self-assembly and function. *Natural Product communications, 1*(11), 1067-1072.

Konczak, B., Cempa, M., Pierzchala, L., & Deska, M. (2021). Assessment of the ability of roadside vegetation to remove particulate matter from the urban air. *Environ Pollut, 268*(Pt B), 115465. doi:10.1016/j.envpol.2020.115465

Kondo, M. C., Fluehr, J. M., McKeon, T., & Branas, C. C. (2018). Urban Green Space and Its Impact on Human Health. *Int J Environ Res Public Health, 15*(3). doi:10.3390/ijerph15030445

Kumar, P., Abhijith, K. V., & Barwise, Y. (2019a). *Implementing Green Infrastructure for Air Pollution Abatement: General Recommendations for Management and Plant Species Selection*. University of Surrey

Kumar, P., Druckman, A., Gallagher, J., Gatersleben, B., Allison, S., Eisenman, T. S., Hoang, U., Hama, S., Tiwari, A., Sharma, A., Abhijith, K. V., Adlakha, D., McNabola, A., Astell-Burt, T., Feng, X., Skeldon, A. C., de Lusignan, S., & Morawska, L. (2019b). The nexus between air pollution, green infrastructure and human health. *Environment International, 133*(Part A), 105181. doi:10.1016/j.envint.2019.105181

Kumar, P., Garmory, A., Ketzel, M., Berkowicz, R., & Britter, R. (2009). Comparative study of measured and modelled number concentrations of nanoparticles in an urban street canyon. *Atmospheric Environment, 43*(4), 949-958. doi:10.1016/j.atmosenv.2008.10.025

Kumar, P., Hama, S., Omidvarborna, H., Sharma, A., Sahani, J., Abhijith, K. V., Debele, S. E., Zavala-Reyes, J. C., Barwise, Y., & Tiwari, A. (2020). Temporary reduction in fine particulate matter due to 'anthropogenic emissions switch-off' during COVID-19 lockdown in Indian cities. *Sustainable Cities and Society, 62*, 102382. doi:10.1016/j.scs.2020.102382

Kumar, P., Morawska, L., Birmili, W., Paasonen, P., Hu, M., Kulmala, M., Harrison, R. M., Norford, L., & Britter, R. (2014). Ultrafine particles in cities. *Environment International, 66*, 1-10. doi:10.1016/j.envint.2014.01.013

Lachowycz, K., & Jones, A. P. (2014). Does walking explain associations between access to greenspace and lower mortality? *Social Science & Medicine, 107*, 9-17. doi:10.1016/j.socscimed.2014.02.023

Lahr, E. C., Schade, G. W., Crossett, C. C., & Watson, M. R. (2015). Photosynthesis and isoprene emission from trees along an urban-rural gradient in Texas. *Global Change Biology 21*(11), 4221-4236. doi:10.1111/gcb.13010

Lake, I. R., Jones, N. R., Agnew, M., Goodess, C. M., Giorgi, F., Hamaoui-Laguel, L., Semenov, M. A., Solmon, F., Storkey, J., Vautard, R., & Epstein, M. M. (2017). Climate Change and Future Pollen Allergy in Europe. *Environ Health Perspect, 125*(3), 385-391. doi:10.1289/EHP173

Lalic, B., & Mihailovic, D. T. (2004). An empirical relation describing Leaf-Area Density inside the forest for environmental modelling. *American Meteorological Society, 43*, 641 - 645.

Laurian, L. (2012). Paris, France: A 21st-Century Eco-City. In *Green cities of Europe : global lessons on green urbansim (Beatley, Timothy)* (pp. 29-64). Washington, DC: Island Press.

Law, A. M. (2014). Chapter 5. Building valid, Credible, and Appropriately Detailed Simulation Models. In *Simulation Modeling and Analysis* (5th ed., pp. 784). New York: McGraw-Hill Education.

Lee, I. M., Shiroma, E. J., Lobelo, F., Puska, P., Blair, S. N., & Katzmarzyk, P. T. (2012). Effect of physical inactivity on major non-communicable diseases worldwide: an analysis of burden of disease and life expectancy. *The Lancet, 380*(9838), 219-229. doi:10.1016/s0140-6736(12)61031-9

Lelieveld, J., Pozzer, A., Poschl, U., Fnais, M., Haines, A., & Munzel, T. (2020). Loss of life expectancy from air pollution compared to other risk factors: a worldwide perspective. *Cardiovascular Research*. doi:10.1093/cvr/cvaa025

Leonard, R. J., McArthur, C., & Hochuli, D. F. (2016). Particulate matter deposition on roadside plants and the importance of leaf trait combinations. *Urban Forestry & Urban Greening, 20*, 249–253.

Li, Q., Kobayashi, M., Wakayama, Y., Inagaki, H., Katsumata, M., Hirata, Y., Hirata, K., Shimizu, T., Kawada, T., Park, B. J., Ohira, T., Kagawa, T., & Miyazaki, Y. (2009). Effect of phytoncide from trees on human natural killer cell function. *International Journal of Immunopathology and Pharmacology, 22*(4), 951 - 959.

Li, Q., Li, Y., Zhu, L., Xing, B., & Chen, B. (2017). Dependence of Plant Uptake and Diffusion of Polycyclic Aromatic Hydrocarbons on the Leaf Surface Morphology and Micro-structures of Cuticular Waxes. *Scientific Reports, 7*, 46235. doi:10.1038/srep46235

Li, S., Yuan, X., Xu, Y., Li, Z., Feng, Z., Yue, X., & Paoletti, E. (2021). Biogenic volatile organic compound emissions from leaves and fruits of apple and peach trees during fruit development. *Journal of Environmental Sciences, 108*, 152-163. doi:10.1016/j.jes.2021.02.013

Li, X., Lu, Q., Lu, S., He, H., Peng, Z., Gao, Y., & Z., W. (2016). The impacts of roadside vegetation barriers on the dispersion of gaseous traffic pollution in urban street canyons. *Urban Forestry & Urban Greening, 17*, 80–91.

Liang, L., & Gong, P. (2020). Urban and air pollution: a multi-city study of long-term effects of urban landscape patterns on air quality trends. *Scientific Reports, 10*(1), 18618. doi:10.1038/s41598-020-74524-9

Lin, J., Kroll, C. N., Nowak, D. J., & Greenfield, E. J. (2019). A review of urban forest modeling: Implications for management and future research. *Urban Forestry & Urban Greening, 43*, 126366. doi:10.1016/j.ufug.2019.126366

Lin, L., Yan, J., Ma, K., Zhou, W., Chen, G., Tang, R., & Zhang, Y. (2017). Characterization of particulate matter deposited on urban tree foliage: A landscape analysis approach. *Atmospheric Environment, 171*, 59-69. doi:10.1016/j.atmosenv.2017.09.012

Lin, X., Chamecki, M., & Yu, X. (2020). Aerodynamic and deposition effects of street trees on PM2.5 concentration: From street to neighborhood scale. *Building and Environment, 185*, 107291. doi:10.1016/j.buildenv.2020.107291

Linzon, S. N. (1972). Effects of Sulphur oxides on vegetation. *The Forestry Chronicle*, 182–186.

Litschke, T., & Kuttler, W. (2008). On the reduction of urban particle concentration by vegetation a review. *Meteorologische Zeitschrift, 17*(3), 229-240. doi:10.1127/0941-2948/2008/0284

Liu, J., Cao, Z., Zou, S., Liu, H., Hai, X., Wang, S., Duan, J., Xi, B., Yan, G., Zhang, S., & Jia, Z. (2018). An investigation of the leaf retention capacity, efficiency and mechanism for atmospheric particulate matter of five greening tree species in Beijing, China. *Science of The Total Environment, 616-617*, 417-426. doi:10.1016/j.scitotenv.2017.10.314

Liu, J., & Slik, F. (2022). Are street trees friendly to biodiversity? *Landscape and Urban Planning, 218*, 104304. doi:10.1016/j.landurbplan.2021.104304

Liu, Y., Pan, J., Fan, C., Xu, R., Wang, Y., Xu, C., Xie, S., Zhang, H., Cui, X., Peng, Z., Shi, C., Zhang, Y., Sun, H., Zhou, Y., & Zhang, L. (2021). Short-Term Exposure to Ambient Air Pollution and Mortality From Myocardial Infarction. *J Am Coll Cardiol, 77*(3), 271-281. doi:10.1016/j.jacc.2020.11.033

Llusià, J., Peñuelas, J., Sardans, J., Owen, S. M., & Niinemets, Ü. (2010). Measurement of volatile terpene emissions in 70 dominant vascular plant species in Hawaii: aliens emit more than natives. *Global Ecology and Biogeography, 19*(6), 863-874. doi:10.1111/j.1466-8238.2010.00557.x

Loreto, F., Dicke, M., Schnitzler, J. P., & Turlings, T. C. (2014). Plant volatiles and the environment. *Plant, Cell and Environment 37*(8), 1905-1908. doi:10.1111/pce.12369

Loreto, F., Fischbach, R. J., Schnitzler J.P., Ciccioli, P., Brancaleoni, E., Calfapietra C., & G., S. (2001). Monoterpene emission and monoterpene synthase activities in the Mediterranean evergreen oak Quercus ilex L. grown at elevated CO2 concentrations. *Global Change Biology, 7*(6), 709-717.

Loreto, F., & Schnitzler, J. P. (2010). Abiotic stresses and induced BVOCs. *Trends in Plant Science, 15*(3), 154-166. doi:10.1016/j.tplants.2009.12.006

Lovett, G. M. (1994). Atmospheric Deposition of Nutrients and Pollutants in North America An Ecological Perspective. *Ecological Applications, 4*(4), 629-650.

Lu, J., Li, B., Li, H., & Al-Barakani, A. (2021). Expansion of city scale, traffic modes, traffic congestion, and air pollution. *Cities, 108*, 102974. doi:10.1016/j.cities.2020.102974

Lu, T., Lin, X., Chen, J., Huang, D., & Li, M. (2019). Atmospheric particle retention capacity and photosynthetic responses of three common greening plant species under different pollution levels in Hangzhou. *Global Ecology and Conservation, 20*. doi:10.1016/j.gecco.2019.e00783

Maas, J., Verheij, R. A., de Vries, S., Spreeuwenberg, P., Schellevis, F. G., & Groenewegen, P. P. (2009). Morbidity is related to a green living environment. *J Epidemiol Community Health, 63*(12), 967-973. doi:10.1136/jech.2008.079038

Manchester City Council. (2017). Manchester Tree Action Plan 2016-2020. Retrieved January 2022 https://www.manchester.gov.uk/downloads/download/6838/manchester_green_and_blue_strategy, from Manchester City Council

Marien, B., Marien, B., Nguyen, X. H., Nguyen, T. C., Nguyen, V. S., & Samson, R. (2019). Particulate matter accumulation capacity of plants in Hanoi, Vietnam. *Environmental Pollution, 253*, 1079-1088. doi:10.1016/j.envpol.2019.07.035

Marucci, D., & Carpentieri, M. (2019). Effect of local and upwind stratification on flow and dispersion inside and above a bi-dimensional street canyon. *Building and Environment, 156*, 74-88. doi:10.1016/j.buildenv.2019.04.013

Matsler, A. M., Meerow, S., Mell, I. C., & Pavao-Zuckerman, M. A. (2021). A ‘green’ chameleon: Exploring the many disciplinary definitions, goals, and forms of “green infrastructure”. *Landscape and Urban Planning, 214*, 104145. doi:10.1016/j.landurbplan.2021.104145

Matsunaga, S. N., Niwa, S., Mochizuki, T., Tani, A., Kusumoto, D., Utsumi, Y., Enoki, T., & Hiura, T. (2013). Seasonal variation in basal emission rates and composition of mono- and sesquiterpenes emitted from dominant conifers in Japan. *Atmospheric Environment, 69*, 124-130. doi:10.1016/j.atmosenv.2012.12.004

Matthews, T., Lo, A. Y., & Byrne, J. A. (2015). Reconceptualizing green infrastructure for climate change adaptation: Barriers to adoption and drivers for uptake by spatial planners. *Landscape and Urban Planning, 138*, 155-163. doi:10.1016/j.landurbplan.2015.02.010

Matzka, J., & Maher, B. A. (1999). Magnetic biomonitoring of roadside tree leaves identification of spatial and temporal variations in vehicle-derived particulates. *Atmospheric Environment, 33*, 4565 - 4569.

Maya Manzano, J. M., Fernández-Rodríguez, S., Monroy-Colín, A., Silva-Palacios, I., Tormo-Molina, R., & Gonzalo-Garijo, Á. (2017a). Allergenic pollen of ornamental plane trees in a Mediterranean environment and urban planning as a prevention tool. *Urban Forestry & Urban Greening, 27*, 352-362. doi:10.1016/j.ufug.2017.09.009

Maya Manzano, J. M., Tormo Molina, R., Fernández Rodríguez, S., Silva Palacios, I., & Gonzalo Garijo, Á. (2017b). Distribution of ornamental urban trees and their influence on airborne pollen in the SW of Iberian Peninsula. *Landscape and Urban Planning, 157*, 434-446. doi:10.1016/j.landurbplan.2016.08.011

Mayor of London. (2012). *Green infrastructure and open environments the all London green grid. Supplementary planning guidance*. London

Mayor of London. (2021). Green Infrastructure. November 2021 https://www.london.gov.uk/what-we-do/environment/parks-green-spaces-and-biodiversity/green-infrastructure.

Mayor of London & Partnership members. (2020). London Urban Forest Plan Retrieved January 2021 https://www.london.gov.uk/sites/default/files/londonurbanforestplan_final.pdf

McDonald, R., Kroeger, T., Boucher, T., Longzhu, W., & Salem, R. (2016). *Planting Healthy Air. A global analisis of the role of urban trees in addressing particulate matter pollution and extreme heat*(pp. 128).

McInnes, R. N., Hemming, D., Burgess, P., Lyndsay, D., Osborne, N. J., Skjoth, C. A., Thomas, S., & Vardoulakis, S. (2017). Mapping allergenic pollen vegetation in UK to study environmental exposure and human health. *Science of The Total Environment, 599-600*, 483-499. doi:10.1016/j.scitotenv.2017.04.136

MEA, M., Ecosystem, Assessment,. (2003). *Ecosystems and Human Well-being*. Retrieved from http://pdf.wri.org/ecosystems_human_wellbeing.pdf

Medl, A., Stangl, R., & Florineth, F. (2017). Vertical greening systems – A review on recent technologies and research advancement. *Building and Environment, 125*, 227-239. doi:10.1016/j.buildenv.2017.08.054

Mell, I. (2008). Green Infrastructure: concepts and planning. *FORUM Ejournal by Newcastle University, 8*, 60-80.

Merlier, L., Jacob, J., & Sagaut, P. (2018). Lattice-Boltzmann Large-Eddy Simulation of pollutant dispersion in street canyons including tree planting effects. *Atmospheric Environment, 195*, 89-103. doi:10.1016/j.atmosenv.2018.09.040

Mitchell, R., Maher, B. A., & Kinnersley, R. (2010). Rates of particulate pollution deposition onto leaf surfaces: temporal and inter-species magnetic analyses. *Environmental Pollution, 158*(5), 1472-1478. doi:10.1016/j.envpol.2009.12.029

Mo, L., Ma, Z., Xu, Y., Sun, F., Lun, X., Liu, X., Chen, J., & Yu, X. (2015). Assessing the Capacity of Plant Species to Accumulate Particulate Matter in Beijing, China. *PLoS One, 10*(10), e0140664. doi:10.1371/journal.pone.0140664

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred Reporting Items for Systematic Reviews and MetaAnalyses: The PRISMA Statement. *PLoS Med, 6*(7), e1000097. doi:10.1371/journal.pmed.1000097

Molina, R. T., Rodríguez, A. M., Palaciso, I. S., & López, F. G. (1996). Pollen production in anemophilous trees. *Grana, 35*(1), 38-46. doi:10.1080/00173139609430499

Moonen, P., Gromke, C., & Dorer, V. (2013). Performance assessment of Large Eddy Simulation (LES) for modelling dispersion in an urban street canyon with tree planting. *Atmospheric Environment, 75*, 66-76.

Moore, C. E., Meacham-Hensold, K., Lemonnier, P., Slattery, R. A., Benjamin, C., Bernacchi, C. J., Lawson, T., & Cavanagh, A. P. (2021). The effect of increasing temperature on crop photosynthesis: from enzymes to ecosystems. *J Exp Bot, 72*(8), 2822-2844. doi:10.1093/jxb/erab090

Moradpour, M., Afshin, H., & Farhanieh, B. (2017). A numerical investigation of reactive air pollutant dispersion in urban street canyons with tree planting. *Atmospheric Pollution Research, 8*(2), 253-266. doi:10.1016/j.apr.2016.09.002

Moradpour, M., & Hosseini, V. (2020). An investigation into the effects of green space on air quality of an urban area using CFD modeling. *Urban Climate, 34*, 100686. doi:10.1016/j.uclim.2020.100686

Morakinyo, T., & Lam, Y. (2016a). Simulation study of dispersion and removal of particulate matter from traffic by road-side vegetation barrier. *Environmental Science and Pollution Research, 23*(7), 6709–6722. doi:10.1007/s11356-015-5839-y)

Morakinyo, T., & Lam, Y. (2016b). Study of traffic-related pollutant removal from street canyon with trees: dispersion and deposition perspective. *Environ Sci Pollut Res Int, 23*(21), 21652-21668. doi:10.1007/s11356-016-7322-9

Morakinyo, T. E., Kong, L., Lau, K. K.-L., Yuan, C., & Ng, E. (2017). A study on the impact of shadow-cast and tree species on in-canyon and neighborhood's thermal comfort. *Building and Environment, 115*, 1-17. doi:10.1016/j.buildenv.2017.01.005

Morakinyo, T. E., & Lam, Y. F. (2016c). Study of traffic-related pollutant removal from street canyon with trees: dispersion and deposition perspective. *Environ Sci Pollut Res Int, 23*(21), 21652-21668. doi:10.1007/s11356-016-7322-9

Morakinyo, T. E., Lam, Y. F., & Hao, S. (2016). Evaluating the role of green infrastructures on near-road pollutant dispersion and removal: Modelling and measurement. *Journal of Environmental Management, 182*, 595-605. doi:10.1016/j.jenvman.2016.07.077

Mori, J., Fini, A., Galimberti, M., Ginepro, M., Burchi, G., Massa, D., & Ferrini, F. (2018). Air pollution deposition on a roadside vegetation barrier in a Mediterranean environment: Combined effect of evergreen shrub species and planting density. *Science of The Total Environment, 643*, 725-737. doi:10.1016/j.scitotenv.2018.06.217

Mori, J., Hanslin, H. M., Burchi, G., & Sæbø, A. (2015). Particulate matter and element accumulation on coniferous trees at different distances from a highway. *Urban Forestry & Urban Greening, 14*, 170–177.

Muhammad, S., Wuyts, K., & Samson, R. (2019). Atmospheric net particle accumulation on 96 plant species with contrasting morphological and anatomical leaf characteristics in a common garden experiment. *Atmospheric Environment, 202*, 328-344. doi:10.1016/j.atmosenv.2019.01.015

Muneer, S., Kim, T. H., Choi, B. C., Lee, B. S., & Lee, J. H. (2014). Effect of CO, NOx and SO2 on ROS production, photosynthesis and ascorbate-glutathione pathway to induce Fragariaxannasa as a hyperaccumulator. *Redox Biol, 2*, 91-98. doi:10.1016/j.redox.2013.12.006

Mygind, L., Kjeldsted, E., Hartmeyer, R., Mygind, E., Bolling, M., & Bentsen, P. (2019). Mental, physical and social health benefits of immersive nature-experience for children and adolescents: A systematic review and quality assessment of the evidence. *Health Place, 58*, 102136. doi:10.1016/j.healthplace.2019.05.014

Natural England. (2011). Natural England's Green Infrastructure Guidance (NE176). Retrieved June 2018 http://publications.naturalengland.org.uk/publication/35033

Neft, I., Scungio, M., Culver, N., & Singh, S. (2016). Simulations of aerosol filtration by vegetation: Validation of existing models with available lab data and application to near-roadway scenario. *Aerosol Science and Technology, 50*(9), 937-946. doi:10.1080/02786826.2016.1206653

Ng, W.-Y., & Chau, C.-K. (2012). Evaluating the role of vegetation on the ventilation performance in isolated deep street canyon. *Int. J. Environment and Pollution, 50*(1/2/3/4), 98-110.

Nguyen, T., Yu, X., & Zhang, H. (2014). Deposition of Particulate Matter of Different Size Fractions on Leaf Surfaces and in Epicuticular Waxes of Urban Forest Species in Summer and Fall in Beijing, China. *International Journal of Sciences, 3*, 12-22.

Nieuwenhuijsen, M. J. (2021). Green Infrastructure and Health. *Annu Rev Public Health, 42*, 317-328. doi:10.1146/annurev-publhealth-090419-102511

Nigam, R., Pandya, K., Luis, A. J., Sengupta, R., & Kotha, M. (2021). Positive effects of COVID-19 lockdown on air quality of industrial cities (Ankleshwar and Vapi) of Western India. *Scientific Reports, 11*(1), 4285. doi:10.1038/s41598-021-83393-9

Niinemets, U., Tenhunen, J. D., Harley, P. C., & Steinbrecher, R. (1999). A model of isoprene emission based on energetic requirements for isoprene synthesis and leaf photosynthetic properties for Liquidambar and Quercus. *Plant, Cell & Environment, 22*(11), 1319-1335.

Nikolova, I., Janssen, S., Vos, P., Vrancken, K., Mishra, V., & Berghmans, P. (2011). Dispersion modelling of traffic induced ultrafine particles in a street canyon in Antwerp, Belgium and comparison with observations. *Science of The Total Environment, 412-413*, 336-343. doi:10.1016/j.scitotenv.2011.09.081

North Hertfordshire District Council. (2017). Tree Strategy 2017. Retrieved March 2022 https://www.north-herts.gov.uk/sites/northherts-cms/files/Tree%20Strategy%202017.pdf

Norton, B. A., Coutts, A. M., Livesley, S. J., Harris, R. J., Hunter, A. M., & Williams, N. S. G. (2015). Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. *Landscape and Urban Planning, 134*, 127-138. doi:10.1016/j.landurbplan.2014.10.018

Nowak , D. (1994). Air pollution removal by Chicago's urban forest. In E. G. McPherson, D. Nowak , & R. Rowan (Eds.), *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Cimate Project*.

Nowak, D., & Crane, D. (1998). The Urban Forest Effects (UFORE) model: Quantifying Urban Forest Structure and Functions. *Integrated Tools Proceedings*, 714 - 720.

Nowak, D., Crane, D., & Stevens, J. (2006). Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening, 4*(3-4), 115-123. doi:10.1016/j.ufug.2006.01.007

Nowak, D. J. (2020). Understanding i-Tree: Summary of Programs and Methods. *Forest Services, General Technical Report NRS-200*. doi:10.2737/nrs-gtr-200

Nowak, D. J., Hirabayashi, S., Doyle, M., McGovern, M., & Pasher, J. (2018). Air pollution removal by urban forests in Canada and its effect on air quality and human health. *Urban Forestry & Urban Greening, 29*, 40-48. doi:10.1016/j.ufug.2017.10.019

Oduber, F., Calvo, A. I., Blanco-Alegre, C., Castro, A., Vega-Maray, A. M., Valencia-Barrera, R. M., Fernández-González, D., & Fraile, R. (2019). Links between recent trends in airborne pollen concentration, meteorological parameters and air pollutants. *Agricultural and Forest Meteorology, 264*, 16-26. doi:10.1016/j.agrformet.2018.09.023

Oke, T., Mills, G., Christen, A., & Vogt, J. (2017a). Chapter 2. Concept. In *Urban Climates* (pp. 30 pp (546pp)). Cambridge, United Kingdom ; New York, NY: Cambridge University Press.

Oke, T., Mills, G., Christen, A., & Vogt, J. (2017b). Urban Climates - Chapter 4. Airflow. In (pp. 45pp (546pp)). Cambridge, United Kingdom ; New York, NY: Cambridge University Press.

Oke, T., Mills, G., Christen, A., & Voogt, J. (2017c). Chapter 11. Air Pollution. In *Urban Climates*: Cambridge University Press.

Oke, T., Mills, G., Christen, A., & Voogt, J. (2017d). *Urban Climates*. Cambridge, United Kingdom ; New York, NY: Cambridge University Press.546pp

Omasa, K., Tobe, K., & Kondo, T. (2002). Absorption of Organic and Inorganic Air Pollutants by Plants. In *Air Pollution and Plant Biotechnology* (pp. 155-178).

Onwuegbuzie, A., & Leech, N. (2015). Linking Research Questions to Mixed Methods Data Analysis Procedures 1. *The Qualitative Report*. doi:10.46743/2160-3715/2006.1663

Ordóñez, C. (2021). Governance lessons from Australian local governments for retaining and protecting urban forests as nature based solutions. *Nature-Based Solutions, 1*. doi:10.1016/j.nbsj.2021.100004

Ortolani, C., & Vitale, M. (2016). The importance of local scale for assessing, monitoring and predicting of air quality in urban areas. *Sustainable Cities and Society, 26*, 150-160. doi:10.1016/j.scs.2016.06.001

Ottelé, M. (2011). *The Green Building Envelope: Vertical Greening.* Technical University Delft, Delft.

Ottelé, M., van Bohemen, H. D., & Fraaij, A. L. A. (2010). Quantifying the deposition of particulate matter on climber vegetation on living walls. *Ecological Engineering, 36*(2), 154-162. doi:10.1016/j.ecoleng.2009.02.007

Ottosen, T.-B., & Kumar, P. (2020). The influence of the vegetation cycle on the mitigation of air pollution by a deciduous roadside hedge. *Sustainable Cities and Society, 53*. doi:10.1016/j.scs.2019.101919

Owen, S. M., MacKenzie, A. R., Stewart, H., Donovan, R., & Hewitt, C. N. (2003). Biogenic volatile organic compound (VOC) emission estimates from an urban tree canopy. *Ecological Applications, 13*(4), 927 - 938.

Oxford Council. (2021). Oxford Urban Forest Strategy A Master Plan to 2050. Retrieved January 2022 https://consultation.oxford.gov.uk/policy-and-communications/urban-forest-strategy/supporting_documents/UFS%20Draft%20Final%2024.06.21.pdf

Ozdemir, H. (2019). Mitigation impact of roadside trees on fine particle pollution. *Science of The Total Environment, 659*, 1176-1185.

Paas, B., & Schneider, C. (2016). A comparison of model performance between ENVI-met and Austal2000 for particulate matter. *Atmospheric Environment, 145*, 392-404. doi:10.1016/j.atmosenv.2016.09.031

Pacifico, F., Harrison, S. P., Jones, C. D., & Sitch, S. (2009). Isoprene emissions and climate. *Atmospheric Environment, 43*, 6121 - 6135. doi:10.1016/j.atmosenv.2009.09.002

Pallares-Barbera, M., Badia, A., & Duch, J. (2011). Cerdà and Barcelona: The need for a new city and service provision. *Urbani izziv, 22*(2), 122-136. doi:10.5379/urbani-izziv-en-2011-22-02-005

Pant, P., & Harrison, R. M. (2013). Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: A review. *Atmospheric Environment, 77*, 78-97. doi:10.1016/j.atmosenv.2013.04.028

Pataki, D. E., Alberti, M., Cadenasso, M. L., Felson, A. J., McDonnell, M. J., Pincetl, S., Pouyat, R. V., Setälä, H., & Whitlow, T. H. (2021). The Benefits and Limits of Urban Tree Planting for Environmental and Human Health. *Frontiers in Ecology and Evolution, 9*. doi:10.3389/fevo.2021.603757

Paull, N. J., Krix, D., Irga, P. J., & Torpy, F. R. (2020). Airborne particulate matter accumulation on common green wall plants. *International Journal of Phytoremediation, 22*(6), 594-606. doi:10.1080/15226514.2019.1696744

Pearce, H., Levine, J. G., Cai, X., & MacKenzie, A. R. (2021). Introducing the Green Infrastructure for Roadside Air Quality (GI4RAQ) Platform: Estimating Site-Specific Changes in the Dispersion of Vehicular Pollution Close to Source. *Forests, 12*(6), 769. doi:10.3390/f12060769

Peñuelas, J., & Staudt, M. (2010). BVOCs and global change. *Trends in Plant Science, 15*(3), 133-144. doi:10.1016/j.tplants.2009.12.005

Perini, K., Chokhachian, A., Dong, S., & Auer, T. (2017). Modeling and simulating urban outdoor comfort: Coupling ENVI-Met and TRNSYS by grasshopper. *Energy and Buildings, 152*, 373-384. doi:10.1016/j.enbuild.2017.07.061

Personal Communication ENVI-met (2020, 5 August). [Wind speed inside a street canyon].

Personal Communication Gromke C. (2020, 6 October). [More information about CODASC].

Pianosi, F. (2014). Computational Models for Environmental Systems. In S. V. Amigoni F. (Ed.), *Methods and Experimental Techniques in Computer Engineering*: SpringerBriefs in Applied Sciences and Technology. Springer, Cham.

Pietzarka, U. (2016). Chapter 11. Tree pruning: method and parameters. In A. Roloff (Ed.), *Urban Tree Management for the sustainanle development of green cities* (pp. 154 - 168). UK: John Wiley & Sons. Ltd.

Popek, R., Gawronska, H., & Gawronski, S. W. (2015). The Level of Particulate Matter on Foliage Depends on the Distance from the Source of Emission. *International Journal of Phytoremediation, 17*(12), 1262-1268. doi:10.1080/15226514.2014.989312

Popek, R., Gawronska, H., Wrochna, M., Gawronski, S. W., & Saebo, A. (2013). Particulate matter on foliage of 13 woody species: deposition on surfaces and phytostabilisation in waxes a 3-year study. *International Journal of Phytoremediation, 15*(3), 245-256. doi:10.1080/15226514.2012.694498

Popek, R., Łukowski, A., & Karolewski, P. (2017). Particulate matter accumulation – further differences between native Prunus padusand non-native P. serotina. *Dendrobiology, 78*, 85-95. doi:10.12657/denbio.078.009

Power, S. A., & Collins, C. M. (2010). Use of Calluna vulgaris to detect signals of nitrogen deposition across an urban–rural gradient. *Atmospheric Environment, 44*(14), 1772-1780. doi:10.1016/j.atmosenv.2010.01.034

Prendez, M., Carvajal, V., Corada, K., Morales, J., Alarcon, F., & Peralta, H. (2013). Biogenic volatile organic compounds from the urban forest of the Metropolitan Region, Chile. *Environmental Pollution, 183*, 143 - 150.

Pretzsch, J. (2016). Governance in urban forestry. In A. Roloff (Ed.), *Urban Tree Management for the Sustainable Development of Green Cities* (1st ed., pp. 221 - 235). Chichester, West Sussex, UK: John Wiley & Sons., Ltd.

Przybysz, A., Saebo, A., Hanslin, H. M., & Gawronski, S. W. (2014). Accumulation of particulate matter and trace elements on vegetation as affected by pollution level, rainfall and the passage of time. *Science of The Total Environment, 481*, 360-369. doi:10.1016/j.scitotenv.2014.02.072

Pugh, T. A., Mackenzie, A. R., Whyatt, J. D., & Hewitt, C. N. (2012a). Effectiveness of green infrastructure for improvement of air quality in urban street canyons. *Environmental Science & Technology, 46*(14), 7692-7699. doi:10.1021/es300826w

Pugh, T. A. M., Cain, M., Methven, J., Wild, O., Arnold, S. R., Real, E., Law, K. S., Emmerson, K. M., Owen, S. M., Pyle, J. A., Hewitt, C. N., & MacKenzie, A. R. (2012b). A Lagrangian model of air-mass photochemistry and mixing using a trajectory ensemble: the Cambridge Tropospheric Trajectory model of Chemistry And Transport (CiTTyCAT) version 4.2. *Geoscientific Model Development, 5*(1), 193-221. doi:10.5194/gmd-5-193-2012

Qin, H., Hong, B., & Jiang, R. (2018). Are Green Walls Better Options than Green Roofs for Mitigating PM10 Pollution? CFD Simulations in Urban Street Canyons. *Sustainability, 10*(8), 2833. doi:10.3390/su10082833

Rafael, S., Vicente B., Rodrigues V., Miranda A.I., Borrego C., & M., L. (2018). Impacts of green infrastructures on aerodynamic flow and air quality in Porto's urban area. *Atmospheric Environment, 190*, 317-330.

Rai, P. K. (2016). Impacts of particulate matter pollution on plants: Implications for environmental biomonitoring. *Ecotoxicology and Environmental Safety, 129*, 120-136. doi:10.1016/j.ecoenv.2016.03.012

Ramyar, R., Ackerman, A., & Johnston, D. M. (2021). Adapting cities for climate change through urban green infrastructure planning. *Cities, 117*, 103316. doi:10.1016/j.cities.2021.103316

Räsänen, J. V., Holopainen, T., Joutsensaari, J., Ndam, C., Pasanen, P., Rinnan, A., & Kivimäenpää, M. (2013). Effects of species-specific leaf characteristics and reduced water availability on fine particle capture efficiency of trees. *Environmental Pollution, 183*, 64-70.

Reading Borough Council. (2021). Tree Strategy March 2021. Retrieved January 2022 https://images.reading.gov.uk/2021/03/Tree-Strategy-March-2021.pdf

Reid, W., Mooney, H., Cropper, A., Capistrano, D., Carpenter, S., Chopra, K., Dasgupta, P., Dietz, T., Kumar Duraiappah, A., Hassan, R., Kasperson, R., Leemans, R., May, R. M., McMichael, T. A. J., Pingali, P., Samper, C., Scholes, R., Watson, R. T., Zakri, A. H., Shidong, Z., Ash, N. J., Bennett, E., Kumar, P., Lee, M. J., Raudsepp-Hearne, C., Simons, H., Thonell, J., & Zurek, M. B. (Eds.). (2005). *Ecosystems and Human Well-being: Synthesis*. Washington, DC.

Ridge, I. (2002). *Plants*: Oxford : Oxford University Press.345 pp

Ries, K., & Eichhorn, J. (2001). Simulation of effects of vegetation on the dispersion of pollutants in street canyons. *Meteorol.*, 1-5.

Riondato, E., Pilla, F., Sarkar Basu, A., & Basu, B. (2020). Investigating the effect of trees on urban quality in Dublin by combining air monitoring with i-Tree Eco model. *Sustainable Cities and Society, 61*, 102356. doi:10.1016/j.scs.2020.102356

Rogers, K., Sacre, K., Goodenough, J., & Doick, K. (2015). *Valuing London's Urban Forest. Results of the London i-Tree Eco Project*. In T. London (Ed.), (pp. 43). Retrieved from https://www.london.gov.uk/sites/default/files/valuing_londons_urban_forest_i-tree_report_final.pdf

Saebo, A., Popek, R., Nawrot, B., Hanslin, H. M., Gawronska, H., & Gawronski, S. W. (2012). Plant species differences in particulate matter accumulation on leaf surfaces. *Science of The Total Environment, 427-428*, 347–354. doi:10.1016/j.scitotenv.2012.03.084

Salim, S. M., Buccolieri, R., Chan, A., Di Sabatino, S., & Cheah, S. C. (2011a). Large eddy simulation of the aerodynamic effects of trees on pollutant concentrations in street canyons. *Procedia Environmental Sciences, 4*, 17-24. doi:10.1016/j.proenv.2011.03.003

Salim, S. M., Cheah, S. C., & Chan, A. (2011b). Numerical simulation of dispersion in urban street canyons with avenue-like tree plantings: Comparison between RANS and LES. *Building and Environment, 46*(9), 1735-1746. doi:10.1016/j.buildenv.2011.01.032

Salmond, J. A., Williams, D. E., Laing, G., Kingham, S., Dirks, K., Longley, I., & Henshaw, G. S. (2013). The influence of vegetation on the horizontal and vertical distribution of pollutants in a street canyon. *Science of The Total Environment, 443*, 287-298. doi:10.1016/j.scitotenv.2012.10.101

Sandifer, P. A., Sutton-Grier, A. E., & Ward, B. P. (2015). Exploring connections among nature, biodiversity, ecosystem services, and human health and well-being: Opportunities to enhance health and biodiversity conservation. *Ecosystem Services, 12*, 1-15. doi:10.1016/j.ecoser.2014.12.007

Santasusagna Riu, A., Tort Donada, J., Vadrí Fortuny, M. T., & Paül Carril, V. (2021). Estimating public space metrics from nineteenth-century urban cartography: Barcelona's Cerdà Plan of urban expansion. *Environment and Planning B: Urban Analytics and City Science, 48*(9), 2640-2655. doi:10.1177/2399808320987562

Santiago, J.-L., Buccolieri, R., Rivas, E., Calvete-Sogo, H., Sanchez, B., Martilli, A., Alonso, R., Elustondo, D., Santamaría, J. M., & Martin, F. (2019). CFD modelling of vegetation barrier effects on the reduction of traffic-related pollutant concentration in an avenue of Pamplona, Spain. *Sustainable Cities and Society, 48*, 101559. doi:10.1016/j.scs.2019.101559

Sasmita, D., & Pramila, P. (2012). Particulate Matter Capturing Ability of Some Plant Species Implication for for phytoremediation of particulate pollution around Rourkela Steel Plant, Rourkela, India. *Nature Environment and Pollution Technology, 11*(4), 657-665.

Schatzmann, Olesen, & Franke. (2010). *COST 732 Model Evaluation Case Studies: Approach and results*. Retrieved from Hamburg, Germany: https://www.cost.eu/publication/cost-732-model-evaluation-case-studies-approach-and-results/

Schroeder, H., Flannigan, J., & Coles, R. (2006). Residents' Attitudes Toward Street Trees in the UK and US Communities. *Arboriculture & Urban Forestry, 32*(5), 236 - 246.

Sedghy, F., Varasteh, A. R., Sankian, M., & Moghadam, M. (2018). Interaction Between Air Pollutants and Pollen Grains The Role on the Rising Trend in Allergy. *Reports of Biochemistry & Molecular Biology, 6*(2), 219 - 224.

SEG. (2014). *Systems Engineering Guide, Verification and Validation of Simulation Models*. In M. Corporation (Ed.), (pp. 461 - 469). Retrieved from https://www.mitre.org/sites/default/files/publications/se-guide-book-interactive.pdf

Seinfeld, J. H., & Pandis, S. N. (2016). *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change.* (3rd ed.). US: Wiley.1120 pp

Selmi, W., Weber, C., Rivière, E., Blond, N., Mehdi, L., & Nowak, D. (2016). Air pollution removal by trees in public green spaces in Strasbourg city, France. *Urban Forestry & Urban Greening, 17*, 192-201. doi:10.1016/j.ufug.2016.04.010

Senechal, H., Visez, N., Charpin, D., Shahali, Y., Peltre, G., Biolley, J. P., Lhuissier, F., Couderc, R., Yamada, O., Malrat-Domenge, A., Pham-Thi, N., Poncet, P., & Sutra, J. P. (2015). A Review of the Effects of Major Atmospheric Pollutants on Pollen Grains, Pollen Content, and Allergenicity. *Scientific World Journal, 2015*, 940243. doi:10.1155/2015/940243

Sett, R. (2017). Responses in Plants Exposed to Dust Pollution. *Horticulture International Journal 1*(2), 53–56. doi:10.15406/hij.2017.01.00010

Sgrigna, G., Baldacchini, C., Esposito, R., Calandrelli, R., Tiwary, A., & Calfapietra, C. (2016). Characterization of leaf-level particulate matter for an industrial city using electron microscopy and X-ray microanalysis. *Science of The Total Environment, 548-549*, 91-99. doi:10.1016/j.scitotenv.2016.01.057

Sgrigna, G., Saebo, A., Gawronski, S., Popek, R., & Calfapietra, C. (2015). Particulate Matter deposition on Quercus ilex leaves in an industrial city of central Italy. *Environmental Pollution, 197*, 187-194. doi:10.1016/j.envpol.2014.11.030

Shabnam, N., Oh, J., Park, S., & Kim, H. (2021). Impact of particulate matter on primary leaves of Vigna radiata (L.) R. Wilczek. *Ecotoxicology and Environmental Safety, 212*, 111965. doi:10.1016/j.ecoenv.2021.111965

Shan, Y., Jingping, C., Liping, C., Zhemin, S., Xiaodong, Z., Dan, W., & Wenhua, W. (2007). Effects of vegetation status in urban green spaces on particle removal in a street canyon atmosphere. *Acta Ecologica Sinica, 27*(11), 4590-4595. doi:10.1016/s1872-2032(08)60007-4

Shao, F., Wang, L., Sun, F., Li, G., Yu, L., Wang, Y., Zeng, X., Yan, H., Dong, L., & Bao, Z. (2019). Study on different particulate matter retention capacities of the leaf surfaces of eight common garden plants in Hangzhou, China. *Science of The Total Environment, 652*, 939-951. doi:10.1016/j.scitotenv.2018.10.182

Shi, J., Zhang, G., An, H., Yin, W., & Xia, X. (2017). Quantifying the particulate matter accumulation on leaf surfaces of urban plants in Beijing, China. *Atmospheric Pollution Research, 8*(5), 836-842. doi:10.1016/j.apr.2017.01.011

Sicard, P., Agathokleous, E., Araminiene, V., Carrari, E., Hoshika, Y., De Marco, A., & Paoletti, E. (2018). Should we see urban trees as effective solutions to reduce increasing ozone levels in cities? *Environmental Pollution, 243*, 163-176. doi:10.1016/j.envpol.2018.08.049

Sienfeld, J., & Pandis, S. (2016a). Chapter 19. Dry deposition. In *Atmopsheric Chemistry nad Physics: From air pollution to climate change* (3rd ed., pp. 1120): John Wiley & Sons, Inc.

Sienfeld, J., & Pandis, S. (2016b). Chapter 20. Wet deposition. In *Atmopsheric Chemistry and Physics: From air pollution to climate change* (3rd ed., pp. 1120): John Wiley & Sons, Inc.

Simonich, S., & Hites, R. (1995). Organic pollutant accumulation in vegetation. *Environmental Science & Technology, 29*(12), 2905-2914. doi:10.1021/es00012a004,

Sindelarova, K., Granier, C., Bouarar, I., Guenther, A., Tilmes, S., Stavrakou, T., Müller, J. F., Kuhn, U., Stefani, P., & Knorr, W. (2014). Global data set of biogenic VOC emissions calculated by the MEGAN model over the last 30 years. *Atmospheric Chemistry and Physics, 14*(17), 9317-9341. doi:10.5194/acp-14-9317-2014

Sinnett, D., Williams, K., Lindsay, M., & Dair, C. (2015). The influences of neighbourhood design and quality on resident's use of public open space. In D. Sinnett, N. Smith, & S. Burgess (Eds.), *Handbook on Green Infrastructure, Planning, Design and Implementation* (pp. 260 - 280). UK: Elgar publishing /inc.

Skjoth, C. A., Sommer, J., Stach, A., Smith, M., & Brandt, J. (2007). The long-range transport of birch (Betula) pollen from Poland and Germany causes significant pre-season concentrations in Denmark. *Clinical and Experimental Allergy, 37*(8), 1204–1212. doi:10.1111/j.1365-2222.2007.02771.x

Smith, A., Coupland, G., Dolan, L., Harberd, N., Jones, J., Martin, C., Sablowski, R., & Amey, A. (2010). *Plant Biology*. New York, NY, USA and Abingdon, UK: Garland Science, Taylor & Francis Group.680 pp

Smith, K., & Jones, K. (2000). Particles and vegetation implications for the transfer of particle-bound organic contaminants to vegetation. *The Science of the Total Environment, 246*, 207-236.

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research, 104*, 333-339. doi:10.1016/j.jbusres.2019.07.039

Song, Y., Maher, B. A., Li, F., Wang, X., Sun, X., & Zhang, H. (2015). Particulate matter deposited on leaf of five evergreen species in Beijing, China: Source identification and size distribution. *Atmospheric Environment, 105*, 53-60.

Speak, A., Escobedo, F. J., Russo, A., & Zerbe, S. (2018). An ecosystem service-disservice ratio: Using composite indicators to assess the net benefits of urban trees. *Ecological Indicators, 95*, 544-553. doi:10.1016/j.ecolind.2018.07.048

Speak, A. F., Rothwell, J. J., Lindley, S. J., & Smith, C. L. (2012). Urban particulate pollution reduction by four species of green roof vegetation in a UK city. *Atmospheric Environment, 61*, 283-293. doi:10.1016/j.atmosenv.2012.07.043

Stabile, L., Arpino, F., Buonanno, G., Russi, A., & Frattolillo, A. (2015). A simplified benchmark of ultrafine particle dispersion in idealized urban street canyons: A wind tunnel study. *Building and Environment, 93*, 186-198. doi:10.1016/j.buildenv.2015.05.045

Stas, M., Aerts, R., Hendrickx, M., Dendoncker, N., Dujardin, S., Linard, C., Nawrot, T. S., Van Nieuwenhuyse, A., Aerts, J.-M., Van Orshoven, J., & Somers, B. (2021). Residential green space types, allergy symptoms and mental health in a cohort of tree pollen allergy patients. *Landscape and Urban Planning, 210*, 104070. doi:10.1016/j.landurbplan.2021.104070

Steffens, J. T., Wang, Y. J., & Zhang, K. M. (2012). Exploration of effects of a vegetation barrier on particle size distributions in a near-road environment. *Atmospheric Environment, 50*, 120-128. doi:10.1016/j.atmosenv.2011.12.051

Steinbrecher, R., Smiatek, G., Köble, R., Seufert, G., Theloke, J., Hauff, K., Ciccioli, P., Vautard, R., & Curci, G. (2009). Intra- and inter-annual variability of VOC emissions from natural and semi-natural vegetation in Europe and neighbouring countries. *Atmospheric Environment, 43*(7), 1380-1391. doi:10.1016/j.atmosenv.2008.09.072

Sternberg, T., Viles, H., Cathersides, A., & Edwards, M. (2010). Dust particulate absorption by ivy (Hedera helix L) on historic walls in urban environments. *Science of The Total Environment, 409*(1), 162-168. doi:10.1016/j.scitotenv.2010.09.022

Stockemer, D. (2019). A Short Introduction to Survey Research. In *Quantitative Methods for the Social Sciences A Practical Introduction with Examples in SPSS and Stata* (1st ed., pp. 23 - 35): Springer International Publishing.

Stone, E. A., Mampage, C. B. A., Hughes, D. D., & Jones, L. M. (2021). Airborne sub-pollen particles from rupturing giant ragweed pollen. *Aerobiologia, 37*(3), 625-632. doi:10.1007/s10453-021-09702-x

Su, J., Wang, L., Gu, Z., Song, M., & Cao, Z. (2019). Effects of real trees and their structure on pollutant dispersion and flow field in an idealized street canyon. *Atmospheric Pollution Research, 10*(6), 1699-1710. doi:10.1016/j.apr.2019.07.001

Sullivan, G. M., & Artino, A. R., Jr. (2013). Analyzing and interpreting data from likert-type scales. *Journal of Graduate Medical Education, 5*(4), 541-542. doi:10.4300/JGME-5-4-18

Takano, Y., & Moonen, P. (2013). On the influence of roof shape on flow and dispersion in an urban street canyon. *Journal of Wind Engineering and Industrial Aerodynamics, 123*, 107-120. doi:10.1016/j.jweia.2013.10.006

Taleghani, M., Clark, A., Swan, W., & Mohegh, A. (2020). Air pollution in a microclimate; the impact of different green barriers on the dispersion. *Science of The Total Environment, 711*, 134649. doi:10.1016/j.scitotenv.2019.134649

Tallis, M., Amorim, J. H., Calfapietra, C., Freer-Smith, P. H., Grimmond, S., Kotthaus, S., Lemes de Oliveira, F., Miranda, A. I., & Toscano, P. (2015). The impacts of green infrastructures on air quality and temperature. In D. Sinnett, N. Smith, & S. Burgess (Eds.), *Handbook on Green Infrastructure, Planning, Desing and Implementation* (pp. 30-49). UK: Edward Elgar Publishing, Inc.

Tallis, M., Taylor, G., Sinnett, D., & Freer-Smith, P. (2011). Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments. *Landscape and Urban Planning, 103*(2), 129-138. doi:10.1016/j.landurbplan.2011.07.003

Tan, X., & Shibata, S. (2022). Factors influencing street tree health in constrained planting spaces: Evidence from Kyoto City, Japan. *Urban Forestry & Urban Greening, 67*, 127416. doi:10.1016/j.ufug.2021.127416

Taylor, L., & Hochuli, D. F. (2017). Defining greenspace: Multiple uses across multiple disciplines. *Landscape and Urban Planning, 158*, 25-38. doi:10.1016/j.landurbplan.2016.09.024

Threlfall, C. G., Mata, L., Mackie, J. A., Hahs, A. K., Stork, N. E., Williams, N. S. G., Livesley, S. J., & Beggs, J. (2017). Increasing biodiversity in urban green spaces through simple vegetation interventions. *Journal of Applied Ecology, 54*(6), 1874-1883. doi:10.1111/1365-2664.12876

Tiwari, A., & Kumar, P. (2020). Integrated dispersion-deposition modelling for air pollutant reduction via green infrastructure at an urban scale. *Science of The Total Environment, 723*, 138078. doi:10.1016/j.scitotenv.2020.138078

Tiwari, A., Kumar, P., Baldauf, R., Zhang, K. M., Pilla, F., Di Sabatino, S., Brattich, E., & Pulvirenti, B. (2019). Considerations for evaluating green infrastructure impacts in microscale and macroscale air pollution dispersion models. *Science of The Total Environment, 672*, 410-426. doi:10.1016/j.scitotenv.2019.03.350

Tiwary, A., Reff, A., & Colls, J. J. (2008). Collection of ambient particulate matter by porous vegetation barriers: Sampling and characterization methods. *Journal of Aerosol Science, 39*(1), 40-47. doi:10.1016/j.jaerosci.2007.09.011

Tiwary, A., Sinnett, D., Peachey, C., Chalabi, Z., Vardoulakis, S., Fletcher, T., Leonardi, G., Grundy, C., Azapagic, A., & Hutchings, T. R. (2009). An integrated tool to assess the role of new planting in PM10 capture and the human health benefits: a case study in London. *Environmental Pollution, 157*(10), 2645-2653. doi:10.1016/j.envpol.2009.05.005

Tiwary, A., Williams, I., & Colls, J. (2019a). *Air Pollution Measurement, Modelling and Mitigation,* (4th ed.): CRC Press Taylor & Francis Group.722 pp

Tiwary, A., Williams, I., & Colls, J. (2019b). Chapter 6. Ambient air quality. In *Air Pollution, Measurement, Modelling and Mitigation* (4th ed., pp. 229 - 287). US: CRC Press Taylor & Francis Group.

Tiwary, A., Williams, I., & Colls, J. (2019c). Chapter 7. Indoor Air Quality. In C. P. T. F. Group. (Ed.), *Air Pollution, Measurement, Modelling and Mitigation* (4th ed., pp. 313-359). US.

Tiwary, A., Williams, I., & Colls, J. (2019d). Chapter 8. Air pollution modelling. In C. P. T. F. Group. (Ed.), *Air Pollution, Measurement, Modelling and Mitigation* (4th ed., pp. 313-359). US.

Tiwary, A., Williams, I., & Colls, J. (2019e). Chapter 10. Air pollution impacts. In *Air Pollution, Measurement, Modelling and Mitigation* (4th ed.). U.S.: CRC Press Taylor & Francis Group.

Todorova, A., Asakawa, S., & Aikoh, T. (2004). Preferences for and attitudes towards street flowers and trees in Sapporo, Japan. *Landscape and Urban Planning, 69*(4), 403-416. doi:10.1016/j.landurbplan.2003.11.001

Tomson, M., Kumar, P., Barwise, Y., Perez, P., Forehead, H., French, K., Morawska, L., & Watts, J. F. (2021). Green infrastructure for air quality improvement in street canyons. *Environment International, 146*, 106288. doi:10.1016/j.envint.2020.106288

Tong, Z., Baldauf, R. W., Isakov, V., Deshmukh, P., & Zhang, K. M. (2016). Roadside vegetation barrier designs to mitigate near-road air pollution impacts. *Science of The Total Environment, 541*, 920–927.

Tower Hamlets Council. (2021). History. January 2021 https://www.towerhamlets.gov.uk/lgnl/leisure_and_culture/parks_and_open_spaces/victoria_park/history.aspx.

Traidl-Hoffmann, C., Kasche, A., Menzel, A., Jakob, T., Thiel, M., Ring, J., & Behrendt, H. (2003). Impact of pollen on human health: more than allergen carriers? *Int Arch Allergy Immunol, 131*(1), 1-13. doi:10.1159/000070428

Trees & Design Action Group, T. (2012). Trees in the townscape A guide for decision makers. *https://www.tdag.org.uk/uploads/4/2/8/0/4280686/tdag_treestownscape2021.pdf*.

Trees & Desing Action Group. (2012). *Trees in the Townscape A Guide for Decision Makers*. UK: Trees & Desing Action Group.84 pp

Trees & Desing Action Group. (2021). *Trees, Planning and Development. A guide for delivery. Issue 1.1/2021*. Retrieved from https://www.tdag.org.uk/trees-planning-and-development.html

Tsoka, S., Tsikaloudaki, A., & Theodosiou, T. (2018). Analyzing the ENVI-met microclimate model's performance and assessing cool materials and urban vegetation applications–A review. *Sustainable Cities and Society, 43*, 55-76. doi:10.1016/j.scs.2018.08.009

UK Government. (2021). *The England Trees Action Plan 2021-2024*. Retrieved from London, UK: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/987432/england-trees-action-plan.pdf

UN DESA. (2019a). *Department of Economic and Social Affairs, Population Division, World Population Prospects 2019, ST/ESA/SER.A/423, 46 pp*. Retrieved from https://population.un.org/wpp/publications/files/wpp2019_highlights.pdf

UN DESA. (2019b). World Urbanization Prospects: The 2018 Revision. *United Nations Department of Economic and Social Affairs (UN DESA) Population Division.* 15th September 2021. Retrieved from https://population.un.org/wup/

University of Hamburg, -. E. E. W. T. L. (2013). Measuring protocol wind tunnels. February 2021 https://www.rivm.nl/bibliotheek/rapporten/680705029.pdf.

Van Renterghem, T., & Botteldooren, D. (2016). View on outdoor vegetation reduces noise annoyance for dwellers near busy roads. *Landscape and Urban Planning, 148*, 203-215. doi:10.1016/j.landurbplan.2015.12.018

Van Selm, M., & Jankowski, N. W. (2006). Conducting Online Surveys. *Quality and Quantity, 40*(3), 435-456. doi:10.1007/s11135-005-8081-8

Vardoulakis, S., Fisher, B. E. A., Koulis, P., & Gonzalez-Flesca, N. (2003). Modelling air quality in street canyons a review. *Atmospheric Environment, 31*, 155-182.

Vaz Monteiro, M., Handley, P., Morison, J., & Doick, K. (2019). *The role of urban trees and greenspaces in reducing urban air temperatures*. Retrieved from UK: https://www.thenbs.com/PublicationIndex/documents/details?Pub=FC&DocID=324879

Velasquez, C. D., Canon Barriga, J. E., & Hoyos Rincon, I. C. (2021). The removal of PM2.5 by trees in tropical Andean metropolitan areas: an assessment of environmental change scenarios. *Environ Monit Assess, 193*(7), 396. doi:10.1007/s10661-021-09171-2

Versteeg, H. K., & Malalasekera, W. (2007). *An Introduction to Computational Fluid Dynamics, Chapter I: Introduction* (2nd ed.)

von Döhren, P., & Haase, D. (2015). Ecosystem disservices research: A review of the state of the art with a focus on cities. *Ecological Indicators, 52*, 490-497. doi:10.1016/j.ecolind.2014.12.027

Voordeckers, D., Lauriks, T., Denys, S., Billen, P., Tytgat, T., & Van Acker, M. (2021). Guidelines for passive control of traffic-related air pollution in street canyons: An overview for urban planning. *Landscape and Urban Planning, 207*, 103980. doi:10.1016/j.landurbplan.2020.103980

Vos, P. E., Maiheu, B., Vankerkom, J., & Janssen, S. (2013). Improving local air quality in cities: to tree or not to tree? *Environ Pollut, 183*, 113-122. doi:10.1016/j.envpol.2012.10.021

Vranckx, S., Vos, P., Maiheu, B., & Janssen, S. (2015). Impact of trees on pollutant dispersion in street canyons: A numerical study of the annual average effects in Antwerp, Belgium. *Science of The Total Environment, 532*, 474-483. doi:10.1016/j.scitotenv.2015.06.032

Wang, C., Li, Q., & Wang, Z.-H. (2018). Quantifying the impact of urban trees on passive pollutant dispersion using a coupled large-eddy simulation–Lagrangian stochastic model. *Building and Environment, 145*, 33-49. doi:10.1016/j.buildenv.2018.09.014

Wang, H., Shi, H., Li, Y., Yu, Y., & Zhang, J. (2013). Seasonal variations in leaf capturing of particulate matter, surface wettability and micromorphology in urban tree species. *Frontiers of Environmental Science & Engineering, 7*(4), 579-588. doi:10.1007/s11783-013-0524-1

Wang, H., Shi, H., & Wang, Y. (2015a). Effects of weather, time, and pollution level on the amount of particulate matter deposited on leaves of Ligustrum lucidum. *Scientific World Journal, 2015*, 935942. doi:10.1155/2015/935942

Wang, H., Zhou, W., Wang, X., Gao, F., Zheng, H., Tong, L., & Ouyang, Z. (2012). Ozone uptake by adult urban trees based on sap flow measurement. *Environmental Pollution, 162*, 275-286. doi:10.1016/j.envpol.2011.11.026

Wang, L., Gong, H., Liao, W., & Wang, Z. (2015b). Accumulation of particles on the surface of leaves during leaf expansion. *Science of The Total Environment, 532*, 420-434. doi:10.1016/j.scitotenv.2015.06.014

Wang, L., Su, J., Gu, Z., & Tang, L. (2021). Numerical study on flow field and pollutant dispersion in an ideal street canyon within a real tree model at different wind velocities. *Computers & Mathematics with Applications, 81*, 679-692. doi:10.1016/j.camwa.2019.12.026

Wania, A., Bruse, M., Blond, N., & Weber, C. (2012). Analysing the influence of different street vegetation on traffic-induced particle dispersion using microscale simulations. *Journal of Environmental Management, 94*(1), 91-101. doi:10.1016/j.jenvman.2011.06.036

Wannia, A. (2007). *Urban vegetation - detection and function evaluation for air quality assessment.* (PhD). l'Université Louis Pasteur, Strasbourg.

Weber, F., Kowarik, I., & Saumel, I. (2014). Herbaceous plants as filters: immobilization of particulates along urban street corridors. *Environmental Pollution, 186*, 234-240. doi:10.1016/j.envpol.2013.12.011

Weerakkody, U., Dover, J. W., Mitchell, P., & Reiling, K. (2017). Particulate matter pollution capture by leaves of seventeen living wall species with special reference to rail-traffic at a metropolitan station. *Urban Forestry & Urban Greening, 27*, 173-186. doi:10.1016/j.ufug.2017.07.005

Weerakkody, U., Dover, J. W., Mitchell, P., & Reiling, K. (2018). Quantification of the traffic-generated particulate matter capture by plant species in a living wall and evaluation of the important leaf characteristics. *Science of The Total Environment, 635*, 1012-1024. doi:10.1016/j.scitotenv.2018.04.106

Weerakkody, U., Dover, J. W., Mitchell, P., & Reiling, K. (2019). Topographical structures in planting design of living walls affect their ability to immobilise traffic-based particulate matter. *Science of The Total Environment, 660*, 644-649.

White Rose Forest. (2021). Planting for our future. White Rose Forest Action Plan 2021-2025. *North and West Yorkshire*, 21. Retrieved from https://whiteroseforest.org/about/actionplan/

WHO. (2017). *Urban green spaces: a brief for action*. Retrieved from Copenhagen, Denmark: https://www.euro.who.int/__data/assets/pdf_file/0010/342289/Urban-Green-Spaces_EN_WHO_web3.pdf

WHO. (2021a). Ambient (outdoor) air pollution. November 2021 https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health.

WHO. (2021b). *WHO global air quality guidelines. Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide.* Retrieved from Geneva: https://apps.who.int/iris/bitstream/handle/10665/345329/9789240034228-eng.pdf?sequence=1&isAllowed=y

Wieser, G., Matyssek, R., Köstner, B., & Oberhuber, W. (2003). Quantifying ozone uptake at the canopy level of spruce, pine and larch trees at the alpine timberline: an approach based on sap flow measurement. *Environmental Pollution, 126*(1), 5-8. doi:10.1016/s0269-7491(03)00184-2

Wilkinson, M. J., Monson, R. K., Trahan, N., Lee, S., Brown, E., Jackson, R. B., Polley, H. W., Fay, P. A., & Fall, R. A. Y. (2009). Leaf isoprene emission rate as a function of atmospheric CO2 concentration. *Global Change Biology, 15*(5), 1189-1200. doi:10.1111/j.1365-2486.2008.01803.x

Winner, W., & Atkinson, C. (1986). Absorption of air pollution by plants, and consequences for growth. *Trends in Ecology & Evolution, 1*(1), 15 - 18.

Womiloju, T. O., Miller, J. D., Mayer, P. M., & Brook, J. R. (2003). Methods to determine the biological composition of particulate matter collected from outdoor air. *Atmospheric Environment, 37*(31), 4335-4344. doi:10.1016/s1352-2310(03)00577-6

Woodland trust. (2022). Plant trees. April 2022 https://www.woodlandtrust.org.uk/trees-woods-and-wildlife/british-trees/.

Wooster, E. I. F., Fleck, R., Torpy, F., Ramp, D., & Irga, P. J. (2022). Urban green roofs promote metropolitan biodiversity: A comparative case study. *Building and Environment, 207*, 108458. doi:10.1016/j.buildenv.2021.108458

Wright, H. (2011). Understanding green infrastructure: the development of a contested concept in England. *Local Environment, 16*(10), 1003-1019. doi:10.1080/13549839.2011.631993

Wu, C. D., MacNaughton, P., Melly, S., Lane, K., Adamkiewicz, G., Durant, J. L., Brugge, D., & Spengler, J. D. (2014). Mapping the vertical distribution of population and particulate air pollution in a near-highway urban neighborhood: implications for exposure assessment. *Journal of Exposure Science and Environmental Epidemiology, 24*(3), 297-304. doi:10.1038/jes.2013.64

Wu, H., & Leung, S.-O. (2017). Can Likert Scales be Treated as Interval Scales?—A Simulation Study. *Journal of Social Service Research, 43*(4), 527-532. doi:10.1080/01488376.2017.1329775

Wu, Y., Hao J., Fu L., Wang Z., & U., T. (2002). Vertical and horizontal profiles of airborne particulate matter near major roads in Macao, China. *Atmospheric Environment, 36*, 4907 - 4918.

Xing, Y., & Brimblecombe, P. (2018). Dispersion of traffic derived air pollutants into urban parks. *Science of The Total Environment, 622-623*, 576-583. doi:10.1016/j.scitotenv.2017.11.340

Xing, Y., & Brimblecombe, P. (2020a). Trees and parks as "the lungs of cities". *Urban Forestry & Urban Greening, 48*, 126552. doi:10.1016/j.ufug.2019.126552

Xing, Y., & Brimblecombe, P. (2020b). Urban park layout and exposure to traffic-derived air pollutants. *Landscape and Urban Planning, 194*, 103682. doi:10.1016/j.landurbplan.2019.103682

Xu, L., Yan, Q., He, P., Zhen, Z., Jing, Y., Duan, Y., & Chen, X. (2022). Combined effects of different leaf traits on foliage dust-retention capacity and stability. *Air Quality, Atmosphere & Health*. doi:10.1007/s11869-021-01141-4

Xu, X., Yu, X., Bao, L., & Desai, A. R. (2019a). Size distribution of particulate matter in runoff from different leaf surfaces during controlled rainfall processes. *Environmental Pollution, 255*(Pt 1), 113234. doi:10.1016/j.envpol.2019.113234

Xu, X., Yu, X., Mo, L., Xu, Y., Bao, L., & Lun, X. (2019b). Atmospheric particulate matter accumulation on trees: A comparison of boles, branches and leaves. *Journal of Cleaner Production, 226*, 349-356. doi:10.1016/j.jclepro.2019.04.072

Xu, X., Zhang, Z., Bao, L., Mo, L., Yu, X., Fan, D., & Lun, X. (2017). Influence of rainfall duration and intensity on particulate matter removal from plant leaves. *Science of The Total Environment, 609*, 11-16. doi:10.1016/j.scitotenv.2017.07.141

Xu, Y., Xu, W., Mo, L., Heal, M. R., Xu, X., & Yu, X. (2018). Quantifying particulate matter accumulated on leaves by 17 species of urban trees in Beijing, China. *Environmental Science and Pollution Research, 25*(13), 12545-12556. doi:10.1007/s11356-018-1478-4

Xue, F., & Li, X. (2017). The impact of roadside trees on traffic released PM 10 in urban street canyon: Aerodynamic and deposition effects. *Sustainable Cities and Society, 30*, 195-204. doi:10.1016/j.scs.2017.02.001

Yan, J., Lin, L., Zhou, W., Han, L., & Ma, K. (2016a). Quantifying the characteristics of particulate matters captured by urban plants using an automatic approach. *Journal of Environmental Science, 39*, 259 - 267.

Yan, J., Lin, L., Zhou, W., Ma, K., & Pickett, S. T. A. (2016b). A novel approach for quantifying particulate matter distribution on leaf surface by combining SEM and object-based image analysis. *Remote Sensing of Environment, 173*, 156-161. doi:10.1016/j.rse.2015.11.033

Yang, J., Chang, Y., & Yan, P. (2015). Ranking the suitability of common urban tree species for controlling PM2.5 pollution. *Atmospheric, 6*, 267-277.

Yin, S., Zhang, X., Yu, A., Sun, N., Lyu, J., Zhu, P., & Liu, C. (2019). Determining PM2.5 dry deposition velocity on plant leaves: An indirect experimental method. *Urban Forestry & Urban Greening, 46*, 126467. doi:10.1016/j.ufug.2019.126467

Ying, J., Zhang, X., Zhang, Y., & Bilan, S. (2021). Green infrastructure: systematic literature review. *Economic Research-Ekonomska Istraživanja*, 1-22. doi:10.1080/1331677x.2021.1893202

Yli-Pelkonen, V., Scott, A. A., Viippola, V., & Setälä, H. (2017). Trees in urban parks and forests reduce O3, but not NO2 concentrations in Baltimore, MD, USA. *Atmospheric Environment, 167*, 73-80. doi:10.1016/j.atmosenv.2017.08.020

Younger, M., Morrow-Almeida, H. R., Vindigni, S. M., & Dannenberg, A. L. (2008). The built environment, climate change, and health: opportunities for co-benefits. *American Journal of Preventive Medicine 35*(5), 517-526. doi:10.1016/j.amepre.2008.08.017

Ysebaert, T., Koch, K., Samson, R., & Denys, S. (2021). Green walls for mitigating urban particulate matter pollution—A review. *Urban Forestry & Urban Greening, 59*. doi:10.1016/j.ufug.2021.127014

Yuan, J. S., Himanen, S. J., Holopainen, J. K., Chen, F., & Stewart, C. N., Jr. (2009). Smelling global climate change: mitigation of function for plant volatile organic compounds. *Trends in Ecology and Evolution, 24*(6), 323-331. doi:10.1016/j.tree.2009.01.012

Yuan, Y., Sun, Z., Kännaste, A., Guo, M., Zhou, G., & Niinemets, Ü. (2020). Isoprenoid and aromatic compound emissions in relation to leaf structure, plant growth form and species ecology in 45 East-Asian urban subtropical woody species. *Urban Forestry & Urban Greening, 53*, 126705. doi:10.1016/j.ufug.2020.126705

Zampieri, M. C. T., Sarkis, J. E. S., Pestana, R. C. B., Tavares, A. R., & Melo-de-Pinna, G. F. A. (2013). Characterization of Tibouchina granulosa (Desr.) Cong. (Melastomataceae) as a biomonitor of air pollution and quantification of particulate matter adsorbed by leaves. *Ecological Engineering, 61*, 316-327. doi:10.1016/j.ecoleng.2013.09.050

Zhang, J. J., Wei, Y., & Fang, Z. (2019a). Ozone Pollution: A Major Health Hazard Worldwide. *Front Immunol, 10*, 2518. doi:10.3389/fimmu.2019.02518

Zhang, L., Zhang, Z., Chen, L., & McNulty, S. (2019b). An investigation on the leaf accumulation-removal efficiency of atmospheric particulate matter for five urban plant species under different rainfall regimes. *Atmospheric Environment, 208*, 123-132. doi:10.1016/j.atmosenv.2019.04.010

Zhang, W., Wang, B., & Niu, X. (2017). Relationship between Leaf Surface Characteristics and Particle Capturing Capacities of Different Tree Species in Beijing. *Forests, 8*(3), 92. doi:10.3390/f8030092

Zhang, X., Han, L., Wei, H., Tan, X., Zhou, W., Li, W., & Qian, Y. (2022). Linking urbanization and air quality together: A review and a perspective on the future sustainable urban development. *Journal of Cleaner Production, 346*, 130988. doi:10.1016/j.jclepro.2022.130988

Zhang, Y., & Steiner, A. L. (2022). Projected climate-driven changes in pollen emission season length and magnitude over the continental United States. *Nature Communications, 13*(1), 1234. doi:10.1038/s41467-022-28764-0

Zhao, N., Prieur, J.-F., Liu, Y., Kneeshaw, D., Lapointe, E. M., Paquette, A., Zinszer, K., Dupras, J., Villeneuve, P. J., Rainham, D. G., Lavigne, E., Chen, H., van den Bosch, M., Oiamo, T., & Smargiassi, A. (2021). Tree characteristics and environmental noise in complex urban settings – A case study from Montreal, Canada. *Environmental Research, 202*, 111887. doi:10.1016/j.envres.2021.111887

Zheng, T., Jia, Y. P., Zhang, S., Li, X. B., Wu, Y., Wu, C. L., He, H. D., & Peng, Z. R. (2021). Impacts of vegetation on particle concentrations in roadside environments. *Environmental Pollution, 282*, 117067. doi:10.1016/j.envpol.2021.117067

Zhou, M., Wang, X., Lin, X., Yang, S., Zhang, J., & Chen, J. (2020). Automobile exhaust particles retention capacity assessment of two common garden plants in different seasons in the Yangtze River Delta using open-top chambers. *Environ Pollut, 263*(Pt A), 114560. doi:10.1016/j.envpol.2020.114560

Zhu, Y., & Hinds, W. C. (2005). Predicting particle number concentrations near a highway based on vertical concentration profile. *Atmospheric Environment, 39*(8), 1557-1566. doi:10.1016/j.atmosenv.2004.11.015

Zinke, P. (1967). Forest interception studies in the United States. *Sopper, W.E., Lull, H.W. (Eds.), Forest Hydrology. Pergamon Press, Oxford*, 137–161.

Ziska, L. H. (2020). An Overview of Rising CO(2) and Climatic Change on Aeroallergens and Allergic Diseases. *Allergy Asthma Immunol Research 12*(5), 771-782. doi:10.4168/aair.2020.12.5.771

Zölch, T., Maderspacher, J., Wamsler, C., & Pauleit, S. (2016). Using green infrastructure for urban climate-proofing: An evaluation of heat mitigation measures at the micro-scale. *Urban Forestry & Urban Greening, 20*, 305-316. doi:10.1016/j.ufug.2016.09.011

Zuo, W., & Chen, Q. (2009). Real-time or faster-than-real-time simulation of airflow in buildings. *Indoor Air, 19*(1), 33-44. doi:10.1111/j.1600-0668.2008.00559.x

Appendices

1 Appendix A. Conceptual Framework

- ### Chapter 2 - Steps in the mixed-methods research process

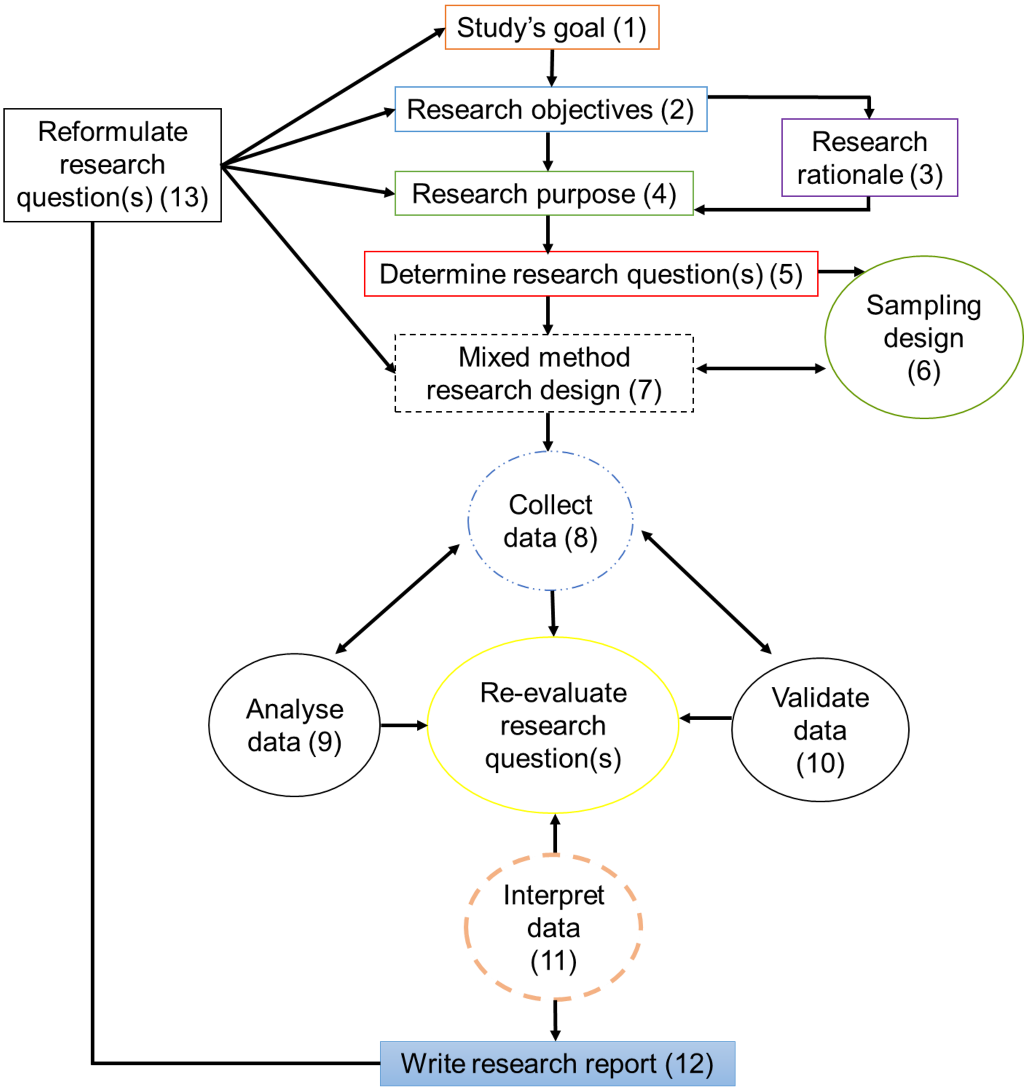


Figure 1. Step of the research process (Collins et al., 2006).

Chapter 2 – Air Quality Standards

Table 1. Air Quality Standards for ambient air pollutants.

		Limit values ($\mu g\ m^{-3}$)	**Air Quality Standards ($\mu g\ m^{-3}$)**	**WHO air quality guidelines ($\mu g\ m^{-3}$)**	
Pollutant	**Concentration measured as**	**United Kingdom**	**European Union**	**WHO 2005(1)**	**WHO 2021(2)**
Sulphur dioxide (SO_2)	1h mean	350	350	NI	NI
	10min mean	NI	NI	500	500
	15min mean	266	NI	NI	NI
	24h mean	125	125	20	40
Nitrogen dioxide (NO_2)	1h mean	200	200	200	200
	24h mean	NI	NI	NI	25
	Annual mean	40	40	40	10
Carbon monoxide (CO)	Maximum daily 8h mean	10^4	10^4	NI	10^4
	24h mean	NI	NI	NI	4×10^3
Ozone (O_3)	Maximum daily 8h mean	100	120	100	100 and 60**
Coarse Particulate Matter (PM_{10})	24h mean	50	50	50	45
	Annual mean	40	40	20	15
Fine Particulate Matter ($PM_{2.5}$)	24h mean	NI	NI	25	15
	Annual mean	25*	25	10	5

NI = No information

(1) WHO Global Air Quality Guidelines, published in 2005

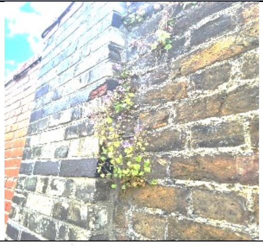
(2) New guidelines. WHO, (2021). WHO global air quality guidelines. Particulate matter ($PM_{2.5}$ and PM_{10}), ozone (O_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and carbon monoxide (CO), Licence: CC BY-NC-SA 3.0 IGO., 300

* Except Scotland, which is 10 ug/m^3 annual mean

** The ozone recommendation is for a peak season ozone. The peak season is defined as the six consecutive months of the year with the highest six-month running-average ozone concentration.

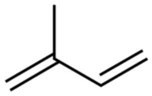
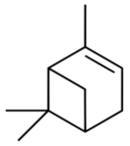
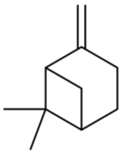
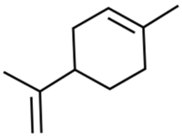
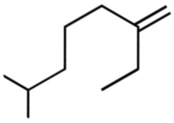
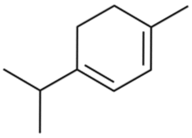
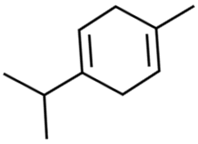
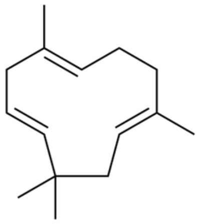
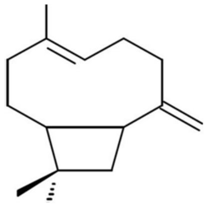
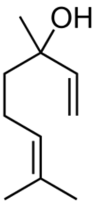
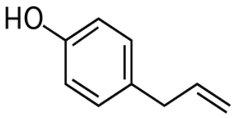
- ### Chapter 2 – Green walls

Table 2. Different types of green wall systems (Adapted from Dover (2015)). Credit: Karina Corada.

Illustrative example	Type
	• **Name:** Direct • **Form:** Plants growing directly on a wall surface • **Material:** Climbing plants
	• **Name:** Direct (green screen) • **Form:** Plants growing up a support material • **Material:** Metal mesh support
	• **Name:** Indirect (façade) • **Form:** Pants growing up support materials • **Material:** Climbing plants + support material (coated steel, galvanised steel support, HDPE)
	• **Name:** Living wall • **Form:** Plants growing in a module subdivided into smaller planters • **Material:** Plants + planter module + support structure
	• **Name:** Living wall • **Form:** Plants growing into panels containing hydroponic stonewool substrate • **Material:** Plants + panel + support structure
	• **Name:** Living wall • **Form:** Plants growing rooted directly in a panel which provides support with nutrients and water supplied hydroponically • **Material:** Plants + modules using a foam-based substrate + support structure

• Chapter 2 – Chemical structures of some BVOC

Table 3. Biogenic Volatile Organic Compounds (BVOC) emitted by plants.

Biogenic VOC	Examples
Isoprene (C_5H_8)	
Monoterpenes ($C_{10}H_{16}$)	 α - pinene  β - pinene  limonene  myrcene  α - terpinene  γ - terpinene
Sesquiterpenes ($C_{25}H_{24}$)	 α - humulene  β - caryophyllene
Oxygenated terpenes	 α - pinene  metil chavicol

2 Appendix B. Dispersion

Results Chapter 3 - General information

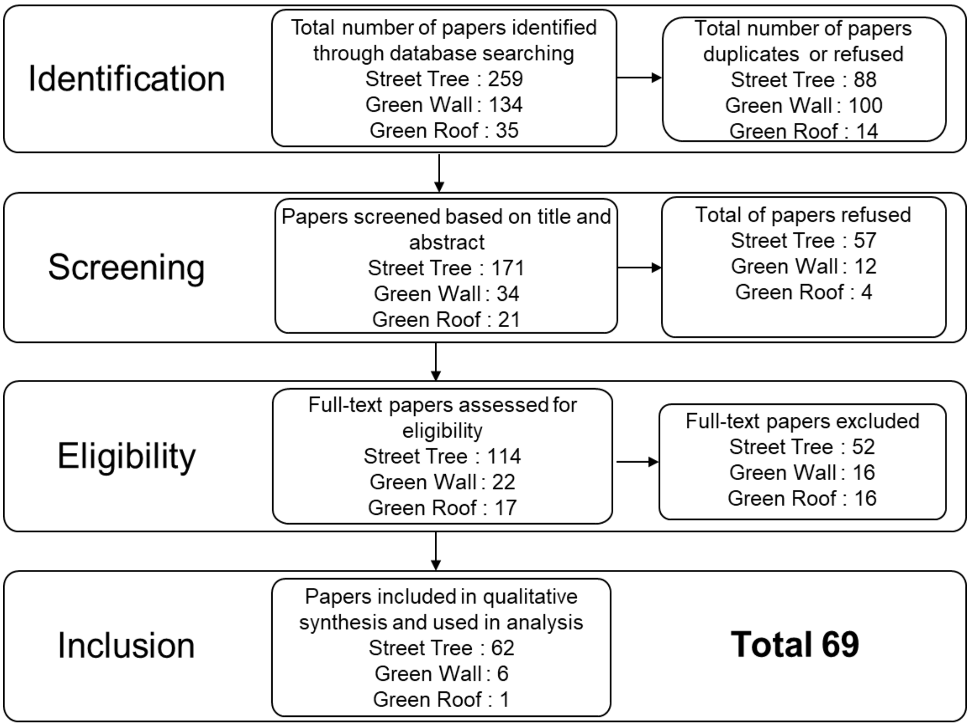


Figure 1. Systematic filtration and selection process for literature identified at the initial identification and scoping phase (PRISMA diagram) (Moher et al., 2009).

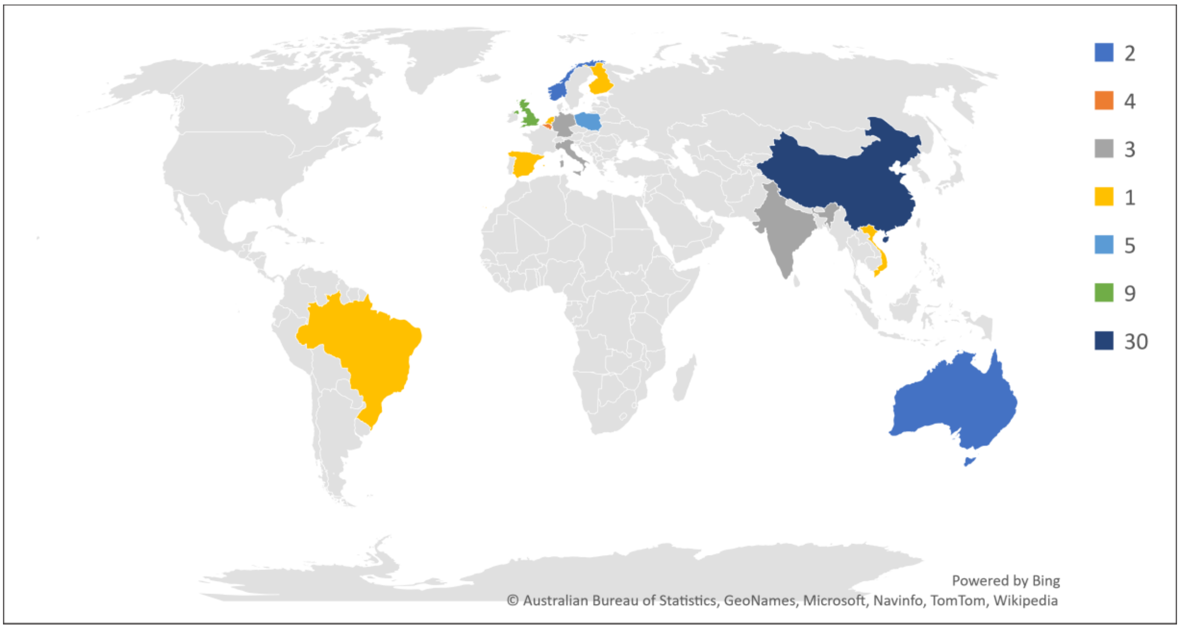


Figure 2. The geographical location of the selected studies. The different colour indicates the number of studies per country.

- ## Results Chapter 3 – Botanical information

Table 2. The level of effectiveness of particulate matter capture as a function of plant species as judged by various studies. Source: Corada et al. (2021).

Species	Common name	Family	Genus	Efficacity capturing PM $^{(1)}$	A specific description of the sampling area	Method $^{(2)}$	PM deposited on a leaf $^{(3)}$	Unit $^{(4)}$	Pollutant $^{(5)}$	Reference
Betula pendula	Silver birch	Betulaceae	Betula	Highly effective for PM_1	Norway	G	6.33 (a)	µg cm^{-2}	PM_1	Sæbø et al., 2012
				Highly effective for PM	Poland		29.71(a)	µg cm^{-2}	PM	
				Less effective	NIA*	WT - SEM	0.043	C_p (%)	PM	Räsänen et al., 2013
Cedrus deodara	Deodar, fountain trees, Indian cedar or Himalayan cedar	Pinaceae	Cedrus	Highly effective for PM_1	NIA	G + SEM	28 (a)	µg cm^{-2}	PM_1	Chen L. et al., 2017
				Less effective for PM in November	NIA	G	40 (b)	µg cm^{-2}	PM	Wang H. et al., 2013
				Highly effective for $PM_{2.5}$	NIA	WT – LPC	61.8	x10^{3} N cm^{-2}	$PM_{2.5}$	Xie C. et al., 2018
				Highly effective for PM_{10}	NIA		26.2	x10^{3} N cm^{-2}	PM_{10}	
Euonymus japonicus	Evergreen spindle or Japanese spindle	Celastraceae	Euonymus	Highly effective for PM	Fuxingmen road	G	23 (a)	g m^{-2}	PM	Wang Lei et al., 2006
				Highly effective for PM_1	5km away from factories and highway	G	3.2 (a)	µg cm^{-2}	PM_1	Zhang Tong. et al., 2017
				Less effective for PM_1	Academy of Sciences		0.5 (a)	µg cm^{-2}	PM_1	
				Less effective for TSP	Academy of Sciences		156.9(a)	µg cm^{-2}	TSP	
				Highly effective for $PM_{2.5}$	King Stone Apartment		268.7(a)	µg cm^{-2}	$PM_{2.5}$	
				Highly effective for TPS	King Stone Apartment		422.8(a)	µg cm^{-2}	PM_{10}	
				Less effective for PM_{10}	Olympic Forest Park		64.3 (a)	µg cm^{-2}	PM_{10}	
				Less effective for $PM_{2.5}$	Chaoyang Park		39.6 (a)	µg cm^{-2}	$PM_{2.5}$	
				Highly effective for PM_{10}	Chaoyang Park		194.1(a)	µg cm^{-2}	PM_{10}	
				Highly effective for PM after raining	NIA	G +SEM	30.43 (b)	µg cm^{-2}	PM	Xu X et al., 2017
Fraxinus chinensis Roxb.	Chinese ash	Oleaceae	Fraxinus	Less effective for PM	NIA	SEM	4.98E+04 (a)	N mm^{-2}	PM	Lin et al., 2017
				Less effective for PM_1	NIA	Dust detector	24.20 (a, b)	µg cm^{-3}	PM_1	Chen J. et al., 2015
				Less effective for $PM_{2.5}$	NIA		61.58 (a, b)	µg cm^{-3}	$PM_{2.5}$	
				Less effective for PM_{10}	NIA		150.98 (a, b)	µg cm^{-3}	PM_{10}	
Ginkgo biloba	Ginkgo	Ginkgoaceae	Ginkgo	Less effective for $PM_{2.5}$	Polluted site	G	1.5 (c)	µg cm^{-2}	$PM_{2.5}$	Chen X. et al., 2015
				Less effective for PM_1 & TPS	Agricultural University		0.1 (b)	µg cm^{-2}	PM_1	
				Less effective for PM on the adaxial side	NIA	SEM	4.64E+5 (a)	N mm^{-2}	PM	Wang Lei et al., 2015
				Less effective for PM on abaxial side	NIA		3.90E+5 (a)	N mm^{-2}	PM	

Species	Common name	Family	Genus	Efficacity capturing PM (1)	A specific description of the sampling area	Method (2)	PM deposited on a leaf (3)	Unit (4)	Pollutant (5)	Reference
Ligustrum lucidum	Chinese privet, glossy privet	Oleaceae	Ligustrum	Less effective for PM	Traffic density (h-) 1114 ± 172	G	100 (c)	µg cm^{-2}	PM	Wang H. et al., 2015
				Highly effective for PM	Affected by a chemical factory		560 (c)	µg cm^{-2}	PM	
Magnolia grandiflora	Bull bay or southern magnolia	Magnoliaceae	Magnolia	Highly effective for PM$_{2.5}$	Agricultural University	G	16 (c)	µg cm^{-2}	PM$_{2.5}$	Chen X. et al., 2015
				Highly effective for TPS			43.5 (c)	µg cm^{-2}	TSP	
				Less effective for PM$_{2.5}$	NIA	WT - laser particle counter	9.5	x10^{3} N cm^{-2}	PM$_{2.5}$	Xie C. et al., 2018
Morus alba	white mulberry or sycamine tree	Moraceae	Morus	Highly effective for PM$_{1}$	Agricultural University	G	1 (c)	µg cm^{-2}	PM$_{1}$	Chen X. et al., 2015
				Less effective for TPS in waxes	Far away from traffic/industrial pollution	G	2 (d)	µg cm^{-2}	TSP	Mo et al., 2015
				Less effective for PM$_{2.5}$ in waxes			0.5 (d)	µg cm^{-2}	PM$_{2.5}$	
Pinus armandi	Chinese white pine	Pinaceae	Pinus	Highly effective for PM	At 50 m away from the street	G	57 (a)	µg cm^{-2}	PM	Xu Y. et al., 2018
				Highly effective for PM$_{1}$	NIA	G +SEM	29 (a)	µg cm^{-2}	PM$_{1}$	Chen L. et al., 2017
Pinus sylvestris	Scot pine	Pinaceae	Pinus	Highly effective for PM on leaf and in waxes over all seasons	From 4 to 6 m from the road	G	14.5 (b)	µg cm^{-2}	PM	Przybysz A. Et al., 2014
				Less effective for PM$_{10}$	At 5 m from the road	G	26 (a)	µg cm^{-2}	PM$_{10}$	Mori et al., 2015
				Less effective for PM$_{10}$	At 25 m from the road		15 (a)	µg cm^{-2}	PM$_{10}$	
				Less effective for PM$_{2.5}$	At 35 m from the road		8 (a)	µg cm^{-2}	PM$_{2.5}$	
				Less effective for PM$_{10}$	At 80 m from the road		16 (a)	µg cm^{-2}	PM$_{10}$	
				Less effective for PM$_{2.5}$	At 80 m from the road		8 (a)	µg cm^{-2}	PM$_{2.5}$	
				Less effective for PM$_{1}$	At 80 m from the road		8 (a)	µg cm^{-2}	PM$_{1}$	
				Highly effective for PM	NIA	WT – SEM	0.2	Cp (%)	PM	Räsänen et al., 2013
Pinus tabulaeformis	Chinese pine	Pinaceae	Pinus	Less effective for PM	NIA	G	72.3	µg cm^{-2}	PM	Song et al., 2015
				Less effective for PM	At 10-20 m from the road	G	91.90 (a)	µg cm^{-2}	PM	Liu et al., 2018
				Highly effective for PM$_{1}$ in autumn	NIA	G	17.2 (b)	µg cm^{-2}	PM$_{1}$	Nguyen et al., 2014
				Highly effective for PM	N/A	WT – AFM	4.3 (a)	µg cm^{-2}	PM	Zhang Weikang et al., 2017
				Highly effective for PM$_{10}$	N/A		2.85 (a)	µg cm^{-2}	PM$_{10}$	
				Highly effective for PM$_{2.5}$	N/A		1.48 (a)	µg cm^{-2}	PM$_{2.5}$	
				Highly effective for PM$_{2.5}$	Botanical Garden	Dust detector	0.56 (a, c)	µg cm^{-2}	PM$_{2.5}$	Zhang WeiKang et al., 2015
				Highly effective for PM$_{10}$			2.9 (a, c)	µg cm^{-2}	PM$_{10}$	
				Highly effective for PM$_{2.5}$	Close to vehicle exhaust and factories		0.48 (a, c)	µg cm^{-2}	PM$_{2.5}$	

Species	Common name	Family	Genus	Efficacity capturing PM (1)	A specific description of the sampling area	Method (2)	PM deposited on a leaf (3)	Unit (4)	Pollutant (5)	Reference
				Highly effective for PM_{10}			3.87 (a, c)	μg cm^{-2}	PM_{10}	
				Less effective for PM	Nanshan Temple	Optical microscopy	6.76 (a)	mg cm^{-2}	PM	Shi et al., 2016
				Highly effective for PM after raining			7.22 (a)	mg cm^{-2}	PM	
Platanus hispanica	London plane	Platanaceae	Platanus	Less effective for PM	At 100 m from Oxford street and Marble Arch	G	6.8	μg cm^{-2}	PM	Beckett et al., 2012
				Less effective for PM	NIA	G	12 (a)	μg cm^{-2}	PM	Dzierżanowski et al., 2011
				Highly effective for PM after wash-off	NIA	WT - light microscope	7,491	N mm^{-2}	PM	Blanusa et al., 2015
				Highly effective for PM	Madrid (Spain)	SIRM	65.91(a)	m^3 kg^{-1}	PM	Rodriguez-Germade I. et al., 2014
				Less effective for PM	Pozuelo de Alarcon (Spain)		15.85(a)	m^3 kg^{-1}	PM	
Platanus acerifolia	London plane	Platanaceae	Platanus	Highly effective for PM	NIA	G	560 (b)	μg cm^{-2}	PM	Wang H. et al., 2013
				Highly effective for PM at a pedestrian level	At 5m height from the road	SIRM	29.3 (c)	x 10^{-6} A	PM	Hofman et al., 2013
				Less effective for PM at 12 m	At 12m height from the road		10.1 (c)	x 10^{-6} A	PM	
				Less effective for PM	At 0.3m from the pollutant source	Photometric sampler	80.99 (c)	μg m^{-3}	PM	Jin et al., 2014
				Less effective for PM	At 1.5m from the pollutant source		76.51 (c)	μg m^{-3}	PM	
				Highly effective for PM after wash-off	NIA	SIRM	14.36(a)	x 10^{-6} A	PM	Hofman et al., 2014
Platycladus orientalis	oriental thuja 'Elegantissi-ma'	Cupressaceae	Platycladus	Highly effective for $PM_{2.5}$ in summer	NIA	G	18.2 (b)	μg cm^{-2}	$PM_{2.5}$	Nguyen et al., 2014
				Highly effective for PM_{10} in summer			137.7 (b)	μg cm^{-2}	PM_{10}	
				Highly effective for TSP in summer			72.85 (b)	μg cm^{-2}	TSP	
				Highly effective for PM_1	NIA	G + SEM	30 (a)	μg cm^{-2}	PM_1	Chen L. et al., 2017
Populus tomentosa	Chinese white poplar	Salicaceae	Populus	Less effective for PM	At 50 m away from streets	G	13 (a)	μg cm^{-2}	PM	Xu Y. et al., 2018
				Less effective for PM_1 in autumn	NIA	G	3 (b)	μg cm^{-2}	PM_1	Nguyen et al., 2014
				Less effective for $PM_{2.5}$ in autumn			7.5 (b)	μg cm^{-2}	$PM_{2.5}$	
				Less effective for PM after rainfall (15mm/h)	NIA	G + SEM	7.95 (b)	μg cm^{-2}	PM	Xu X et al., 2017

Species	Common name	Family	Genus	Efficacity capturing PM $^{(1)}$	A specific description of the sampling area	Method $^{(2)}$	PM deposited on a leaf $^{(3)}$	Unit $^{(4)}$	Pollutant $^{(5)}$	Reference
				Less effective for PM	NIA	WT – AFM	0.97 (a)	μg cm^{-2}	PM	Zhang Weikang et al., 2017
				Less effective for $PM_{2.5}$	Beijing Botanical Garden	Dust detector	0.12 (a, c)	μg cm^{-2}	$PM_{2.5}$	Zhang WeiKang et al., 2015
				Less effective for PM_{10}			0.78 (a, c)	μg cm^{-2}	PM_{10}	
				Less effective for $PM_{2.5}$	Close to vehicle exhaust and factories		0.12 (a, c)	μg cm^{-2}	$PM_{2.5}$	
				Less effective for PM_{10}			1.17 (a, c)	μg cm^{-2}	PM_{10}	
				Highly effective for PM_1	NIA	Dust detector	37.48 (a, b)	μg cm^{-3}	PM_1	Chen J. et al., 2015
				Highly effective for $PM_{2.5}$			116.68 (a, b)	μg cm^{-3}	$PM_{2.5}$	
				Highly effective for PM_{10}			247.20 (a, b)	μg cm^{-3}	PM_{10}	
Quercus ilex	Holm oak	Fagaceae	Quercus	Less effective for PM_{10}	Residential area far away from the city centre	G	18.29 (b, c)	μg cm^{-2}	PM_{10}	Sgrigna et al., 2015
				Less effective for $PM_{2.5}$	Residential area with some greenspaces		11 (b, c)	μg cm^{-2}	$PM_{2.5}$	
				Highly effective for PM	Close to Steel Factory, with large park areas		50.64 (b, c)	μg cm^{-2}	PM_{10}	
				Highly effective for PM	In a street far away from a factory	SEM	1.7 (a, c)	Equivalent diameter (deq) μm	PM	Sgrigna et al., 2016
				Less effective for PM	In a park		1.4 (a, c)	Equivalent diameter (deq) μm	PM	
Salix matsudana	dragon's claw willow or corkscrew willow	Salicaceae	Salix	Less effective for PM	Fuchengmen road	G	0.5 (a)	g m^{-2}	PM	Wang Lei et al., 2006
				Highly effective for PM	NIA	SEM	5.70E+05	N mm^{-2}	PM	Lin et al., 2017
				Less effective for $PM_{2.5}$	N/A	WT – AFM	0.14 (a)	μg cm^{-2}	$PM_{2.5}$	Zhang Weikang et al., 2017
				Less effective for PM_{10}			0.71 (a)	μg cm^{-2}	PM_{10}	
Styphnolobium japonicum or Sophora japonica	Japanase pagoda	Fabaceae	Styphnolobium	Highly effective for PM	At 10-20 m from a road	G	295.2 (a)	μg cm^{-2}	PM	Liu et al., 2018
				Highly effective for $PM_{2.5}$ in autumn	NIA	G	22.5 (b)	μg cm^{-2}	$PM_{2.5}$	Nguyen et al., 2014
				Highly effective for PM_{10} in autumn			149.6 (b)	μg cm^{-2}	PM_{10}	
				Highly effective for PTS in autumn			156.25 (b)	μg cm^{-2}	TPS	
				Less effective for PM_{10} in WISC		G	26 (c)	μg cm^{-2}	PM_{10}	

Species	Common name	Family	Genus	Efficacity capturing PM $^{(1)}$	A specific description of the sampling area	Method $^{(2)}$	PM deposited on a leaf $^{(3)}$	Unit $^{(4)}$	Pollutant $^{(5)}$	Reference
				Less effective for TPS in WISC	Wuhan Iron and Steel Company (polluted site)		29.51 (c)	µg cm^{-2}	TSP	Chen X. et al., 2015
				Less effective for PM_{10} on leaf	Far away from traffic/industries	G	6.08 (c)	µg cm^{-2}	PM_{10}	Mo et al., 2015
				Less effective for PM_{10} in waxes	Far away from traffic/industrial pollution		0.1 (c)	µg cm^{-2}	PM_{10}	
				Less effective for $PM_{2.5}$ in waxes			0.5 (c)	µg cm^{-2}	$PM_{2.5}$	
				Less effective for PM in April	NIA	G	29 (b)	µg cm^{-2}	PM	Wang H. et al., 2013
Ulmus pumila	Siberian elm or dwarf elm	Ulmaceae	Ulmus	Highly effective for $PM_{2.5}$	NIA	G	69.71(a)	µg cm^{-2}	$PM_{2.5}$	Chen L. et al., 2016
				Highly effective for PM_{10}			71.47(a)	µg cm^{-2}	PM_{10}	
				Highly effective for $PM_{2.5}$ on adaxial side	NIA	SEM	4.21E+5	N mm^{-2}	$PM_{2.5}$	Wang Lei et al., 2015
				Highly effective for PM_{10} on adaxial side			2.25E+4	N mm^{-2}	PM_{10}	
				Highly effective for PM_1 on abaxial side	NIA		1.44E+6	N mm^{-2}	PM_1	
				Highly effective for PM_{10} on abaxial side			1.68E+4	N mm^{-2}	PM_{10}	
Hedera helix	Common ivy	Araliaceae	Hedera	Less effective for PM on a leaf in late spring	Rural area. The distance between plants and road ranges from 4 to 6 m	G	17.1 (b)	µg cm^{-2}	PM	Przybysz A. et al., 2014
				Less effective for PM in waxes in early and late spring			2.2 (b)	µg cm^{-2}	PM	
				Less effective for PM in waxes in early spring			1.4 (b)	µg cm^{-2}	PM	
				Less effective for PM in wax in late winter	Roadside (4 to 6 m from the road)		0.8 (b)	µg cm^{-2}	PM	
				Highly effective for particle diameters of <1.5 µm on the adaxial side in early autumn	Sound barrier near local traffic at 0.25m from the ground	SEM	8,221 (a)	Number of particles	$PM_{d = <1.5\ \mu m}$	Ottelé et al., 2010
				Highly effective for particle diameters of 2.5-4µm on the adaxial side in late autumn			468.5 (a)	Number of particles	$PM_{d = 2.5-4\ \mu m}$	
				Highly effective for particle diameters of <1.5 µm on the adaxial side in late autumn			17,524 (a)	Number of particles	$PM_{d = <1.5\ \mu m}$	
				Highly effective for particle diameters of 2.5-4µm on the adaxial side in late autumn			1,023 (a)	Number of particles	$PM_{d = 2.5-4\ \mu m}$	
				Highly effective for particle diameters of <1.5 µm on abaxial side in late autumn	Sound barrier near local traffic at 2.5m from the ground		23,894.5 (a)	Number of particles	$PM_{d = <1.5\ \mu m}$	

Species	Common name	Family	Genus	Efficacity capturing PM (1)	A specific description of the sampling area	Method (2)	PM deposited on a leaf (3)	Unit (4)	Pollutant (5)	Reference
				Highly effective for particle diameters of <1.5 μm on the adaxial side in early autumn			1,959.5 (a)	Number of particles	$PM_{d\ =\ <1.5\ \mu m}$	
				Highly effective for particle diameters of <1.5 um on the adaxial side in early autumn	Close to woods at 0.25m from the ground		1,959.5 (a)	Number of particles	$PM_{d\ =\ <1.5\ \mu m}$	
				Less effective for particle diameters of 2.5-4 μm on the adaxial side in early autumn			253 (a)	Number of particles	$PM_{d\ =\ 2.5-4\ \mu m}$	
				Less effective for particle diameters of 2.5-4 μm on the adaxial side in late autumn			454.5 (a)	Number of particles	$PM_{d\ =\ 2.5-4\ \mu m}$	
				Less effective for particle diameters of <1.5 μm on the abaxial side in late autumn			6,033 (a)	Number of particles	$PM_{d\ =\ <1.5\ \mu m}$	
				Less effective for particle diameters of 2.5-4 μm on the abaxial side in late autumn			511.5 (a)	Number of particles	$PM_{d\ =\ 2.5-4\ \mu m}$	
				Less effective for particle diameters of <1.5μm on the abaxial side in early autumn			7,644.5 (a)	Number of particles	$PM_{d\ =\ <1.5\ \mu m}$	
				Less effective for particle diameters of 2.5-4μm on the abaxial side in early autumn	Close to woods at 2.5m from the ground		880.5 (a)	Number of particles	$PM_{d\ =\ 2.5-4\ \mu m}$	
				Highly effective for PM	Busy road	SEM	1.27E+4 (c)	N mm^{-2}	PM	Sternberg et al., 2010
				Less effective for PM	Woodland at 6km from a busy road		1.69E+2 (c)	N mm^{-2}	PM	

* NIA = No Information Available, N/A = Not Applicable

(1) Note: efficacity capturing PM is within the study. Due to the absence of PM background concentration and standard sampling method to measure PM on leaves, it was impossible to compare across studies

(2) G = Gravimetric / SEM = Scanning Electron Microscope / SIRM = Saturation Isothermal Remanent Magnetisation / WT = Wind Tunnel. / LPC = laser particle counter Note: Wind tunnel experiment measures PM on leaf with different techniques, one of them is AFM = atomic force microscopy.

(3) Note: The total PM concentration value on leaves is approximated due to the varieties of the data analysis: (a) concentrations through graphs, (b) the same species was evaluated in different temporal scales (e.g. years, months, weeks) or seasons (e.g. winter and summer), (c) at a different location (road, woodland, motorway), (d) different side leaf (adaxial and/or abaxial, adaxial or wax). Thus, the total value of PM deposited on leaves is the sum of PM deposited during the temporal scale or season studied.

(4) Note: There are different unit of concentrations according to the method used in the study. C_p (%) = Capture efficiency; x10^3 N cm^{-2} = Number of particles per cm^2; g m^{-2} = density; N mm^{-2} = number of particles per mm^2; m^3 kg^{-1} = low frequency magnetic susceptibility; x 10^{-6} A = Mean leaf SIRM

(5) Note: The effectiveness of PM capture varies according to the particle size. PM_1 = Particulate matter 1μm in aerodynamic diameter; $PM_{2.5}$ = Particulate matter 2.5μm in aerodynamic diameter; PM_{10} = Particulate matter 10μm in aerodynamic diameter; TSP= total suspended particles; $PM_{d\ =\ 2.5-4\ \mu m}$ = Particulate matter between 2.5 - 4μm in aerodynamic diameter; $PM_{d\ =\ <1.5\ \mu m}$ = Particulate matter less than 1μm in aerodynamic diameter.

- **Results Chapter 3 – Leaf shapes**

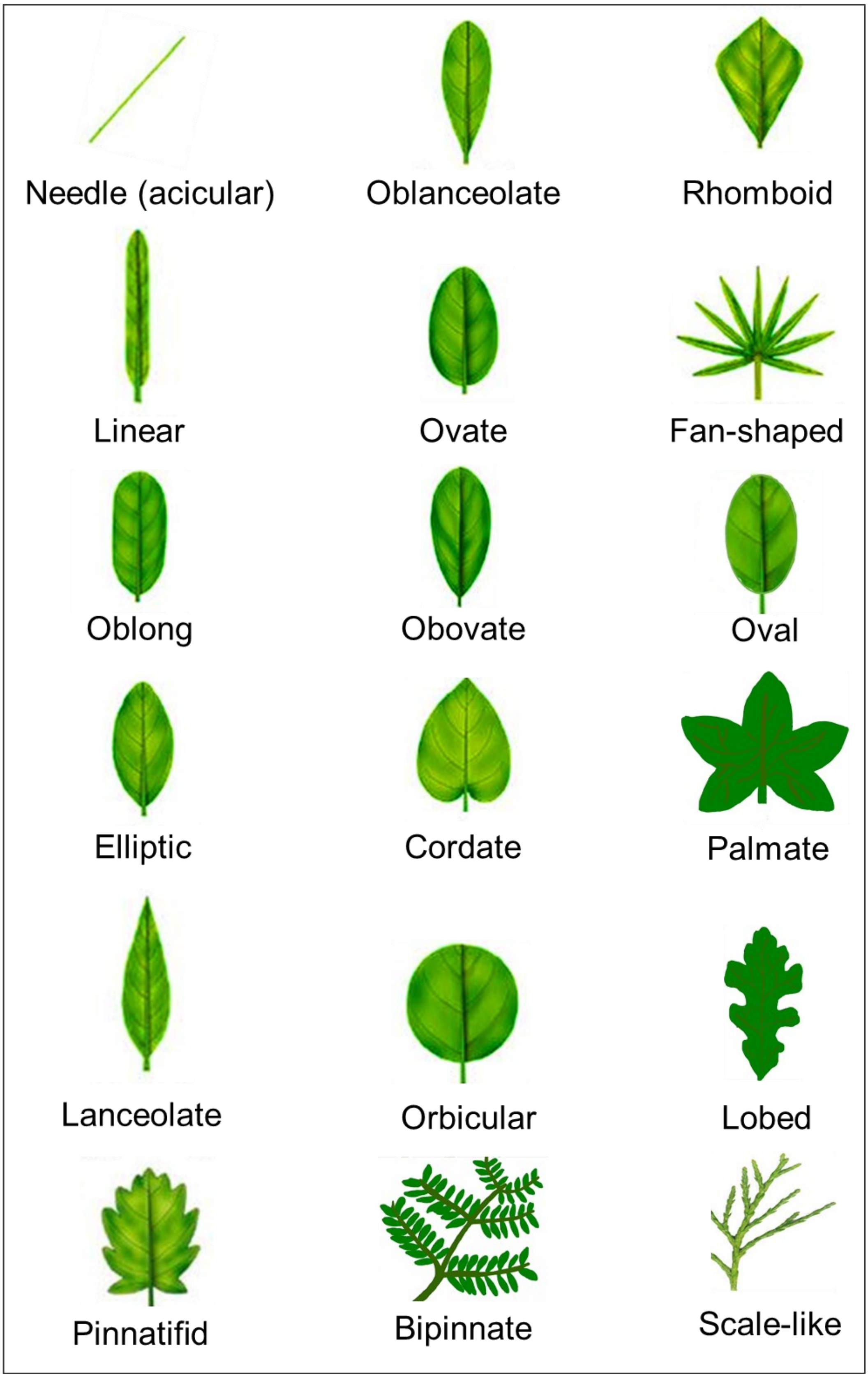
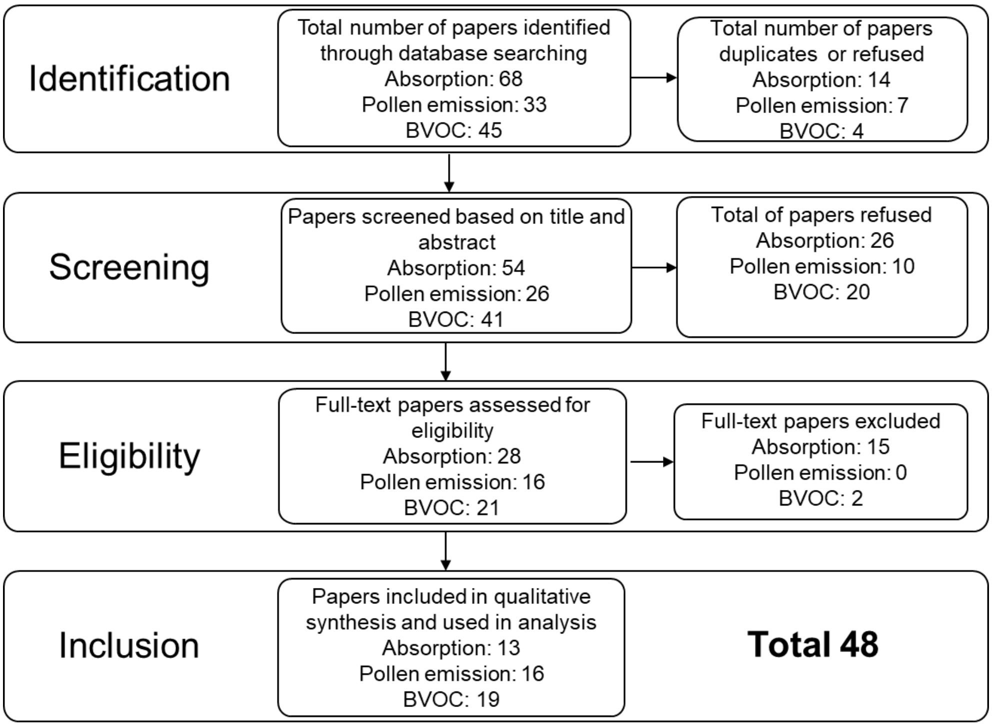


Figure 3. Type of leaf shape cited in this research. Source: Own elaboration.

3 Appendix C. Absorption and Biogenic emissions

- ## Results Chapter 4 – General information



Identification

Total number of papers identified through database searching
Absorption: 68
Pollen emission: 33
BVOC: 45

Total number of papers duplicates or refused
Absorption: 14
Pollen emission: 7
BVOC: 4

Screening

Papers screened based on title and abstract
Absorption: 54
Pollen emission: 26
BVOC: 41

Total of papers refused
Absorption: 26
Pollen emission: 10
BVOC: 20

Eligibility

Full-text papers assessed for eligibility
Absorption: 28
Pollen emission: 16
BVOC: 21

Full-text papers excluded
Absorption: 15
Pollen emission: 0
BVOC: 2

Inclusion

Papers included in qualitative synthesis and used in analysis
Absorption: 13
Pollen emission: 16
BVOC: 19

Total 48

Figure 1. Systematic filtration and selection process for literature identified at the initial identification and scoping phase.

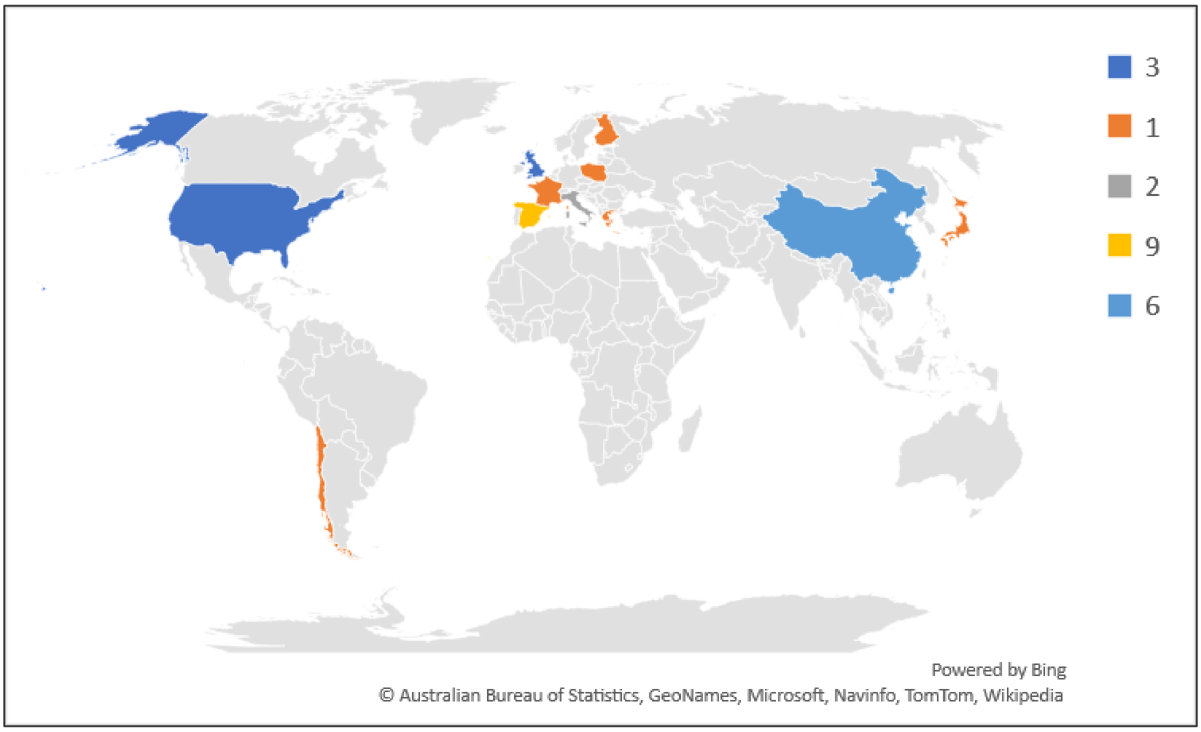


Figure 2. The geographical location of the selected studies. The different colours indicate the number of studies per country.

Table 1. Summary of the selected articles for inclusion in the literature review on absorption and biogenic emissions.

No	Reference	Objective [(1)]	Method [(2)]	Sampling area	Intrinsic (GI) and extrinsic characteristics[(3)]	Mechanisms
1	Hosker and Lindberg, 1982	Review the interaction of airborne with vegetative canopies	Literature review	N/A	PAR Leaf surface Precipitation Chemical and biological properties of pollutant	Absorption
2	Simonich and Hites, 1995	Show the advances of accumulation of pollutants by vegetation	Literature review	N/A	Chemical and physical properties of pollutants Environmental condition Plant species temperature Air pollutants concentration	Absorption
3	Khan and Abbasi, 2000	Describe a case of study in which a greenbelt was designed	Literature review	N/A	Stomata resistance Leaf traits Meteorological parameters Type of species	Absorption
4	Fujii et al., 2005	Measure changes in pollutant concentration uptake	Indoor chamber	N/A	Seasonal effect Illuminance	Absorption
5	Sternberg et al., 2010	Study absorption of particles in Hedera helix	SEM	Oxford, UK.	Canopy placement Site characteristics	Absorption
6	Wang Hua et al., 2012	Quantify and compare O3 uptake by different urban species	Sap flow measurements	Beijing, China	Seasonal effect Stomatal control Water availability	Absorption
7	Yli-Pelkonen et al., 2017a	Explore the influence of urban tree-cover on the concentrations of gaseous air pollutants NO2 and O3 under early summertime conditions	Passive collectors	Baltimore, USA	Canopy cover Type of GI. Meteorological parameters Regional and local ambient pollutant levels	Absorption
8	Yli-Pelkonen et al., 2017b	Explore the capacity of urban greenbelts to remove the traffic-derived gaseous pollutant NO2 under summertime and wintertime	Passive collectors	Helsinki, Finland	GI location Seasonal effect Species	Absorption
9	Baraldi et al., 2018	Investigate the potential ability of common species, to mitigate urban pollutants by analysing functional and structural leaf species-specific properties, namely CO2 absorption, BVOC emission and leaf micromorphology	Laboratory analysis chamber and cuvettes	Bologna, Italy	Stomata density Leaf traits Type of species	Absorption, Biogenic emission (BVOC)
10	Fowler et al., 2009	Describe the state of understanding the processes involved in the exchange of gases and aerosols between the earth's surface and the atmosphere.	Literature review	N/A	Chemical reaction Physiological and physico-chemical controls of emissions	Absorption Biogenic emission (BVOC)
11	Tiwari et al., 2019	Detailed review of parameterisation for GI modelling. Evaluate the effectiveness of	Literature review	N/A	Stomata LAI	Absorption

No	Reference	Objective $^{(1)}$	Method $^{(2)}$	Sampling area	Intrinsic (GI) and extrinsic characteristics$^{(3)}$	Mechanisms
		microscale and macroscale air pollution dispersion models to estimate pollutant concentration reductions by GI.			PAR Type of GI. Type of pollutant Chemical properties of pollutants Wettability GI porosity	
12	Delian, 2020	Summarise the role played by stomata, under the conditions of climate change	Literature review	N/A	Stoma description Stomata density Temperature Stomata conductance CO2 concentration Soil moisture O3 concentrations	Absorption
13	Gong et al., 2021	Quantify the NOx removal by urban trees	Gravimetric – Isotopic technique	Beijing, China	NOx uptake GI location Species Tree size and age	Absorption
1	Tormo Molina et al., 1996	Calculate the total pollen production per individual treen in ten arboreal species	Field measurement (branch selection)	Badajoz, Spain	Height Diameter of the crown Length of the anthers Number of flowers Light	Biogenic emission (pollen)
2	Gonzalez and Candau, 1997	Contribute to the useful knowledge of Olea europaea for allergists	Cour collector	Seville, Spain	Temperature Precipitation	Biogenic emission (pollen)
3	Damialis et al., 2005	Examine the relationship between the atmospheric pollen content and the prevailing winds in the study area	Volumetric trap	Thessaloniki, Greece	Meteorological parameters	Biogenic emission (pollen)
4	Emberlin et al., 2007	Investigate changes and features in the pollen seasons of the early flowering spring species of trees	Burkard volumetric trap	Worcester, UK	Temperature Urban heat island	Biogenic emission (pollen)
5	Jianan et al., 2007	Summary of species composition, phenological characteristics and influential factors of allergenic pollen plants	Literature review	N/A	Temperature Urban heat island	Biogenic emission (pollen)
6	Fernandez-Rodriguez et al., 2014	Study different environmental parameters related to meteorological parameters and the surrounding vegetation on pollen concentrations	Pollen monitoring	Badajoz, Spain	Meteorological parameters Species	Biogenic emission (pollen)
7	Cariñanos et al., 2014	Estimate the allergenic potential of urban green spaces	Allergenicity Index and field study	Granada, Spain	Maintenance Cover area by species Number of the species Pollination period	Biogenic emission (pollen)

No	Reference	Objective (1)	Method (2)	Sampling area	Intrinsic (GI) and extrinsic characteristics(3)	Mechanisms
					Meteorological parameters	
8	Senechal et al., 2015	Study links between atmospheric pollution, airborne pollen, allergenicity, and allergy	Literature review	N/A	Air pollutants	Biogenic emission (pollen)
9	Maya-Manzano et al., 2017a	Analyse the urban Platanus airborne pollen concentration in the air and geolocate the pollen sources in public areas	Field measurement - Volumetric spore traps	Five Spanish cities (Badajoz, Caceres, Plasencia, Don Benito, Zafra)	Wind directions Degree of maturity Pruning Water availability Number of the species	Biogenic emission (pollen)
10	Maya-Manzano et al., 2017b	Analyse the relationship between the density or abundance of ornamental trees and airborne pollen records from three urban environment	Volumetric spore traps	Don Benito, Plasencia and Zafra, Spain	Number of species Pollination system Wind direction	Biogenic emission (pollen)
11	McInnes et al., 2017	Map different plant types associated with allergy and allergic asthma in the UK.	Mapping pollen in the UK.	United Kingdom	Maintenance Meteorological parameters Water availability	Biogenic emission (pollen)
12	Sedghy et al., 2018	Explain the interaction between air pollutants and pollen grains and allergens	Literature review	N/A	Air pollutants	Biogenic emission (pollen)
13	Oduber et al., 2019	Evaluate pollen concentration (related to allergies) and atmospheric pollutants	Hirst volumetric trap	León, Spain	Species Meteorological parameters Pollutant concentration	Biogenic emission (pollen)
14	Bogawski et al., 2019	Determine whether the combination of LiDAR parameters and wind direction data could be used to explain pollen concentration variability.	Aerial laser scanning (Light Detection and Ranging—LiDAR) and volumetric trap	Poznań, Poland	Crown	Biogenic emission (pollen)
15	Cariñanos et al., 2020	Study Platanus allergens and understand its reproductive behaviour in urban scenarios	Pollen sampling, Pollen counts provided by the Aerobiological Monitoring Unit	Granada, Spain	Tree age Crown volume Pruning Meteorological parameters Pollutant concentration	Biogenic emission (pollen)
16	Cariñanos et al., 2021	Study the interactions between atmospheric pollutants and meteorological variables with pollen type	Volumetric suction Hirst-type sampler	Granada, Spain	Meteorological parameters Type of pollutants	Biogenic emission (pollen)
1	Kesselmeier and Staudt, 1999	Overview the actual knowledge of BVOC	Literature review	N/A	Light Temperature PAR	Biogenic emission (BVOC)
2	Harley et al., 1999	Summarise current knowledge of isoprene production within the plant species	Literature review	N/A	Light Temperature PAR	Biogenic emission (BVOC)

No	Reference	Objective $^{(1)}$	Method $^{(2)}$	Sampling area	Intrinsic (GI) and extrinsic characteristics$^{(3)}$	Mechanisms
3	Kim, 2001	Study environmental factors that control the nature and distribution of monoterpenes emitted by species	Enclosure technique	Florida, EEUU	Temperature Seasonal effect Tree age Leaf traits	Biogenic emission (BVOC)
4	Kim et al., 2005	Understand the relative emission rate of monoterpenes and their contribution to the total emission among conifers	Enclosure technique	Indoor and field study	Tree species Species age Seasonal effect Temperature PAR	Biogenic emission (BVOC)
5	Yuan J. et al., 2009	Summarise how emission patterns and concentrations of VOCs could change environments from the perspectives of plant defence	Literature review	N/A	Plant-insect interaction Plant-plant interaction Plant species Genotype CO2 concentration O3 concentrations Temperature Drought stress Nutrient availability GI allocation Light conditions Plant growth stages	Biogenic emission (BVOC)
6	Llusia et al., 2010	Study the factor involved in BVOC emissions in native and alien species	Enclosure technique	Oahu (Hawaii), US.	Species Temperature	Biogenic emission (BVOC)
7	Holopainen & Gershenzon, 2010	Summarise the basic effects of single stress factors on the volatile emission of plants	Literature review	N/A	Temperature High light intensity Mechanical leaf damage Pathogen attack	Biogenic emission (BVOC)
8	Loreto & Schnitzler, 2010	Study abiotic stresses enhance BVOCs emission rates and patterns, altering the communication with other organisms and the photochemical cycles	Literature review	N/A	Temperature Drought and salt Pollutants UV-B radiation CO2 concentrations	Biogenic emission (BVOC)
9	Bracho-Nunez et al., 2011	Investigate potential differences in VOC emissions of young and mature leaves of nine typical endemic tree and shrub species	Chamber system + PTR-MS, GC-FID, GC-MS and online GC-FID	Montpellier, France	Leaf age Species	Biogenic emission (BVOC)
10	Prendez et al., 2013	Study the BVOC emission of native and alien species	Static enclosure technique	Santiago, Chile	Type of species	Biogenic emission (BVOC)
11	Calfapietra et al., 2013	Summarise the interaction between plants and biogenic emissions in urban environments	Literature review	N/A	Type of species Temperature	Biogenic emission (BVOC)

No	Reference	Objective (1)	Method (2)	Sampling area	Intrinsic (GI) and extrinsic characteristics(3)	Mechanisms
					Oxidative stress conditions Herbivory and pathogens attacks	
12	Matsunaga et al., 2013	Determine the biogenic emissions from mature trees	Enclosure technique + TENAX tubes	Shiiba, and Miyazaki, Japan	Seasonal effect Site conditions Species Leaf age	Biogenic emission (BVOC)
13	Loreto et al., 2014	Understand the effect of BVOC emission and interaction in urban environments	Literature review	N/A	Type of species Urban stress	Biogenic emission (BVOC)
14	Churkina et al., 2015	Study interactions between plants and urban ambient conditions and O3 formation	Literature review	N/A	Seasonal effect Temperature Tree age Leaf age	Biogenic emission (BVOC)
15	Chen J. et al., 2019	Investigate the composition of BVOC emissions, determine the dynamic normalised BVOC emission rates and clarify the effects of environmental variables, and physiological parameters on dynamic emission rates	Dynamic enclosure system	Beijing, China	Temperature Light intensity Species Net photosynthetic rate Stomatal conductance Transpiration rate	Biogenic emission (BVOC)
16	Baraldi et al., 2019	Examine species-specific leaf functional traits, assess species specific VOC emission, estimate at plant level PM10 and O3 removal and assess CO2 storage and sequestration	SEM + i-Tree software	Bologna, Italy	Type of species	Biogenic emission (BVOC), absorption
17	Chen J. et al., 2020	Evaluate temporal emission patterns, get a better understanding of the driving factors (e.g., environmental variables and physiological parameters) for the observed BVOC variations.	Dynamic enclosure technique	Beijing, China	Temperature PAR Net photosynthetic rate Transpiration rate Stomatal Conductance Intercellular CO2 concentration Growing season	Biogenic emission (BVOC)
18	Yuan Y. et al., 2020	Investigated BVOC emissions and study leaf structure and longevity (evergreen vs. deciduous), growth form (shrub vs. tree) and temperature, light and water requirements to characterise the overall frequency of volatile emissions in relation to species characteristics.	Semi-closed system	Southeast China	Foliage Species Water content Robust leaves Stress tolerant species	Biogenic emission (BVOC)
19	Li S. et al., 2021	Investigate BVOC emissions from leaves and fruits	Static enclosure technique	Beijing, China	Species Leaf age	Biogenic emission (BVOC)

(1) GI – Green Infrastructure
(2) RANS - Reynolds-averaged Navier–Stokes equations, SEM - Scanning Electron Microscope, SEM-EDS - Scanning Electron Microscopy with Energy Dispersive Spectroscopy
(3) N/A - Not applicable.
LAD - Leaf Area Density, LAI – Leaf Area Index, PAR - Photosynthetically active radiation

- ## Discussion Chapter 4

Table 2. List of species with high absorption of pollutants and tolerant to air pollution.

Deciduous tree with larger stomata conductance (1)	**Tolerant to air pollution (2)**	
Fagus japonica	*Acer platanoides*	*Malus (all)*
Weigela floribubda	*Acer pseudoplatanus*	*Mespilus germanica*
Firniana simplex	*Aesculus (all)*	*Metasequoia glyptostroboides (conifer)*
Ulmus davidiana	*Ailanthus altissima*	*Morus nigra*
Lagerstroemia indica	*Alnus cordata*	*Platanus (all)*
Stachyurus praecox	*Alnus glutinosa*	*Populus*
Ginkgo biloba	*Alnus cordata*	*Prunus avium*
Euronymus sieboldianus	*Alnus incana*	*Prunus cerasifera*
Certis chinensis	*Amelanchier*	*Prunus (Japanese cherries)*
Cronus controversa	*Betula kenaica*	*Prunus padus*
Magnolia stellata	*Betula pendula*	*Pterocarya (all)*
Hamamelis virginiana	*Carpinus betulus*	*Pyrus*
Robinia pseudoacasia	*Catalpa bignonioides*	*Quercus x crenata*
Batula tauschii	*Crataegus*	*Quercus ilex*
Fosythia suspensa	*Davidia involucrata*	*Rhus (all)*
Liriodendron tulipifera	*Eucalyptus*	*Robinia pseudoacacia*
Sambucus sieboldiana	*Fagus (all)*	*Rosa*
Prunus sargentii	*Fraxinus (all)*	*Salix*
Lespedeza bicolor	*Ginkgo biloba (conifer)*	*Sorbus aria*
Sapium sebiferum	*Ilex x altaclerensis*	*Sorbusaucuparia*
Carylopsis spicata	*Ilex aquifolium*	*Taxus baccata (conifer)*
Prunus itosakura	*Laburnum*	*Taxus x media (conifer)*
Quercus mongolia	*Ligustrum lucidum*	*Tilia x euchlora*
Prunus persica	*Liriodendron tulipifera*	*Tilia x europaea*
Castanea crenata	*Magnolia grandiflora*	*Tilia x platyphyllos*
Diospyros kaki	*Magnolia x loebneri*	*Torreya californica (conifer)*
Quercus acutissima	*Magnolia x soulangeana*	
Celastrus orbiculatus		
Prunus mume		
Hibiscus syriacus		
Juglans regia		
Catalpa ovata		
Populus nigra		
Junglans sieboidiana		
Certis sinensis		
Melia azedarach		
Broussonetia kazinoki		
Ailanthus altissima		
Zelkoba serrata		
Paulownia tomentosa		
Styrax japonica		

(1) Omasa, K., Tobe, K., & Kondo, T. (2002). Absorption of Organic and Inorganic Air Pollutants by Plants. In Air Pollution and Plant Biotechnology (pp. 155-178).

(2) Hillier Nurseries, & RHS. (2019). The Hillier Manual of Trees & Shrubs: Revised & updated with 1,500 new plants (R. L. Dawn Edwards & Rosalyn Marshall, Richard Sandfor, Ninth Ed). London: Royal Horticultural Society.

4 Appendix D. Dispersion

• Results Chapter 5 - General information

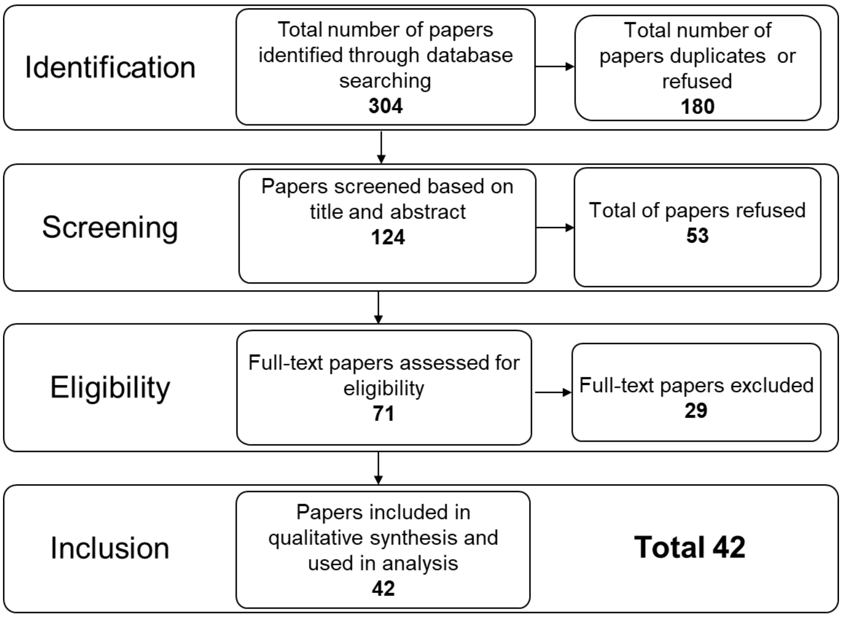


Figure 1. Systematic filtration and selection process for literature identified at the initial identification and scoping phase.

Table 1. Summary of the selected articles for inclusion for the literature review on dispersion.

No	Reference	Objective [(1)]	Method [(2)]	Sampling area	GI Characteristics [(3)]	Mechanisms
1	Khan and Abbasi, 2000	Describe a case of study in which a greenbelt was designed	Literature review + case of study	N/A	Wind velocity; Canopy Leaf traits; Stomata resistance	De, Dis, Ab
2	Ries & Eichhorn, 2001	Demonstrate the effect of vegetation in mass concentrations	Numerical model MISCAM	N/A	Type of vegetation; Wind speed Leaf area and density	Dis
3	Tiwary et al., 2005	Assess the role of hedgerows in the near-ground through-flow deposition process	CFD model	N/A	Wind velocity; Foliage; Leaf traits; Porosity	De; Dis
4	Shan Y. et al., 2007	Discuss the best configuration of vegetation in traffic greenbelts	Monitoring data	Shanghai, China	Canopy density Porosity	Dis
5	Balczo et al., 2009	Investigate the influence of trees planted along street	CFD model - MISKA	N/A	Leaf area density	Dis
6	Buccolieri et al., 2009	Analyse aerodynamic effect of tree planting on pollutant concentration	CFD model - FLUENT	N/A	Street canyon aspect ratio Wind speed; Crown porosity Tree positioning and arrangement	Dis
7	Salim et al., 2011	Study the aerodynamic effect of trees and compare their results with previous research	CFD model - FLUENT	N/A	Street canyon aspect ratio	Dis
8	Baik et al., 2012	Examine the effects of building roof greening on air quality in street canyons	CFD model - RANS	Seoul, Korea	Green infrastructure Wind direction	Dis
9	Hagler et al., 2012	Quantify the impact of a narrow roadside tree stand on near-road and on -road air pollution	Air sampler, portable Aethalometer	North Carolina, USA	Tree species; Tree stand; GI location	Dis
10	Wania et al., 2012	Evaluate the effect of trees and hedges in different street configurations	ENVI-met model	N/A	Type of GI; Wind velocity; Street design	De; Dis
11	Ng et al., 2012	Examine the effects of vegetation on pollutant dispersion	CFD model - FLUENT	N/A	Canopy density; GI arrangements	Dis
12	Vos et al., 2013	Investigate how urban vegetation can be used to improve the local air quality	ENVI-met model	N/A	Type of pollutant; Street design Type of GI; Wind direction Porosity; Height; Filter capacity	De; Dis
13	Chen X. et al., 2015	Study the accumulation of particles on leaf surfaces	Gravimetric	Wuhan, China	Type of GI; Leaf traits	De; Dis
14	Gallagher et al., 2015	Examine the effectiveness of vegetation barrier to optimise local dispersion	Literature review	N/A	Build environment; Meteorological parameters; Air flow; Crown ; Porosity; Street design; Tree density; Tree height Tree spacing	Dis
15	Vranckx et al., 2015	Examine the influence of vegetation on the concentrations of traffic pollutants in urban street canyons	CFD model - OpenFOAM	Antwerp, Belgium	Vegetation type; Wind direction; Type of pollutants; Porosity; Deposition velocity	Dis
16	Hofman et al., 2016	Evaluate the effect of a detailed tree crown representation on the PM_{10} concentrations	ENVI-met model	Antwerp, Belgium	3D trees; Tree crown	De ; Dis

No	Reference	Objective (1)	Method (2)	Sampling area	GI Characteristics (3)	Mechanisms
17	Neft et al., 2016	Understand the effect of vegetation on wind flow	CFD model - CONVERGE	N/A	LAD; Deposition velocity	De; Dis
18	Morakinyo et al., 2016a	Investigate the combined role of near-road vegetation barrier on dispersion and mass removal in an open-street environment	ENVI-met model	N/A	Thickness; GI location; LAD; Particle size	De; Dis
19	Morakinyo et al., 2016b	Investigate the effect of two types of vegetation barrier on dispersion	ENVI-met model	Kowloon, Hong Kong	Wind direction; Height; Thickness GI location; LAD; Type of GI.	De Dis
20	Tong Z. et al., 2016	Study the effectiveness of vegetation barrier as a potential mitigation strategy	CTAG model + field data	N/A	Density. Particle size; Wind direction LAD; Width; GI location; Height	De Dis
21	Selmi et al., 2016	Demonstrate the potential of urban trees to improve air quality	i-Tree model	Strasbourg, France	Tree cover; Meteorological parameters Foliage; Pollutants	De Dis
22	Gromke et al., 2016	Study the effect of roadside hedges on pollutant dispersion	Wind tunnel experiment	N/A	Wind direction; GI location; Permeability	Dis
23	Li et al., 2016	Investigate the impacts of vegetation barrier and attempt to find the optimal vegetation barrier height to reduce pollutants on streets	CFD model-FLUENT	Shanghai, China	Wind direction; Street design; Height	De Dis
24	Hong et al., 2017	Evaluate the effect of vegetation characteristics and ambient $PM_{2.5}$ dispersion	CFD model - Phoenics	N/A	Tree crown morphologies; LAD; Tree aspect ratio	Dis
25	Abhijith et al., 2017	Develop generic recommendations on the selection and design characteristics of suitable green infrastructure in different urban environments	Literature review	N/A	Type of GI; Street design; Tree crown LAI and LAD; Porosity; Thickness Tree spacing ; GI location; Stand density; Type of GI; Meteorological parameters	De Dis
26	Xue & Li, 2017	Evaluate the aerodynamic and deposition effects of trees on street canyon air quality	CFD model - Pheonics	N/A	Porosity; LAD; Species (deposition velocity); Wind direction	De Dis
27	Baldauf et al., 2017	Describe the characteristics of roadside vegetation	Literature review	N/A	Type of GI; Vegetation emissions Leaf traits; Seasonal effects Porosity; Density; Thickness Vegetation cover; Vegetation height	De Dis
28	Jeanjean et al., 2017	Investigate the effect of tree in a real scenario	CFD model - OpenFOAM	London, UK	Building environment; Tree species Deposition velocity	De, Dis
29	Moradpour et al., 2017	Investigate the effects of vegetation on the dispersion of reactive air pollutants in the urban environment	CFD model - RANS	N/A	LAD; Tree aspect ratios	Dis
30	Rafael et al., 2018	Study the effect of green infrastructure to improve local air quality	CFD model - VADIS	Porto, Portugal	Traffic emission ; Wind direction Wind Velocity; Street canyon; LAD	Dis
31	Qin et al., 2018	Evaluate the influence of green roofs and green walls on airflow fields and PM10 dispersion under different leaf area densities	CFD model - Phoenics	N/A	LAD; Aspect ratio; Greenery coverage Type of GI; LAI; Precipitation	De Dis
32	Buccolieri et al., 2018	Assess the effect of trees of different leaf area density on ventilation, Nox and PM2.5	CFD model - OpenFoam	London, UK	Meteorological parameters; LAD	De Dis

No	Reference	Objective $^{(1)}$	Method $^{(2)}$	Sampling area	GI Characteristics $^{(3)}$	Mechanisms
33	Tiwari et al., 2019	Detailed review of parameterisation for GI modelling. Evaluate the effectiveness of microscale and macroscale air pollution dispersion models to estimate pollutant concentration reductions by GI.	Literature review	N/A	Type of GI; Type of pollutant Chemical properties of pollutants Wettability; Porosity; Meteorological parameters; Build environment	De Dis Ab
34	Abhijith & Kumar, 2019	Assess the air quality improvement potential of different type of GI in the near-road environment	Aerosol monitors +SEM-EDS	Guildford, UK.	Type of GI; LAD; Type of pollutant GI Location ; Wind direction; Thickness	De Dis
35	Santiago et al., 2019	Study the effective type of vegetative barrier to improve air quality	CFD model (STAR-CCM+from Siemens) - RANS	Pamplona, Spain	Vegetation width; Vegetation height Type of GI.	De Dis
36	Taleghani et al., 2020	Evaluates the temporal variations of NO2	ENVI-met model	Manchester, UK.	Type of GI.	De Dis
37	Tiwari A. & Kumar, 2020	Evaluate the effectiveness of GI under different scenarios	ADMS-Urban model	Guildford, UK	GI location; Pollutant concentration GI Percentage cover; Type of GI GI's geometry; LAD; Density	De Dis
38	Abhijith & Kumar, 2020	Quantify the deposition and overall PM reduction by GI in near-road environments	SEM	Guildford, UK.	Seasonal effects; Vegetation height Particle size	De Dis
39	Moradpour & Hosseini, 2020	Study the impacts of GI on air quality	CFD model - Fluidyn-PANACHE	Tehran, Iran	Wind direction; Pollutant concentration LAD	De Dis
40	Ottosen & Kumar, 2020	Assess the influence of annual vegetation cycle, wind direction and hight across a hedge	Low-cost air quality monitors	Guildford, UK.	Vegetation cycle; Type of pollutant Type of GI; Wind direction	De Dis
41	Jo et al., 2020	Quantify the carbon uptake and PM2.5 deposition on street trees	Mathematical model	Republic of Korea	Species; Density; Tree size; Type of GI.	De Dis
42	Tomson et al., 2021	Summarise previous research on GI in street canyons and assess the suitability of different GI forms in terms of local air quality improvement	Literature review	N/A	Type of GI; Micro and macro morphology; Leaf traits; Street design	De Dis

(1) GI – Green Infrastructure

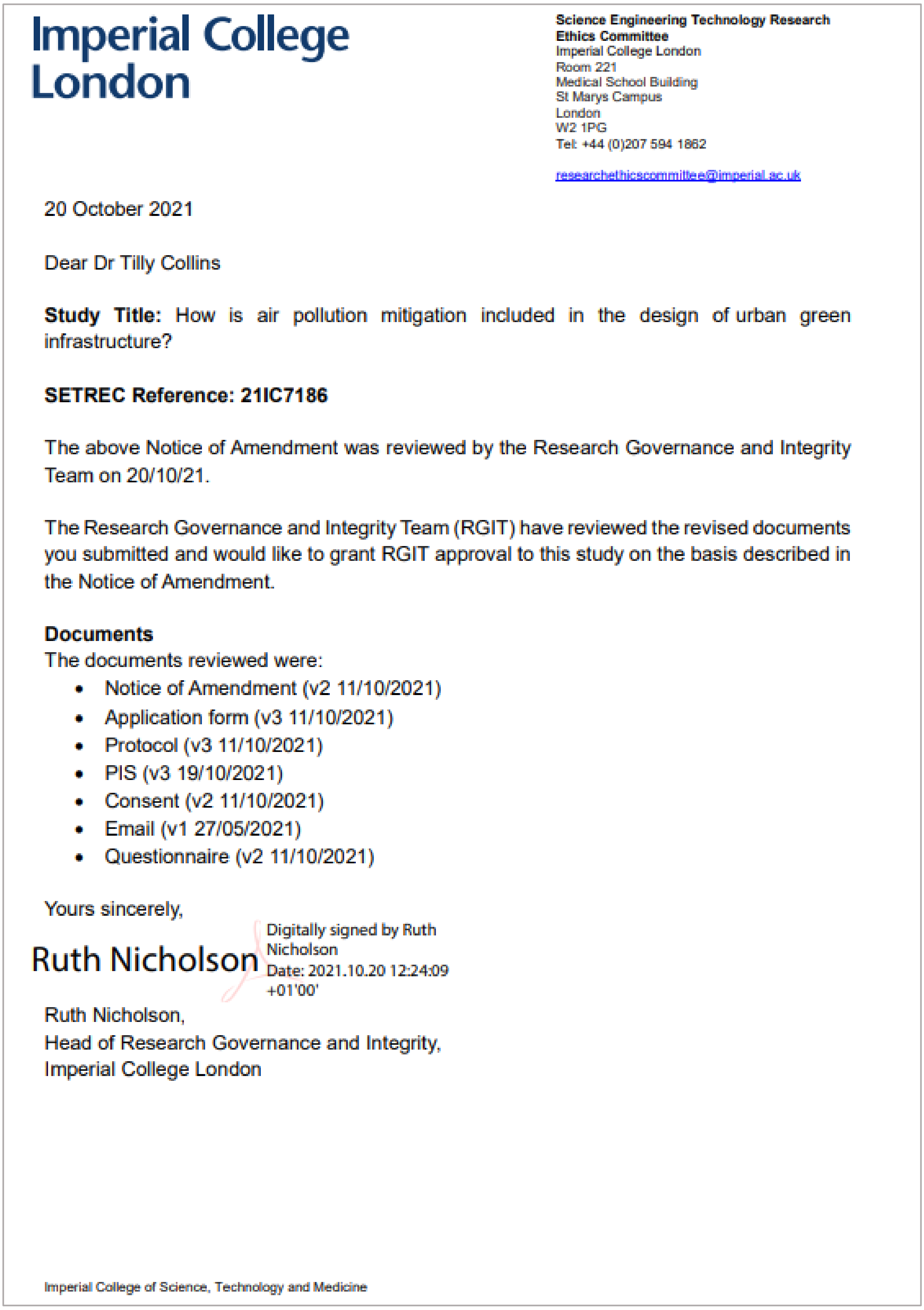
(2) RANS - Reynolds-averaged Navier–Stokes equations. SEM - Scanning Electron Microscope, SEM-EDS - Scanning Electron Microscopy with Energy Dispersive Spectroscopy, CTAG = Comprehensive Turbulent Aerosol Dynamics and Gas Chemistry

(3) N/A - Not applicable, LAD - Leaf Area Density, LAI – Leaf Area Index, PAR - Photosynthetically active radiation

(4) De = deposition. Dis = Dispersion, Ab = Absorption

5 Appendix E. Survey

Method Chapter 6 – Ethical approval



Imperial College London

Science Engineering Technology Research Ethics Committee
Imperial College London
Room 221
Medical School Building
St Marys Campus
London
W2 1PG
Tel: +44 (0)207 594 1862

researchethicscommittee@imperial.ac.uk

20 October 2021

Dear Dr Tilly Collins

Study Title: How is air pollution mitigation included in the design of urban green infrastructure?

SETREC Reference: 21IC7186

The above Notice of Amendment was reviewed by the Research Governance and Integrity Team on 20/10/21.

The Research Governance and Integrity Team (RGIT) have reviewed the revised documents you submitted and would like to grant RGIT approval to this study on the basis described in the Notice of Amendment.

Documents
The documents reviewed were:

- Notice of Amendment (v2 11/10/2021)
- Application form (v3 11/10/2021)
- Protocol (v3 11/10/2021)
- PIS (v3 19/10/2021)
- Consent (v2 11/10/2021)
- Email (v1 27/05/2021)
- Questionnaire (v2 11/10/2021)

Yours sincerely,

Ruth Nicholson Digitally signed by Ruth Nicholson
Date: 2021.10.20 12:24:09 +01'00'

Ruth Nicholson,
Head of Research Governance and Integrity,
Imperial College London

Imperial College of Science, Technology and Medicine

- **Method Chapter 6 – Statistical evaluation**

Section 1: Respondent information

- Organisation
- Position
- Years of experience
- Qualification for role/position
- Work city, area or region

Section 2: GI definition

1.1. Do you think there is a common understanding of green infrastructure in your workplace?

○ Yes
○ Yes, but some differences between people/departments
○ I don't know
○ No consensus
○ Prefer not to say
○ Other

Section 3: Guides, recommendations, and resources available to practitioners

2.1. Do you consult any guidance or recommendations (books, websites etc.) when selecting appropriate street side green infrastructure? *Please, could you share the link or the name of your principal source?*

○ Yes, we consult guidance or recommendations.
Please provide the name/names of principal sources below
____
○ No, we do not consult any guidance or recommendations
○ Prefer not to say
○ Other ____________

2.2. Which of the following do you use to inform your planting decisions? *Please select the resource(s) that apply.*

○ Our own local strategic guidance or criteria
○ City-wide or National guidance
○ Current academic information
○ Guidance from professional bodies (landscaping or arboricultural)
○ Nursery staff recommendations (nursery guidelines)
○ Suggestions from local people (e.g., wildlife groups, stakeholders)
○ We do not follow specific guidance, our planting is based on practitioner experience
○ Prefer not to say
○ Other, please specify: __________________

2.3. How do you feel about the guidance documents you are using? *Please scale how you feel about the guidance document you use.*

	Totally agree	Agree	Neutral	Disagree	Totally disagree	Unsure
It needs membership to access						
It is easy to read and navigate						
Sometimes it is too technical						
A non-specialist could understand it						
It includes future maintenance applications						
It considers air pollution (e.g., specific species or plant characteristics)						
It considers biogenic volatile organic compounds emissions (BVOCs)						
It considers pollen						
It has clear principles of species selection						
It is up-to-date and reviewed regularly						
It identifies many benefits (multifunctionality) of GI.						

Section 4: Planting decision making

3.1. Do you have experience in planning/planting street side green infrastructure in cities?

- ○ Yes
- ○ No

3.2. In your experience, what aspects do you personally find the most challenging when planning street side plantings?
*Please select your top **three** aspects*

- ○ Economic aspects (cost of stock, planting, maintenance)
- ○ Social aspects (what local people want and value or other key stakeholders)
- ○ Designing the best (most suitable) infrastructure type
- ○ Identifying the best species
- ○ Identifying the best locations for successful planting
- ○ Future maintenance (planning, extra resources, and costs)
- ○ Considering and optimising multiple co-benefits
- ○ Time available for planting
- ○ There are no challenging aspects
- ○ Prefer not to say
- ○ Other, please specify: _____________

3.3. Which of the following options would you like to have access to improve your planting decisions? *Please select **two** options that you find necessary*

- ○ Scientific journals
- ○ Academic seminars
- ○ Easy-to-use modelling tool
- ○ Practical workshops
- ○ Other, please specify: ________________

3.4. How often do you aim to provide the following benefits when planting street side green infrastructure? *With one being not often to five being very often.*

	Not often			Very often	
	1	2	3	4	5
Soil quality improvements					
Water management improvements					
Urban cooling (urban heat island)					
Air pollution improvement					
Air flow manipulation					
Enhanced cultural connections and sense of place					
Improved health and wellbeing					
Increased land-values (economic improvements)					
Improved aesthetics					
Enhanced biodiversity					

3.5. Are there any other benefits that you often seek to provide when designing street side green infrastructure?

- ○ Yes, please specify: __________
- ○ No
- ○ Prefer not to say

3.6. For each site characteristic below, please rate how important or influential each characteristic is to your planting decisions. With one being not important to ten being extremely important

	Not important					Extremely important				
	1	2	3	4	5	6	7	8	9	10
Urban morphology (slope, building height etc.)										
Street/road type (e.g., urban canyon or open road)										
Street/road type (use - residential / shopping / quiet / busy)										
Rooting environment										
Future urban developments										
Meteorological conditions (wind direction, wind speeds, rainfall)										
Type of air pollution or pollutant concentrations present										
Type of soil pollution or pollutant concentrations present										
Matching other nearby species										
Site history: what other species were previously there										
Increasing biodiversity										
Budget										

Section 5: Species selection

4.1. Which type of street side green infrastructure do you most often plant?
*Please **rank** these by <u>dragging and dropping</u> each option into your chosen order of preference, with one being the most planted.*

_______ Tree
_______ Hedge
_______ Shrub
_______ Green wall
_______ Verges
_______ Other

4.2. What are the top five species you usually select when designing your street side plantings? Please type in the top five species you plant below.

4.3. For each **species characteristic** below, please rate how important or influential each characteristic is to your planting decisions. *With one being not important to ten being extremely important.*

	Not important						Extremely important			
	1	2	3	4	5	6	7	8	9	10
Size (height)										
Size (spread or crown shape)										
Longevity (life expectancy)										
Structural density (e.g., leaf area density)										
Leaf surface traits (waxy, hairy)										
Leaf shape (ovate, palmate, elliptic, linear)										
Water requirement										
Biogenic volatile compound emissions (BVOCs)										
Pollen production										
Flowering characteristics										
Fruiting characteristics										
Tolerance to soil conditions										
Adapted to future climate conditions										
Drought tolerant										
Pollution tolerant										
Species tolerant to traffic										
Pest and disease resistant										
Aesthetics										
Maintenance needs (e.g. regularity of pruning)										
Experience/familiarity with the species										
Evergreen / deciduous										
Native species										
Plant availability (nursery stock levels)										

4.4. How often is air pollution mitigation a main consideration when planning street side green infrastructure? *Please tick **one** of the following options*

○ Always
○ Most times, but not always
○ Very rarely
○ Never
○ Prefer not to say

4.5. How important do you think each of the following features are to consider when selecting street side green infrastructure **for air pollution mitigation**? *With one being not important to ten being extremely important*

	Not important					Extremely important				
	1	2	3	4	5	6	7	8	9	10
Type of green infrastructure (tree, hedge, shrub etc.)										
Plant species selection										
Species-specific leaf features										
Street/road type (e.g., urban canyon or open road)										
Location of green infrastructure										
Biogenic volatile organic compound emissions (BVOCs)										
Pollen emissions										

Section 6: Final comments

5.1. Please share any additional comments or suggestions about your experience of planting street side green infrastructure in cities.

Table 1. Modifications to the first wave questionnaire.

Modifications	First wave	Second wave
Respondent information	Position, years of experience, and qualification for role	City/area/region of work was added.
Questionnaire design	It was divided into 4 sections: Section 1. General definitions of green infrastructure Section 2. Guides, recommendations, and sources available to practitioners Section 3. Planting Characteristics Section 4. Species selection	Sections have been altered slightly: • Section 1 and 2 remain the same • Section 3. Planting decision making • Section 4. Final comments
Questions	Question 2.2. Which of the following do you use to inform your planting decisions? Please select the resource(s) that apply	Same question, but one alternative was added: *Nursery staff recommendations (nursery guideline)*
	Question 3.2. was: *What aspects do you personally find the most challenging when planning street side plantings? Please select your top three aspects.*	Question 3.2 was modified *3.2.. In your experience, what are the most challenging aspects of planning/planting green Infrastructure in street- scapes? Please select your top three aspects*
		A question *3.3. Which of the following options would you like to have access to improve your planting decisions* was added
	Question *3.5. For each site characteristic below, please rate how important or influential each characteristic is to your planting decisions* had 14 alternatives.	• Same question but it was number 3.6. • Two alternatives: *plant availability* and *nearby green spaces (access to green spaces)* were removed. • The alternative: *Planting context: what other species are near* was modified to *Matching other nearby species*
	Question 4.3. *For each species characteristic below, please rate how important or influential each characteristic is to your planting decisions* had 20 alternatives	• Two alternatives: *Species tolerant to traffic* and *Plant availability (nursery stock levels)* were added • One alternative: *Aesthetically pleasing* was modified to *aesthetics.*
Scales	The scale in tables was from 1 (very often/extremely important) to 5/10 (not often/not important)	The scale in the tables was reversed, leaving small numbers as minimum importance and larger numbers as extremely important. Scale from 1 (not often/not important) to 5/10 (very often/extremely important)
Follow-up	Considered a follow-up for an interview	The open box that offers follow-up for an interview was removed.

- **Results Chapter 7 – General information**

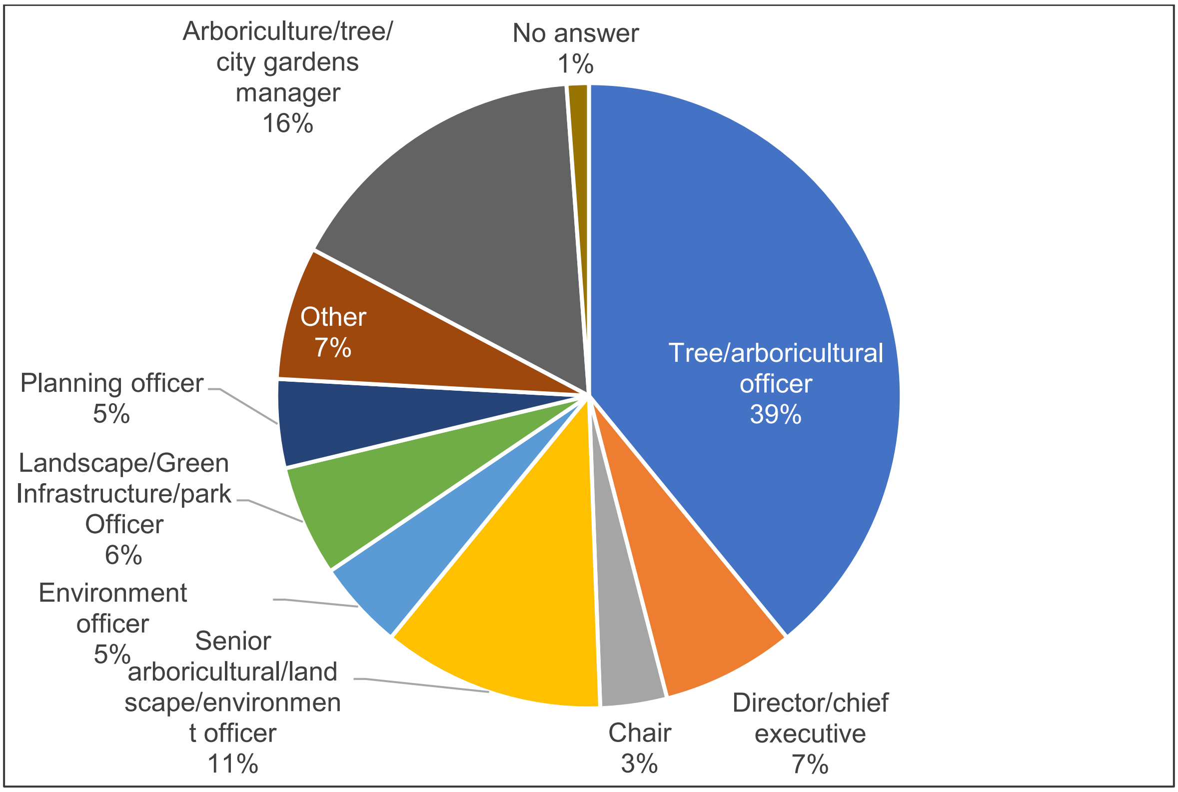


Figure 1. Job position of respondents.

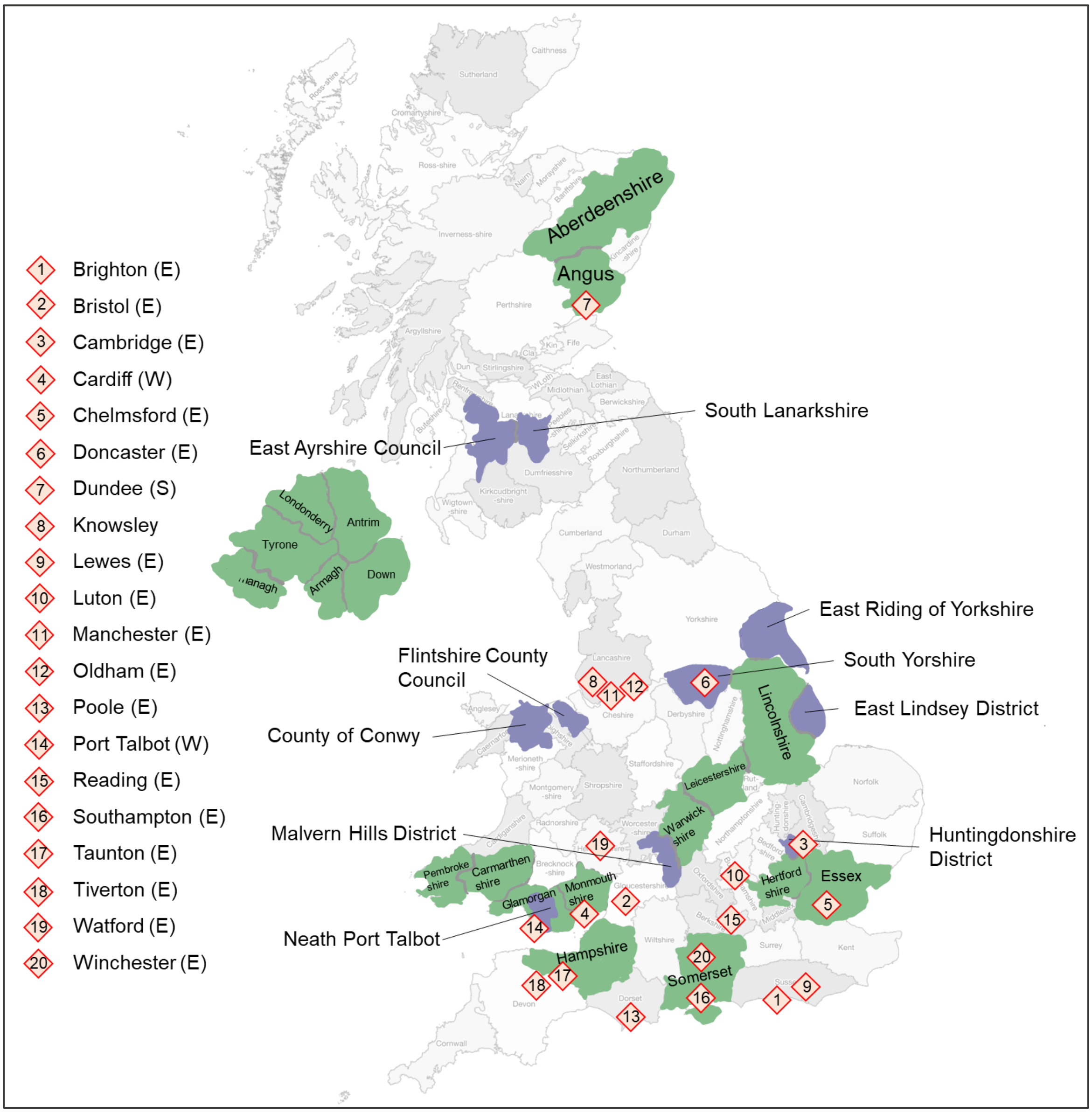


Figure 2. Geographic location of respondents. The red rhombus identifies specific cities in England (E), Scotland (S) and Wales (W). The purple colour represents particular district or council zone. The green colour represents counties represented in the survey.

Figure 3. London boroughs (green colour) represented in the survey.

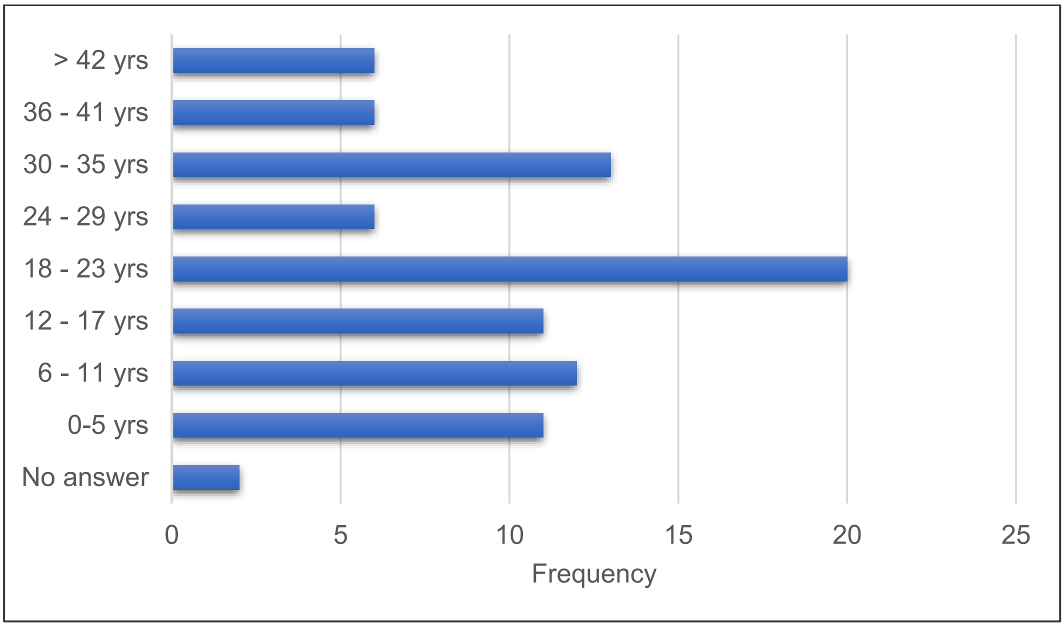


Figure 4. Year of experience of respondents.

Table 2. Most common planted species.

Family	Specific species	Frequency	Total	Percentage (%)
Acer (maple)		20	48	14
	Acer campestre	20		
	Acer campestre 'Elsrijk' or 'Streetwise'	2		
	Acer campestre 'Elegance'	1		
	Acer campestre 'Lineco'	1		
	Acer platanoides	3		
	Acer pseudoplatanus	1		
Prunus (cherry)		23	37	10
	Prunus 'Sunset Boulevard'	3		
	Prunus 'accolade'	2		
	Prunus Hillieri Spire	1		
	Prunus incise Louisa Leo	1		
	Prunus avium	4		
	Prunus sargentii 'Rancho'	1		
	Prunus ‘Amanogawa’	1		
	Prunus serrula	1		
Tillia (lime)		13	31	9
	Tilia cordata	5		
	Tilia Tomentosa	1		
	Tilia euchlora	1		
	Tilia 'Rancho'	1		
	Tilia × europaea	10		
Betula (birch)		21	30	8
	Betula Ermanii	2		
	Betula utilis Jaquemontii	1		
	Betula pendula	5		
	Betula kenaica	1		
Sorbus (rowan)		18	26	7
	Sorbus aucuparia ' Sheerwater Seedling'	4		
	Sorbus torminalis	2		
	Sorbus Aria	1		
	Sorbus intermedia	1		
Quercus (common oak)		9	25	7
	Quercus ilex	2		
	Quercus palustris	3		
	Quercus koster	1		
	Quercus robur 'Fastigiata'	1		
	Quercus robur	8		
	Quercus robur ‘Koster’	1		
Carpinus sp. (hornbeam)		2	18	5
	Carpinus betulus fastigiata	2		
	Carpinus betulus	14		
Liquidambar (star gum)		8	17	4.8
	Liquidambar styraciflua (Sweet gum)	9		
Platanus (plane)		4	16	4.5
	Platanus x hispanica	7		
	Platanus acerifolia	5		
Pyrus (common pear)		3	13	4
	Pyrus calleryana 'Chanticleer'	8		
	Pyrus calleryana	2		
Crataegus sp. (hawthorn)		10	10	3
Ginkgo biloba (Maidenhair tree)		10	10	3

Table 3. Descriptive and statistical analysis of green infrastructure characteristics and local parameters for two groups of respondents. Group 1 (G1) grouped the alternative 'Always' or 'Most of the time' and Group 2 (G2) 'Very rarely' or 'Never' consider air pollution mitigation in urban planning street side Green Infrastructure.

		Group 1. Always or most of the time					**Group 2. Very rarely or never**												
		Descriptive analysis					**Descriptive analysis**					**Parametric statistical analysis**				**Non-parametric statistical analysis**			
No Question	**Characteristics**	**Mean**	**Median**	**Lower CI 95%**	**Upper CI 95%**	**Total**	**Mean**	**Median**	**Lower CI 95%**	**Upper CI 95%**	**Total**	**Mean diff**	**t - test**	**df**	**p**	**U - test**	**Z**	**r**	**p**
3.4	Soil quality improvements	2.53	2.00	2.19	2.87	51	2.27	2.00	1.86	2.68	34	0.26	0.65	83	0.517	783	-0.78	0.08	0.437
3.4	Water management improvements	3.35	3.00	2.99	3.71	51	2.70	3.00	2.18	3.22	34	0.65	2.06	83	0.043	653.5	-1.96	0.21	0.05
3.4	Urban cooling (urban heat island)	4.06	5.00	3.71	4.41	51	3.06	3.00	2.59	3.53	35	1.00	3.27	84	0.002	536	-3.26	0.35	0.001
3.4	Air pollution improvement	4.25	4.00	4.02	4.53	51	2.97	3.00	2.57	3.37	34	1.28	5.68	84	<0.001	331.5	-5.12	0.55	<0.001
3.4	Air flow manipulation	2.67	2.00	2.25	3.09	51	1.76	2.00	1.43	2.09	33	0.91	3.12	82	0.002	560	-2.69	0.29	0.007
3.4	Enhanced cultural connections and sense of place	3.76	4.00	3.44	4.09	51	3.70	4.00	3.29	4.11	33	0.07	0.26	82	0.794	814	-0.26	0.03	0.793
3.4	Improved health and wellbeing	4.47	5.00	4.24	4.70	51	4.21	4.00	3.91	4.52	35	0.26	1.32	84	0.191	732	-1.58	0.17	0.115
3.4	Increased land-values (economic improvements)	2.69	3.00	2.33	3.04	51	2.39	2.00	1.93	2.85	34	0.30	1.17	83	0.244	732	-1.24	0.13	0.214
3.4	Improved aesthetics	4.55	5.00	4.32	4.78	51	4.58	5.00	4.36	4.79	35	-0.03	-0.14	84	0.89	858.5	-0.36	0.04	0.719
3.4	Enhanced biodiversity	4.31	5.00	4.05	4.57	51	4.03	4.00	3.63	4.43	34	0.28	1.14	83	0.258	761	-1.04	0.11	0.3
3.6	Urban morphology (slope, building heights etc.)	8.16	8.00	7.72	8.61	51	5.97	6.00	5.04	6.90	35	2.19	4.91	84	<0.001	458	-3.87	0.42	<0.001
3.6	Street/road type (e.g., urban canyon or open road)	8.27	9.00	7.82	8.71	50	7.35	8.00	6.65	8.06	35	0.92	2.64	83	0.01	616.5	-2.35	0.26	0.019
3.6	Street/road type (use – residential / shopping / quiet / busy)	8.27	8.00	7.74	8.79	51	8.03	8.50	7.38	8.67	35	0.24	0.94	84	0.348	798	-0.85	0.09	0.396
3.6	Rooting environment	8.98	10.0	8.58	9.38	51	8.18	9.00	7.48	8.88	35	0.80	2.17	84	0.033	686	-1.92	0.21	0.054
3.6	Future urban developments	7.61	8.00	6.93	8.29	51	6.03	6.00	5.19	6.87	35	1.58	3.22	84	0.002	533	-3.2	0.34	0.001
3.6	Meteorological conditions (wind direction, wind speeds, rainfall)	6.88	7.00	6.23	7.53	51	6.32	7.00	5.49	7.16	35	0.56	1.27	84	0.206	750.5	-1.26	0.14	0.207
3.6	Type of air pollution or pollutant concentrations present	7.00	7.00	6.34	7.66	51	4.03	4.00	3.23	4.83	34	2.97	5.95	83	<0.001	322.5	-4.92	0.53	<0.001

		Group 1. Always or most of the time					Group 2. Very rarely or never												
		Descriptive analysis					Descriptive analysis					Parametric statistical analysis				Non-parametric statistical analysis			
3.6	Type of soil pollution or pollutant concentrations present	6.88	7.00	6.19	7.57	51	4.38	4..5	3.54	5.22	34	2.50	4.72	83	<0.001	386	-4.35	0.47	<0.001
3.6	Matching other nearby species	6.41	7.00	5.66	7.16	52	5.91	6.00	5.11	6.71	35	0.50	0.80	85	0.429	783.5	-1.11	0.12	0.269
3.6	Site history: what other species were previously there	7.78	8.00	7.23	8.32	51	6.91	7.50	6.13	7.69	35	0.87	2.18	84	0.032	654	-2.14	0.23	0.032
3.6	Increasing biodiversity	8.33	9.00	7.89	8.77	51	7.03	7.00	6.28	7.78	35	1.30	3.44	84	<0.001	545	-3.11	0.33	0.002
3.6	Plan availability *	7.69	8.00	6.76	8.61	16	7.12	8.50	4.39	9.86	8	0.57	-0.56	22	0.580	58	-0.38	0.08	0.742
3.6	Budget	8.35	9.00	7.76	8.93	50	7.44	8.00	6.59	8.30	35	0.91	1.62	83	0.108	708	-1.55	0.17	0.122
3.6	Nearby green spaces (access to green spaces)*	7.44	8.00	6.25	8.62	16	6.00	6.50	4.16	7.84	8	1.44	-1.50	22	0.158	36.5	-1.72	0.35	0.093
4.3	Size (height)	8.94	10.0	8.49	9.39	51	8.30	8.00	7.78	8.82	34	0.64	1.68	83	0.096	635.00	-2.18	0.24	0.03
4.3	Size (spread or crown shape)	9.10	10.0	8.74	9.46	51	8.61	9.00	8.11	9.10	34	0.49	1.57	83	0.121	686.00	-1.73	0.19	0.08
4.3	Longevity (life expectancy)	7.63	8.00	7.02	8.24	51	6.82	7.00	6.18	7.45	34	0.81	1.74	83	0.086	637.00	-2.09	0.23	0.04
4.3	Structural density (e.g., leaf area density)	7.06	8.00	6.43	7.70	51	5.73	6.00	5.01	6.44	34	1.33	2.68	83	0.009	563.00	-2.77	0.30	0.01
4.3	Leaf surface traits (waxy, hairy, study)	5.33	5.00	4.58	6.08	51	4.09	4.00	3.28	4.90	33	1.24	2.15	82	0.035	624.00	-2.01	0.22	0.04
4.3	Leaf shape (e.g., ovate, palmate, elliptic, linear)	4.35	4.00	3.62	5.08	51	3.39	3.00	2.59	4.20	34	0.96	1.59	83	0.116	690.50	-1.60	0.17	0.11
4.3	Water requirement	7.96	8.00	7.39	8.53	51	6.79	7.00	6.03	7.55	34	1.17	2.35	83	0.021	606.00	-2.38	0.26	0.02
4.3	Biogenic volatile compound emissions (BVOCs)	5.04	5.00	4.27	5.81	51	3.39	3.00	2.67	4.11	34	1.65	2.94	83	0.004	568.50	-2.71	0.29	0.01
4.3	Pollen production	6.14	6.00	5.47	6.82	51	3.70	3.00	3.00	4.40	34	2.44	4.36	83	<0.001	437.50	-3.89	0.42	<0.001
4.3	Flowering characteristics	7.18	7.00	6.59	7.78	50	5.39	6.00	4.66	6.13	34	1.79	3.72	82	<0.001	486.00	-3.35	0.37	<0.001
4.3	Fruiting characteristics	7.65	8.00	7.10	8.21	51	6.12	6.00	5.37	6.87	33	1.53	3.26	82	0.002	507.50	-3.09	0.34	<0.001
4.3	Tolerance to soil conditions	8.37	9.00	7.84	8.89	51	6.79	7.00	5.97	7.61	34	1.58	3.35	83	0.001	525.50	-3.12	0.34	<0.001
4.3	Adapted to future climate conditions	8.35	9.00	7.84	8.85	51	6.94	8.00	6.28	7.60	34	1.41	3.41	83	0.001	476.50	-3.57	0.39	<0.001
4.3	Drought tolerant	8.20	8.00	7.68	8.73	51	6.58	7.00	5.84	7.31	34	1.62	3.64	83	<0.001	473.50	-3.58	0.39	<0.001
4.3	Pollution tolerant	8.00	8.00	7.54	8.46	51	5.48	6.00	4.63	6.34	34	2.52	5.60	83	<0.001	349.50	-4.70	0.51	<0.001
4.3	Species tolerant to traffic	7.89	8.00	7.22	8.55	35	5.69	6.00	4.62	6.76	26	2.20	3.74	59	<0.001	235.50	-3.23	0.41	<0.001

		Group 1. Always or most of the time					Group 2. Very rarely or never												
		Descriptive analysis					**Descriptive analysis**					**Parametric statistical analysis**				**Non-parametric statistical analysis**			
4.3	Pest and disease resistant	8.73	9.00	8.29	9.18	51	7.18	7.00	6.52	7.85	34	1.55	4.02	83	<0.001	444.50	-3.89	0.42	<0.001
4.3	Aesthetics	7.96	8.00	7.41	8.51	51	7.61	8.00	6.97	8.24	34	0.35	0.82	83	0.417	750.50	-1.07	0.12	0.29
4.3	Maintenance needs (e.g., regularity of pruning)	8.33	9.00	7.80	8.85	51	7.06	8.00	6.27	7.85	34	1.27	2.79	83	0.007	548.00	-2.91	0.32	<0.001
4.3	Experience/familiarity with the species	7.18	8.00	6.53	7.84	50	6.42	7.00	5.63	7.22	34	0.76	1.35	82	0.180	674.50	-1.63	0.18	0.10
4.3	Evergreen / deciduous	6.59	7.00	5.87	7.32	51	5.36	6.00	4.54	6.19	34	1.23	2.19	83	0.031	622.50	-2.21	0.24	0.03
4.3	Native species	5.90	6.00	5.08	6.72	51	5.30	6.00	4.31	6.30	34	0.60	0.88	83	0.381	772.00	-0.86	0.09	0.39
4.3	Plant availability (nursery stock levels)	7.83	8.00	7.11	8.55	35	7.12	7.00	6.26	7.97	26	0.71	1.31	59	0.196	367.00	-1.31	0.17	0.19
4.5	Type of green infrastructure (tree, hedge, shrub etc.)	8.49	9.00	8.02	8.96	51	8.03	8.00	7.29	8.77	33	0.46	1.11	82	0.268	748.00	-0.88	0.10	0.38
4.5	Plant species selection	8.84	9.00	8.40	9.29	51	8.03	8.00	7.30	8.76	33	0.81	2.04	82	0.044	628.00	-2.04	0.22	0.04
4.5	Species-specific leaf features	6.94	7.00	6.28	7.60	51	6.00	7.00	5.00	7.00	33	0.94	1.65	82	0.102	675.50	-1.54	0.17	0.12
4.5	Street/road type (e.g., urban canyon or open road)	8.63	9.00	8.27	8.98	51	7.88	8.00	7.19	8.57	33	0.75	2.14	82	0.035	650.50	-1.80	0.20	0.07
4.5	Location of green infrastructure	8.69	9.00	8.33	9.04	51	8.30	9.00	7.57	9.04	33	0.38	1.05	82	0.296	804.50	-0.36	0.04	0.72
4.5	Bioorganic volatile organic compound emissions (BVOCs)	6.27	7.00	5.44	7.11	51	5.27	5.00	4.38	6.17	33	1.00	1.60	82	0.114	641.00	-1.85	0.20	0.06
4.5	Pollen emissions	6.41	6.00	5.74	7.08	51	5.00	5.00	4.18	5.82	33	1.41	2.68	82	0.009	568.50	-2.52	0.28	0.01

* Only data for the 2nd wave

Table 4. Descriptive statistical analysis of the survey for two groups of respondents. Group 1 (G1) grouped the alternative 'Always' or 'Most of the time', and Group 2 (G2) 'Very rarely' or 'Never' considered air pollution mitigation in urban planning street-side Green Infrastructure.

		Group 1. Always or most of the time			Group 2. Very rarely or never		
		Descriptive analysis			Descriptive analysis		
No Question	**Alternatives**	**Count**	**Mean**	**Standard deviation (1)**	**Count**	**Mean**	**Standard deviation (1)**
1.1. Do you think there is a common understanding of green infrastructure in your workplace?	Yes	12	23.1	0.895	10	28.6	0.873
	Yes, but some differences between people/departments	32	61.5		21	60.0	
	I don't know	1	1.9		0	0	
	No consensus	7	13.5		4	11.4	
2.1. Do you consult any guidance or recommendations (books, websites etc.) when selecting appropriate street side green infrastructure?	Yes, we consult	45	86.5	0.637	22	62.9	1.056
	No, we do not	5	9.6		8	22.9	
	Other	2	3.8		5	14.3	
2.2. Which of the following do you use to inform your planting decisions?	Our own local strategic guidance or criteria	32	61.5	Not applicable	19	54.3	Not applicable
	City-wide or National guidance	26	50.0		11	31.4	
	Current academic information	27	51.9		13	37.1	
	Guidance from professional bodies	33	63.5		24	68.6	
	Nursery staff recommendations	14	26.9		8	22.9	
	Suggestion from local people	25	48.1		8	22.9	
	We do not follow specific guidance; our planting is based on practitioner experience	10	19.2		6	17.1	
	Prefer not to say	0	0		5	5.1	
	Other	11	21.2		7	20.0	
3.1. Do you have experience in planning/planting street side green infrastructure in cities?	Yes	44	84.6	0.279	25	71.4	0.448
	No	4	7.7		9	25.7	
3.2. In your experience, what aspects do you personally find the most challenging when planning street side plantings?	Economic aspects (cost of stock, planting, maintenance)	19	36.5	Not applicable	15	42.9	Not applicable
	Social aspects (what local people want and value or other key stakeholders)	18	34.6		15	42.9	

	Designing the best (most suitable) infrastructure type	11	21.2		14	40.0	
	Identifying the best species	9	17.3		5	14.3	
	Identifying the best locations for successful planting	25	48.1		23	65.7	
	Future maintenance (planning, extra resources and cost)	29	55.8		20.0	57.1	
	Considering and optimizing multiple co-benefits	6	11.5		2	5.7	
	Time available for planting	5	9.6		6	17.1	
	There are no challenging aspects	0	0		0	0	
	Other	16	30.8		6	17.1	
3.3. Which of the following options would you like to have access to improve your planting decisions?	Scientific journals	9	17.3	Not applicable	3	8.6	Not applicable
	Academic seminars	13	25.0		8	22.9	
	Easy-to-use modelling tool	14	14		17	48.6	
	Practical workshops	19	26.9		14	40.0	
	Other	13	25.0		5	14.3	

(1) Blank cells cannot be computed because the standard deviations of both groups are cero.

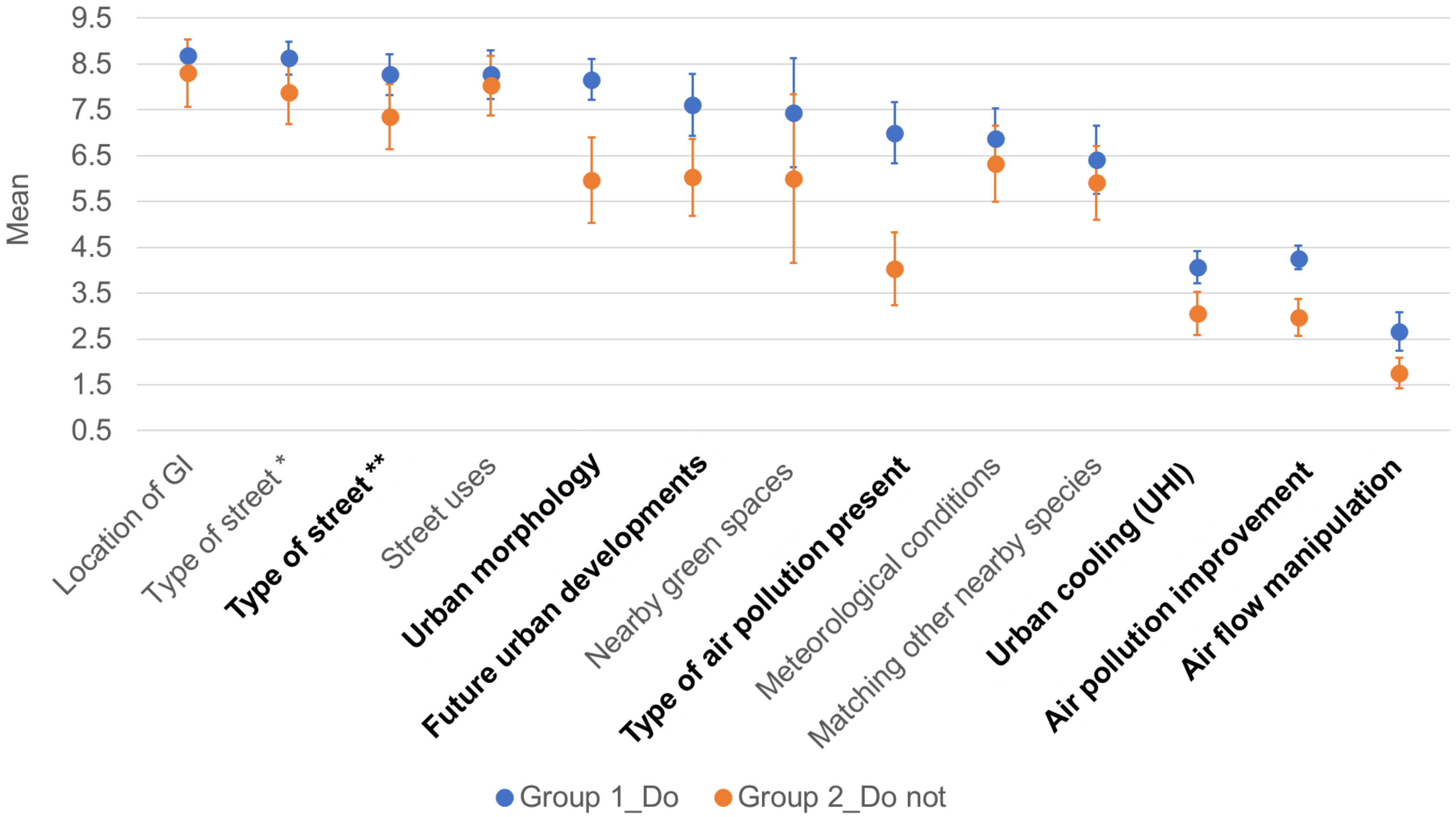
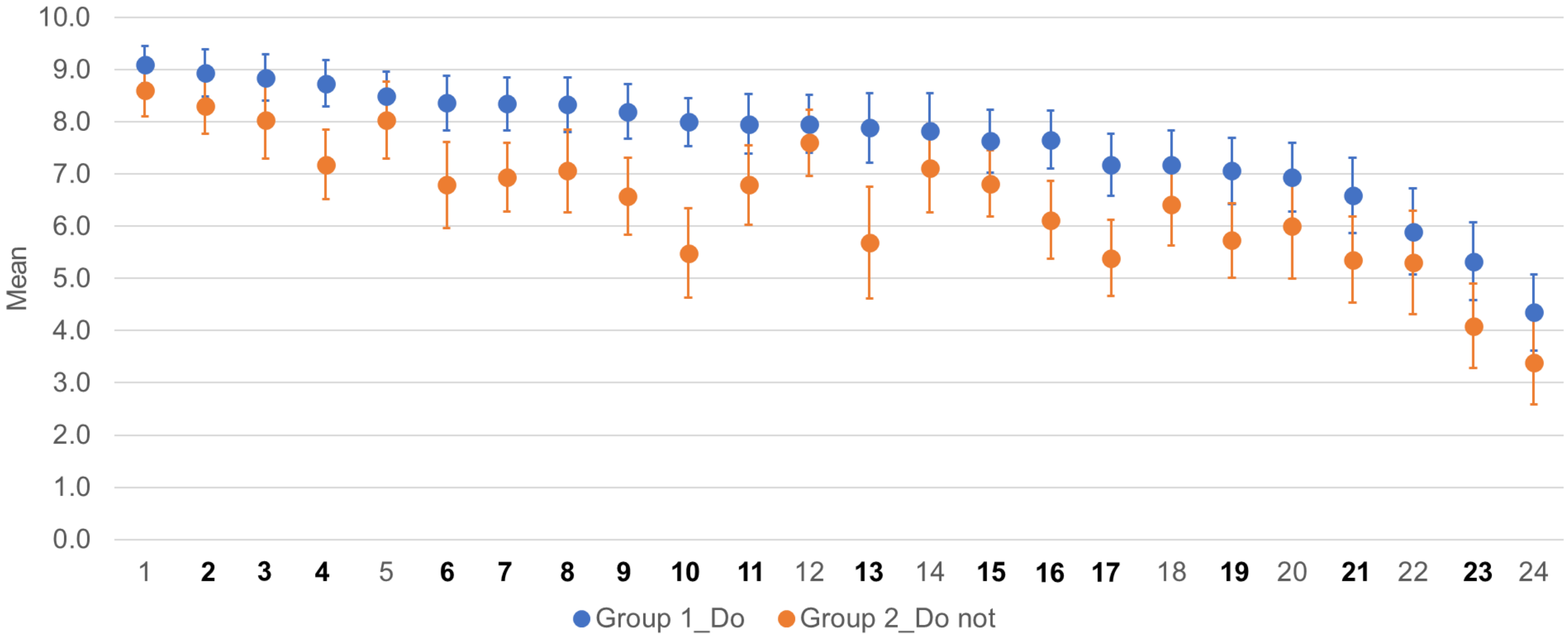


Figure 5. Mean score from 1-10 scale with 95% coefficient intervals (CI) for site specific characteristics related to air quality. Bold characteristics or features are statistically significant. Blue dots are group 1 (G1) respondents that 'Always' or 'Most of the time' considered air pollution mitigation in their urban planting. Orange dots are group 2 (G2) respondents that 'Very rarely' or 'Never' considered air pollution mitigation in their urban planting. Type of street was asked in two questions: Question 4.5 How important type of street (urban canyon and open road) is considered when selecting street side green infrastructure for air pollution mitigation (*) and Question 3.6. to rate how important or influential type of street is in planting decisions (**)



1 Size (spread or crown shape)
2 Size (height)
3 Plant species selection
4 Pest and disease resistant
5 Type of green infrastructure
6 Tolerance to soil conditions
7 Adapted to future climate conditions
8 Maintenance needs
9 Drought tolerant
10 Pollution tolerant
11 Water requirement
12 Aesthetics
13 Species tolerant to traffic (1)
14 Plant availability
15 Longevity
16 Fruiting characteristics
17 Flowering characteristics
18 Experience/familiarity with the species
19 Structural density
20 Species-specific leaf features
21 Evergreen / deciduous
22 Native species
23 Leaf surface traits
24 Leaf shape

Figure 6. Mean score from 1-10 scale with 95% coefficient intervals (CI) for species specific characteristics related to air quality. Bold characteristics are statistically significant. Blue dots are group 1 (G1) respondents that 'Always' or 'Most of the time' considered air pollution mitigation in their urban planting. Orange dots are group 2 (G2) respondents that 'Very rarely' or 'Never' considered air pollution mitigation in their urban planting.

6 Appendix F. The ENVI-met model

Method Chapter 7 – Wind tunnel experiment CODASC

Concentration Data of Street Canyons (CODASC) is a wind tunnel experiment performed by the Laboratory of Building and Environmental Aerodynamics at the Institute for Hydromechanics at the University of Karlsruhe. The database containing concentration measurement data of street canyons with tree planting, commonly used for validating computational fluid dynamics modelling results (CODASC, 2008).

Wind flow in CODASC

The street canyon in the wind tunnel was exposed to an atmospheric boundary layer flow perpendicular (90˚) to the length of the canyon. An atmospheric boundary-layer flow was simulated using a power-law equation for the vertical profile of mean horizontal velocity U(z) according to:

$$\frac{U(z)}{U(z_{ref})} = \left(\frac{z}{z_{ref}}\right)^{\alpha} \tag{1}$$

Where U(z) is the mean flow velocity at height (z), z_{ref} is the reference height (z_{ref} = H, H building height) (Gromke & Ruck, 2008b). The flow velocity of U(z_{ref} = H) = 4.65ms^{-1} was taken at the building roof height of 120 mm (H= 18m in real scale) with α = 0.30 (Gromke & Ruck, 2008b). The surface roughness of the wind tunnel was z_0=0.0037m (Personal Communication Gromke C., 2020). For further details about the parametrisation of the wind tunnel, see Gromke and Ruck (2007, 2008b, 2008a, 2012).

Trees-avenue models in CODASC

The porous media of trees is represented in the wind tunnel using a lattices cage with a metallic mesh (mesh size 8mm) filled with fibre-like synthetic material. This filled lattice cage was aligned symmetrically along the street canyon (y-axis) parallel to the buildings.

The lattice cage was filled with synthetic wadding material so that a pore volume of P_{vol}=97.5% (loosely filled lattice cage). The lattice cage filled with twice the mass of wadding material as before, resulting in a pore volume of P_{vol}=96% (densely filled lattice cage) (Gromke & Ruck, 2008b).

The aerodynamic characteristics of trees are defined by porosity and internal crown structure (e.g., pore-size distribution, arrangement and form of the crown, surface), represented by the pressure loss coefficient (λ) [Pa (Pa m)-1]. The coefficient is a parameter depending on the structure of the material and is an appropriate quantity to describe the permeability (P_{Vol}=7.5% and 96.0% (Gromke & Ruck, 2008b, 2012)). It is measured for different flow velocities, using the difference in static pressure ΔP_{stat} at the windward and leeward of the porous sample according to (2) (CODASC, n.d.).

$$\lambda = \frac{\Delta P_{stat}}{P_{dyn} \times d} = \frac{P_{windward} - P_{leeward}}{(1/2) \times \rho \times u^2 \times d} \qquad (2)$$

Where P_{dyn} is the dynamic pressure, d is the porous sample thickness in the streamwise direction, $P_{windward}$ is static pressure windward of the porous sample, $P_{leeward}$ is static pressure leeward of the porous sample, ρ density of the fluid, and u mean velocity component in streamwise direction (CODASC, n.d.) (Figure 1).

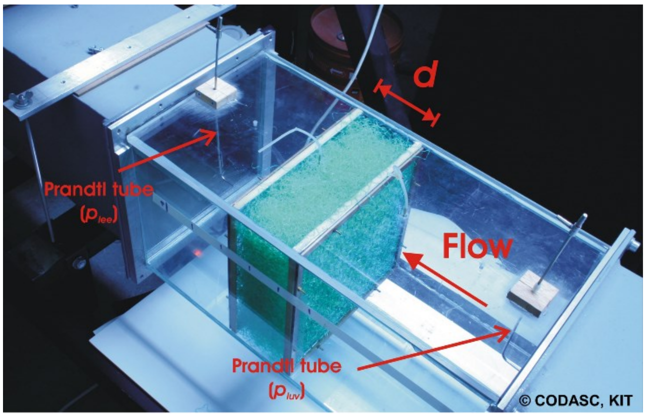


Figure 1. Measured pressure loss coefficients (λ) for different flow velocities. Source: © CODASC data base Laboratory of Building- and Environmental Aerodynamics, IfH Karlsruhe Institute of Technology

Measurements resulted in a value of $\lambda = 80\text{m}^{-1}$ for a loosely filled lattice cage (P_{vol}=97.5%), and $\lambda = 200\text{m}^{-1}$ for densely filled lattice cage (P_{vol}=96%) (Gromke & Ruck, 2008b).

- **Pollutant source**

A sulphur hexafluoride (SF_6) was used as a tracer gas and emitted from the line source at ground level and an electron capture detector (ECD) measured its concentrations (ppm). At 5mm (0.042 H) from the leeward and windward walls, respectively, mean concentrations of SF_6 were measured near the canyon interior walls.

- Method Chapter 6 – ENVI-met model

ENVI-met model is based on the physical laws of fluids and thermodynamics. It uses mathematical equations of fluids and dispersion derived from the basic principles of conservation and transport in the atmosphere (Vardoulakis et al., 2003). Atmospheric motions are governed by two physical laws of mechanics and one law of thermodynamics: conservation of mass, conservation of momentum, and conservation of energy (Holton, 2004). The model uses these laws to calculate the flow of particles for each cell in the model domain.

ENVI-met is subdivided into grid cells (x, y, z) which define the model's resolution. The horizontal spacings, Δx and Δy, are constant for all grid domains, while the vertical spacing, Δz, can be either constant or splits the lowest grid cells into sub-grid cells (0.2 Δz). The lower vertical resolution of the grid cells closest to the ground is advantageous because the exchange processes between atmosphere and ground can be simulated more accurately at this level.

- ### Vegetation in ENVI-met

The ENVI-met model has a vegetation database where different three-D vegetation species can be used. In addition, users can modify these three-D species or create their species to simulate more accurate scenarios. Canopy shape, height and leaf area density (LAD) can be changed in the model to obtain more realistic vegetation (ENVI-met, 2020).

The model includes both dispersion and deposition model to simulate particles and gases' dynamics (Wania et al., 2012; Morakinyo & Lam, 2016c). It uses the sink concept to measure the amount of deposed particle mass on both non-porous surfaces (buildings and soils) and porous surfaces (vegetation). The influence of surface vegetation in the deposition of particles is parameterised by a sink term (S_x) introduced in the mathematical equation (3). The flux of particles towards the leaf surface (S_x) is expressed by:

$$S_x = LAD(x, y, z) \times f_{cap} \times v_d \times C(z) \qquad (3)$$

Where S_x represents the flux of particles toward the leaf surface or sinks term (µg $m^{-3}s^{-1}$), LAD is leaf area density (m^2 m^{-3}), f_{cap} The filter capacity ranges from 1 for a fresh and clean leaf to 0 for a dirty leaf (unitless). v_d is the deposition velocity (m s^{-1}), C(z) represents pollutant concentration at z level or local PM concentration next to leaf surface (µg m^{-3}) (Bruse, 2007).

- ### Trees and other green infrastructures in ENVI-met

ENVI-met has a large database of different types of GI. Large, medium, and small trees, green walls, and green roof can be created in ENVI-met (Figure 2). Users can create their own GI according to their interests.

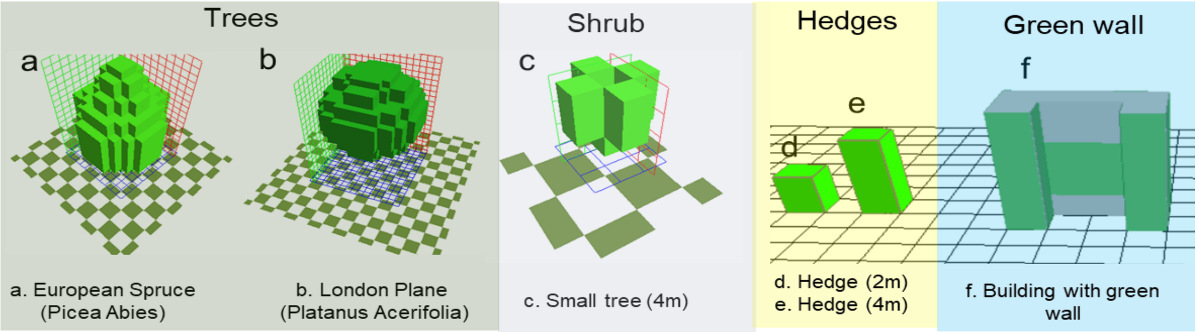


Figure 2. Examples of different types of green infrastructure simulated in ENVI-met.

- ## Pollutant source in ENVI-met

The concentration of pollutants (gas or particle) is calculated with the standard atmospheric diffusion equations (Eulerian approach) (Bruse, 2007). The model includes deposition and dispersion models to simulate pollutant behaviour, but the resuspension of particles is not taken into account in the model (Wania et al., 2012). The traffic emissions are represented by line sources (Bruse, 2007).

- ## Tree configuration

As ENVI-met scenarios are in full scale is necessary to transfer wind tunnel model scale results to a full scale. So, the normalised pressure losses (normalised by the dynamic pressure P_{dyn}) have to be equal in full-scale (fs) and model-scale (ms) according to (4) (Gromke & Ruck, 2012)

$$\left[\frac{\Delta p}{P_{dyn}}\right]_{fs} = \left[\frac{\Delta p}{P_{dyn}}\right]_{ms} \qquad (4)$$

Which derivates

$$\frac{\lambda_{fs}}{\lambda_{ms}} = \frac{d_{ms}}{d_{fs}} = M \qquad (5)$$

According to equation (3), the ratio of the pressure loss coefficients has to be equal to the wind tunnel model scale factor M (M=1:150). The full-scale pressure loss coefficient for a high porosity tree is λ_{fs}= 0.53 m^{-1}.

Tree trunks were not physically represented in the wind tunnel, but the filled lattice cage was suspended in the street canyon, leaving 1/3H above the ground representing the tree trunk space.

Table 1. Results of the statistical evaluation of other scenarios studied using the ENVI-met model and the CODASC experiment. Highlighted cells represent unacceptable values.

Model domain (m)			Resolution (m)			Roughness length	Nesting grid [1]	Split (dz) [2]	Wind direction (°)	Wind velocity (ms^{-1})	W/H	Vegetation [3]	Pollutant	Validation results ENVI-met model against CODASC [4] Leeward				Windward				Comments
Δx	Δy	Δz	X	y	z									NMSE	R	FAC2	FB	NMSE	R	FAC2	FB	
31	32	20	0.5	0.5	2	0.1	40	No	90	1	1	NV	$PM_{2.5}$	1.5	0.67	0	1.02	0.07	0.8	0.85	0.02	4h simulation
31	32	20	0.5	0.5	2	0.1	40	No	90	1	1	NV	$PM_{2.5}$	1.1	0.68	0.29	0.91	0.11	0.8	0.86	-0.12	8h simulation
31	32	20	0.5	0.5	2	0.01	40	No	90	1	1	NV	$PM_{2.5}$	0.75	0.68	0.57	0.77	0.2	0.8	0.86	-0.28	Start simulation at 2am
31	32	20	0.5	0.5	2	0.01	40	No	90	1	1	NV	$PM_{2.5}$	0.72	0.69	0.57	0.76	0.24	0.81	0.86	-0.31	Start simulation at 7am
90	70	40	0.5	0.5	2	0.01	10	Yes	90	1	1	NV	$PM_{2.5}$	0.24	0.85	0.71	-0.16	2.32	0.84	0.29	-1.01	No comments
90	70	40	0.5	0.5	2	0.01	0	No	90	7	1	NV	$PM_{2.5}$	1.7	0.83	0	1.1	0.03	0.86	1	0.11	No comments
110	71	30	1	1	2	0.001	10	Yes	270	1	1	NV	$PM_{2.5}$	0.28	0.8	0.86	-0.36	8.04	0.85	0.43	-1.58	No comments
110	160	60	1	1	1	0.01	10	No	45	3	1	NV	$PM_{2.5}$	1.74	0.99	0	1.1	0.01	0.99	0.29	0.13	Middle of the canyon comparisons
110	160	60	1	2	1	0.01	10	No	45	3	1	NV	$PM_{2.5}$	37.1	10.8	0	1.9	37.4	Error	0	1.9	North corner comparisons
110	160	60	1	1	1	0.01	10	No	45	3	1	NV	$PM_{2.5}$	0.6	0.62	0.43	0.71	2.38	6	0	-1.14	South corner comparisons
86	102	60	2	2	2	0.01	10	No	90	3	1	NV	$PM_{2.5}$	0.35	0.82	0.57	0.54	0.35	0.85	0.29	-0.5	No comments
86	102	60	1	1	1	0.01	10	No	90	3	1	NV	$PM_{2.5}$	0.17	0.95	0.86	0.39	0.54	0.84	0.57	-0.62	No comments
86	102	60	1	1	1	0.01	10	No	90	5	1	NV	$PM_{2.5}$	0.1	0.8	0.96	0.3	0.72	0.85	0.43	-0.73	No comments
292	361	72	1	1	1	0.01	10	No	90	3	1	NV	CO_2	0.44	0.76	0.86	0.61	0.14	0.86	0.57	-0.22	No comments
191	253	54	1	1	1	0.01	0	No	90	3	2	NV	NO_2	0.09	0.93	0.86	-0.17	0.74	0.96	2.22	-0.76	No comments
180	250	72	1	1	1	0.01	10	No	90	3	1	NV	$PM_{2.5}$	0.16	0.77	0.86	0.27	0.39	0.86	1	-0.51	Constante weather conditions
180	250	72	1	1	1	0.01	10	No	90	3	1	NV	$PM_{2.5}$	0.07	0.78	0.78	0.24	0.53	0.85	1.83	-0.61	Variable weather conditions
180	250	72	1	1	1	0.01	10	No	90	3	1	T	$PM_{2.5}$	0.03	0.8	0.87	0.12	1.4	0.82	2.5	-0.86	Variable weather conditions

Model domain (m)			Resolution (m)			Roughness length	Nesting grid (1)	Split (dz) (2)	Wind direction (°)	Wind velocity (ms^{-1})	W/H	Vegetation (3)	Pollutant	Validation results ENVI-met model against CODASC (4)								Comments
														Leeward				Windward				
Δx	Δy	Δz	X	y	z									NMSE	R	FAC2	FB	NMSE	R	FAC2	FB	
166	102	60	1	1	1	0.01	10	No	90	3	1	NV	PM$_{2.5}$	1.14(A) 0.61(B)	0.8(A) 0.79 (B)	0.34(A) 0.86(B)	0.93 (A) 0.71 (B)	0.07(A) 0.13(B)	0.85 (A) 0.85 (B)	0.87(A) 1.0(B)	-0.02 (A) -0.23 (B)	Double Canyon*
166	102	60	1	1	1	0.01	10	No	90	10	1	NV	PM$_{2.5}$	5.38(A) 4.49(B)	0.79 (A) 0.80 (B)	0.0(A) 0.0(B)	1.50 (A) 1.44 (B)	0.75(A) 0.56(B)	0.85 (A) 0.85 (B)	0.43(A) 0.43(B)	0.79 (A) 0.70 (B)	Double Canyon*
298	364	108	2	2	2	0.1	0	No	90	3	1	NV	PM$_{2.5}$	0.16	0.77	0.86	0.37	0.39	0.86	1	-0.51	No comments
298	364	108	2	2	2	0.1	0	No	90	3	1	T	PM$_{2.5}$	0.44	0.81	0.86	-0.53	6.15	0.8	0.43	-1.47	No comments
189	263	90	1	1	1	0.003	0	No	90	3	1	NV	PM$_{2.5}$	0.17	0.77	0.86	-0.34	2.04	0.86	0.57	-1.1	No comments
189	263	90	1	1	1	0.003	0	No	90	3	1	T	PM$_{2.5}$	0.44	0.81	0.86	-0.53	6.14	0.8	0.43	-1.47	No comments
86	102	60	1	1	1	0.001	10	No	90	5	1	NV	PM$_{2.5}$	Did not respond								
20	30	30	0.5	0.5	2	0.1	40	Yes	90	1	1	NV	PM$_{2.5}$	Did not respond								
45.5	35.5	30	0.5	0.5	2	0.001	5	Yes	45	1	1	NV	PM$_{2.5}$	Did not respond								
42	40	30	1	1	2	0.01	0	Yes	90	1	1	NV	PM$_{2.5}$	Practice, no statistical evaluation was performed.								
46	36	30	0.5	0.5	2	0.1	0	Yes	90	1	1	NV	PM$_{2.5}$	Practice, no statistical evaluation was performed.								
110	71	30	1	1	2	0.001	10	Yes	225	1	1	NV	PM$_{2.5}$	Practice, no statistical evaluation was performed.								
110	71	30	1	1	2	0.001	10	Yes	270	1	1	NV	PM$_{2.5}$	Practice, no statistical evaluation was performed.								
110	71	30	1	1	2	0.001	10	Yes	315	1	1	NV	PM$_{2.5}$	Practice, no statistical evaluation was performed.								
150	118	50	1	1	2	0.001	40	Yes	270	1.5	1	NV	PM$_{2.5}$	Practice, no statistical evaluation was performed.								
20	30	30	0.5	0.5	2	0.001	40	Yes	90	1	1	NV	PM$_{2.5}$	Practice, no statistical evaluation was performed.								
62	64	20	1	1	2	0.001	40	Yes	90	1	1	NV	PM$_{2.5}$	Practice, no statistical evaluation was performed.								
124	128	20	2	2	2	0.001	40	Yes	90	1	1	NV	PM$_{2.5}$	Practice, no statistical evaluation was performed.								
253	130	20	0.5	0.5	2	0.001	40	Yes	90	1	1	NV	PM$_{2.5}$	Practice, no statistical evaluation was performed.								

(1) Nesting grid consists of a band of extra grid cells that increase in horizontal resolution the border of the grid domain.
(2) Dz lowest gridbox is split into 5 subcells. In ENVI-met, the horizontal spacings, Δx and Δy, are constant for all grid domain, while the vertical spacing, Δz, can be constant or split the lowest grid cell. In constant vertical spacing, all grid cells have the same height, but in the split configuration, the lowest grid cell is divided into sub grid cells equally to $0.2\Delta z$.
(3) NV = No vegetation, T = Line of tree in the middle of the canyon $P_{Vol} = 97.5\%$ ($\lambda = 80m^{-1}$).
(4) MSE normalized mean square error (NMSE <4); R correlation coefficient (R>0.8); FAC2 fraction of the model predictions within a factor of two of the measured values ($0.5 \leq FAC2 \leq 2.0$, FB fractional bias ([−0.3, 0.3]) (Chang and Hanna 2004).

- **Result Chapter 7 – Part 1. General airflow and vertical velocity**

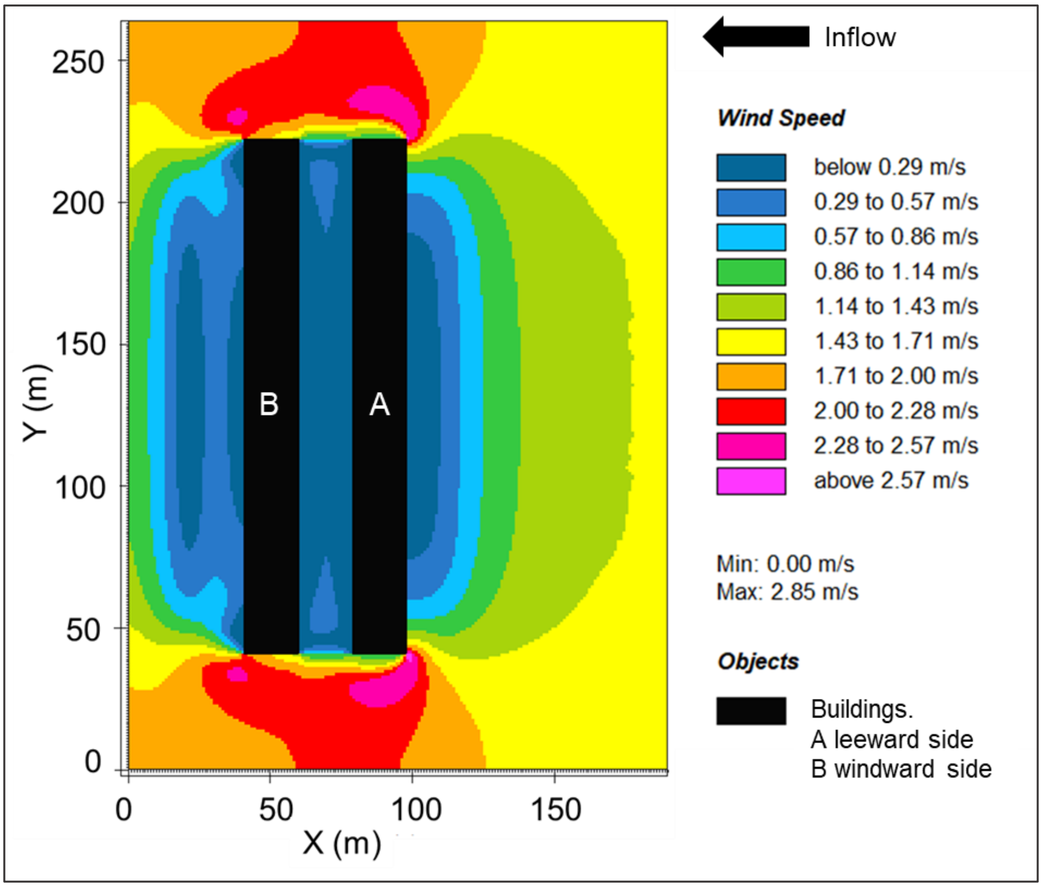


Figure 3. Plan view of ENVI-met wind speed patterns along the street canyon at 0.5 m height.

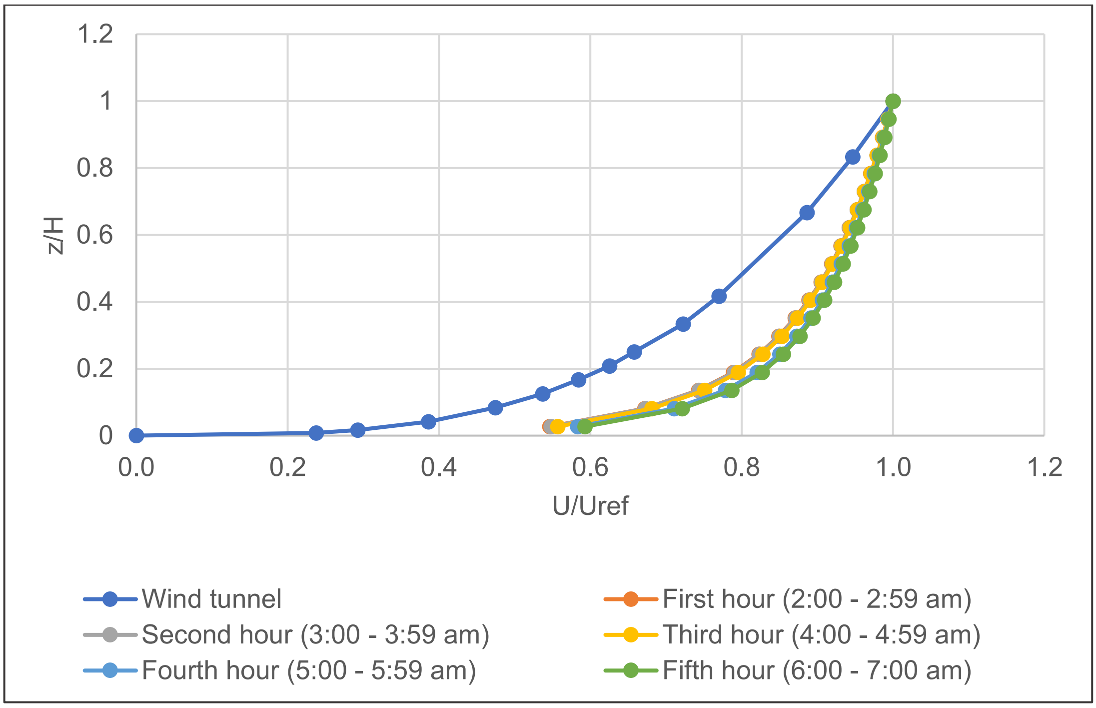
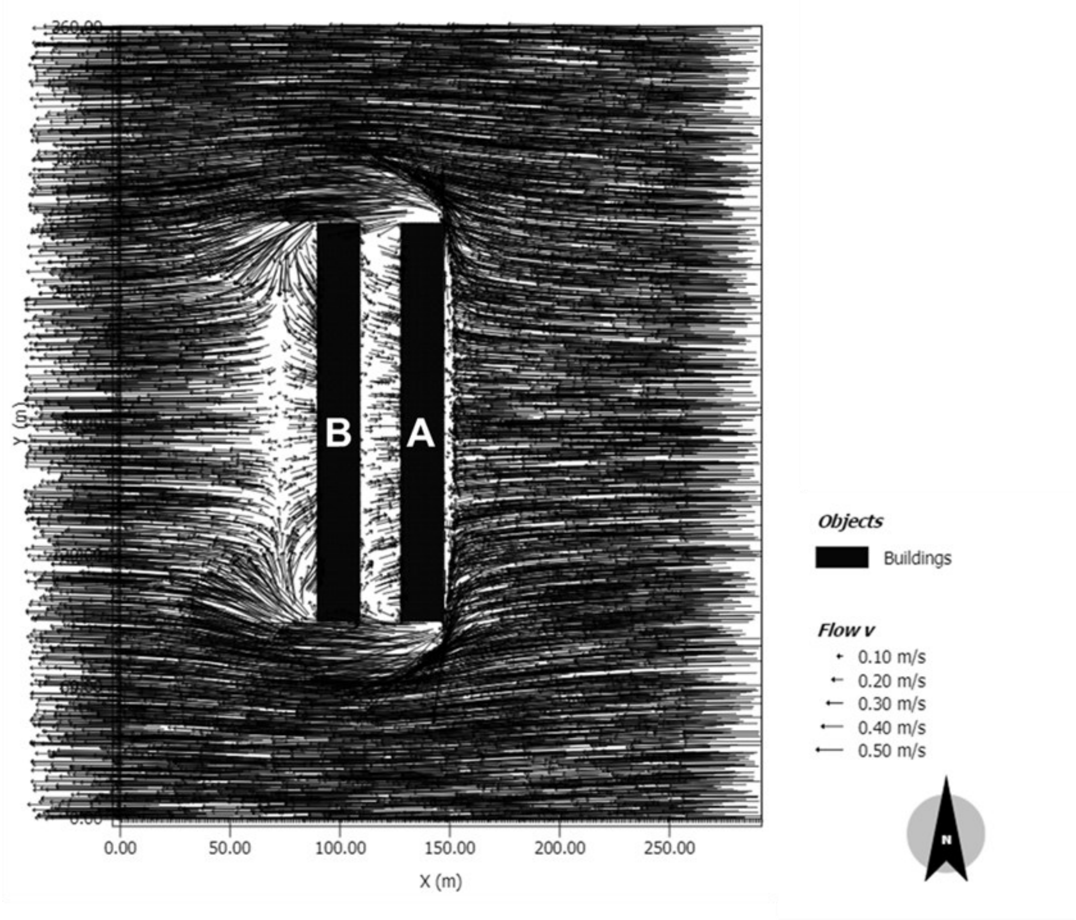


Figure 4. Profile of normalised vertical velocity (U_{ref}) for the inflow at different hours of simulation in ENVI-met.

A. Plan view studied scenario



B. Cross section studied scenario

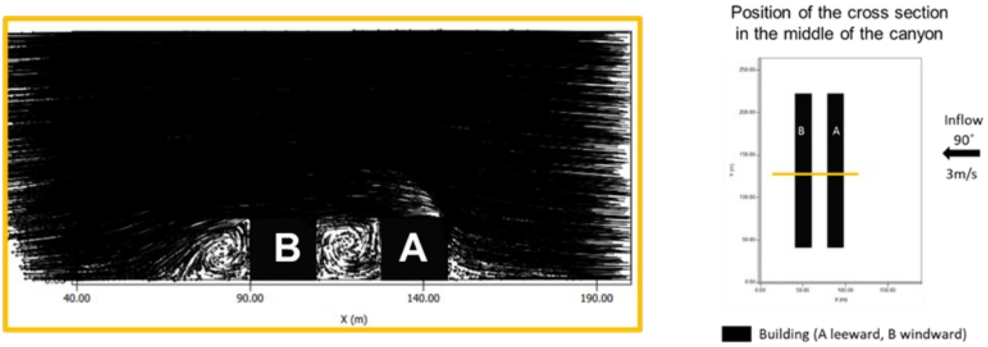
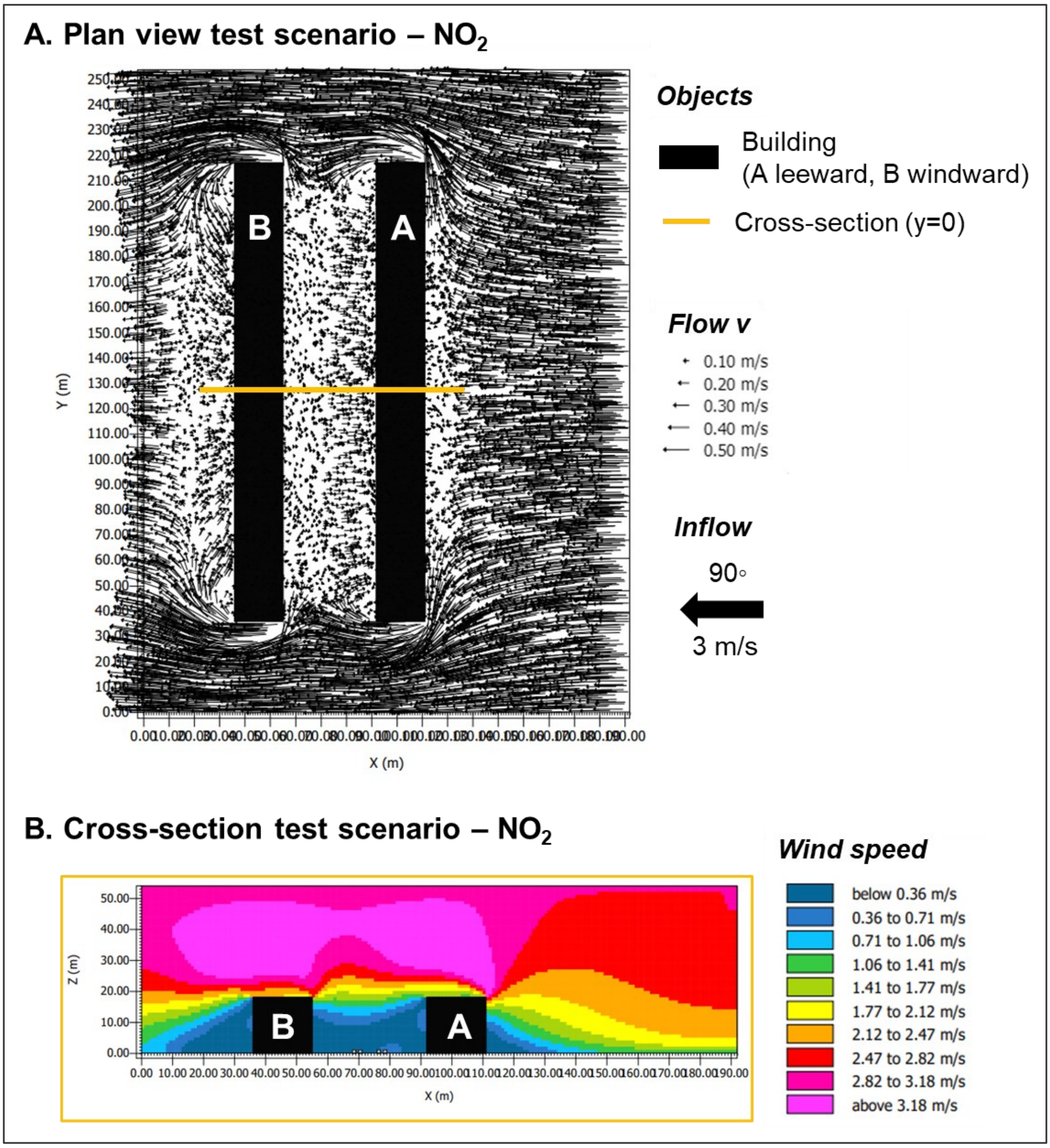


Figure 5. Horizontal flow pattern under perpendicular winds.
Figure A shows a plan view of the study area (z=0.5m). Figure B shows the canyon vortex in the middle of the canyon, x/z cut at j=180 (y=180.5m). The figure on the left-hand right side is the plan view of the street canyon. The yellow line indicates street canyon cross-section

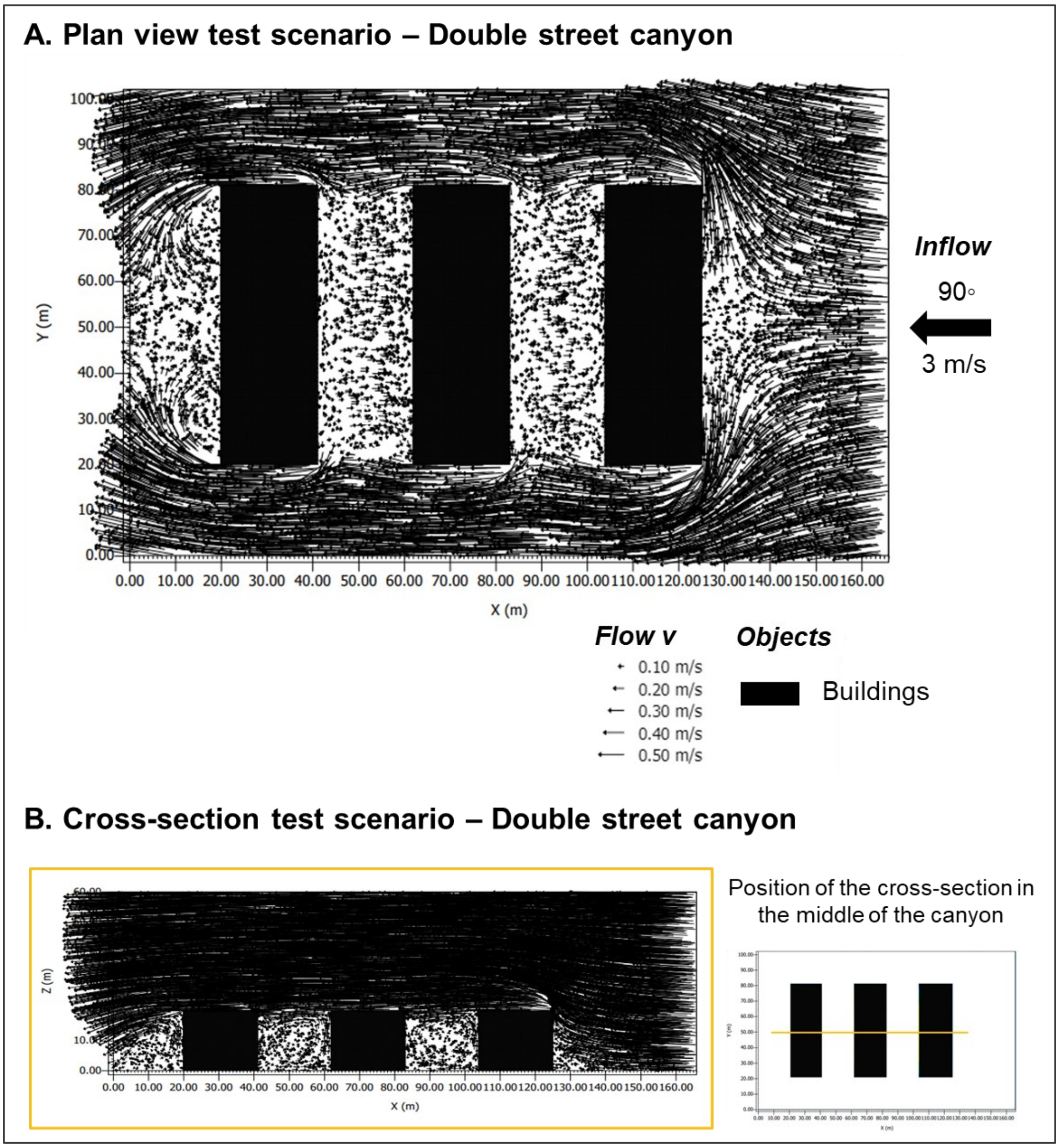
- **Result Chapter 7 – Part 1. General airflow and vertical velocity, extra scenarios studied**



A. Plan view test scenario – NO_2

B. Cross-section test scenario – NO_2

Figure 6. Horizontal flow pattern under perpendicular winds of a test scenario – NO_2. The computational domain for this scenario covered a horizontal area of 184m × 254m and a vertical height of 54m. A resolution 1m × 1m × 1m. The inflow direction was set to 90° and the wind speed at reference height (10 m above the ground level) was set to 3 m/s. The pollutant used was a gas, NO_2. Figure A shows a plan view of the study area (z=0.5m). Figure B shows the wind speed (m/s) in the middle of the canyon, x/z cut at j=125 (y=125m).

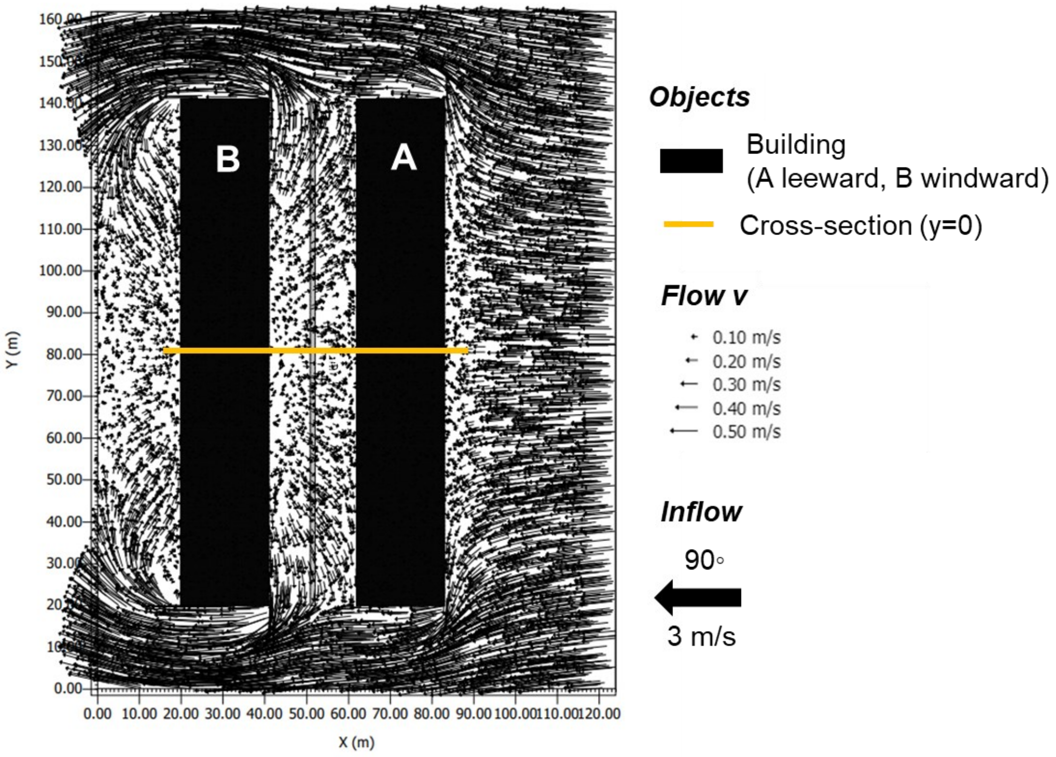


A. Plan view test scenario – Double street canyon

B. Cross-section test scenario – Double street canyon

Figure 7. Horizontal flow pattern under perpendicular winds of test scenario – double street canyon. The computational domain for this scenario covered a horizontal area of 166m × 120m and a vertical height of 60m. A resolution 1m × 1m × 1m. The inflow direction was set to 90° and the wind speed at reference height (10 m above the ground level) was set to 3 m/s. The pollutant used was fine particles, $PM_{2.5}$. Figure A shows a plan view of the study area (z=0.5m). Figure B shows the canyon vortex in the middle of the canyon, x/z cut at j=50 (y=50m). The figure on the left-hand right side is the plan view of the street canyon. The yellow line indicates street canyon cross-section.

A. Plan view test scenario – Height-asymmetric street canyon



B. Cross-section test scenario – height-asymmetric street canyon

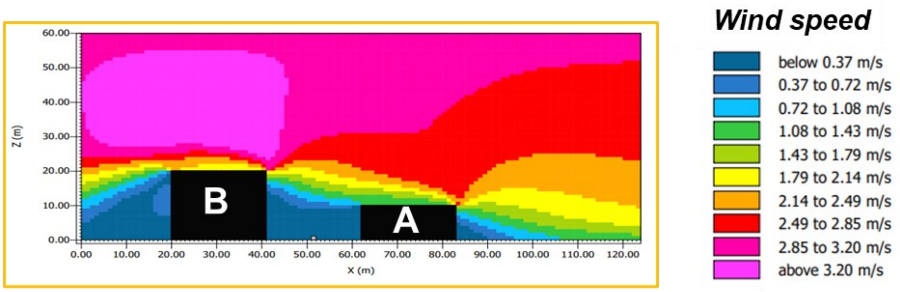


Figure 8. Horizontal flow pattern under perpendicular winds of a test scenario – Height asymmetric street canyon. The computational domain for this scenario covered a horizontal area of 124m × 162m and a vertical height of 60m. A resolution 1m × 1m × 1m. The inflow direction was set to 90° and the wind speed at reference height (10 m above the ground level) was set to 3 m/s. The pollutant used was fine particles, $PM_{2.5}$. Height of building B was double of building A (10m height). Figure A shows a plan view of the study area (z=0.5m). Figure B shows the wind speed (m/s) in the middle of the canyon, x/z cut at j=80 (y=80.5m).

- **Result Chapter 7 – Statistical evaluation**

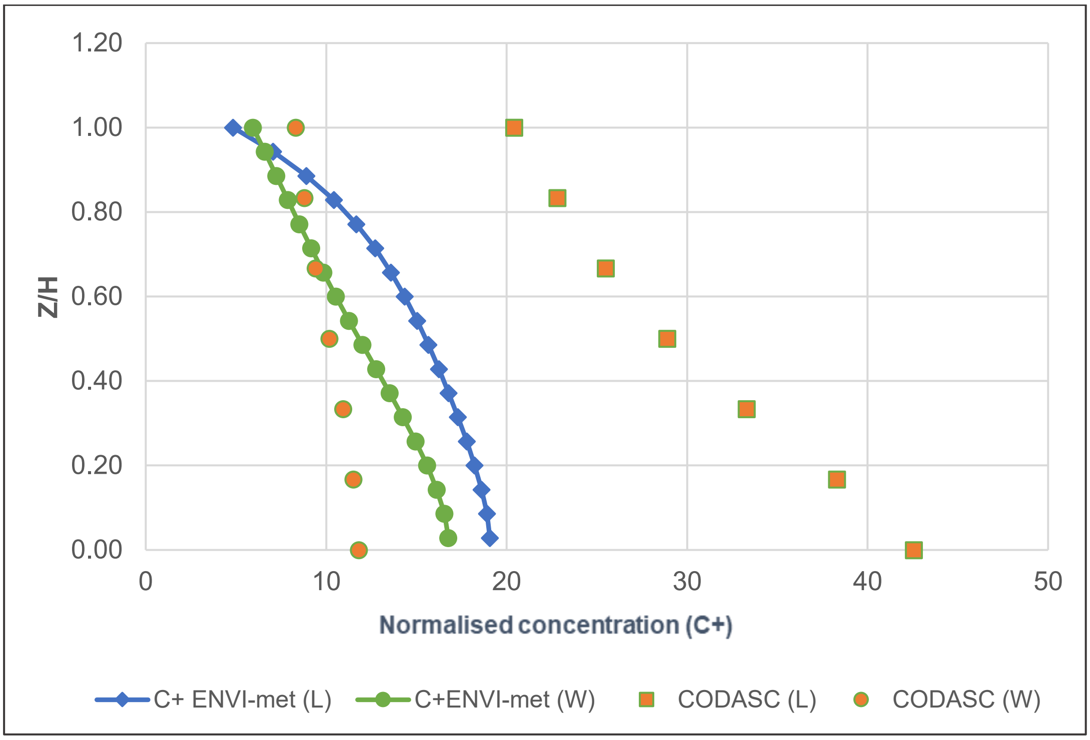


Figure 9. ENVI-met normalised concentration against wind tunnel data for windward (w) and leeward (L) wall of the street canyon for the treeless scenario. Data extracted in the middle of the street canyon (y/H=0).

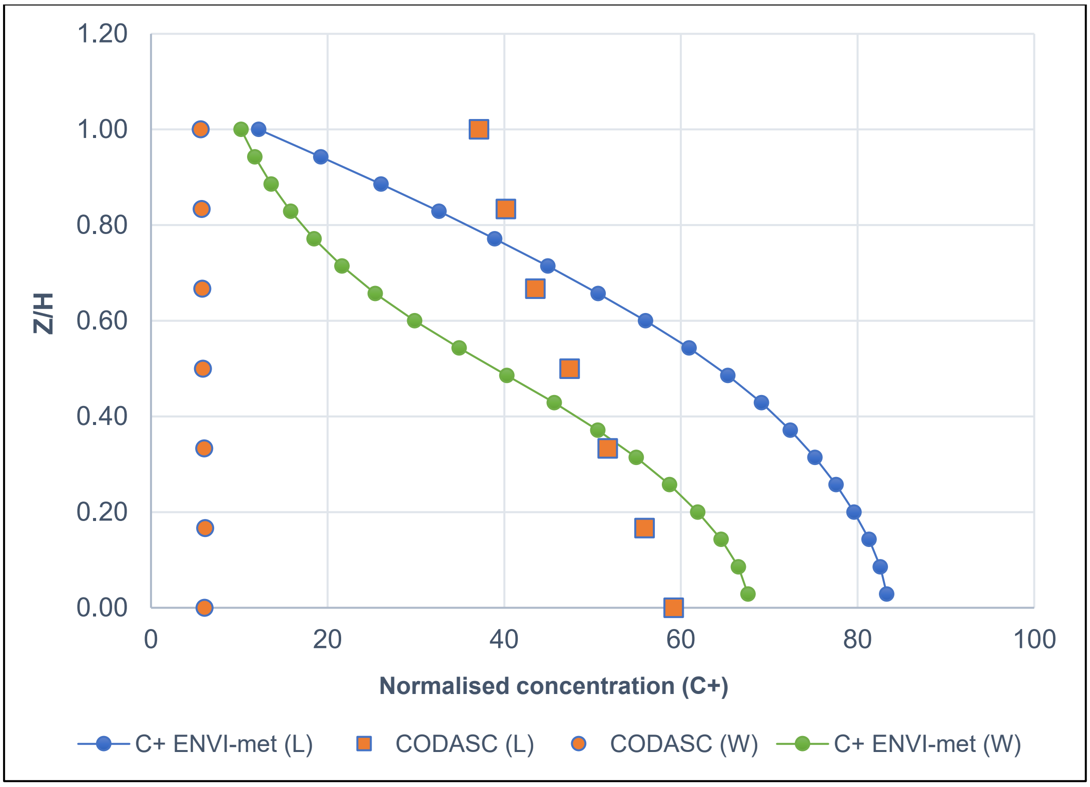


Figure 10. ENVI-met normalised concentration against wind tunnel for windward (w) and leeward (L) side of the street canyon for the scenario with trees. Data extracted in the middle of the street canyon (y/H=0).