Quantification of Particulate Matter Deposition on Leaves of Climbing Plants

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by

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Cover: Experimental climbing plant setup at the Hortus Botanicus in Delft
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TU Delft

Preface

This thesis marks the end of my time as a student in Delft. Over the past eight years, the city and the university have started to feel more like home than any of the previous places I have lived. The creation of the new master's program allowed me to specialise in Resource and Waste Engineering, a field of study which is much closer aligned with my interests, and one that was entirely off my radar when I started university. I have genuinely enjoyed this master's program, and am excited to use the knowledge I have gained from my classes and this thesis project in the future.

First I would like to thank my thesis committee for their support during the research process. Thank you to my daily supervisor Max Veeger and committee chair Marc Ottelé for allowing me to conduct research on a topic that I initially had very little to no knowledge of, but that I now have learned so much about. Thank you to Steven van der Linden for being my external supervisor and providing interesting insights into my research from a different perspective. Besides the informative discussions I have had with each of you, I would also like to express my gratitude for your flexibility and encouragement throughout this process.

My experiments would not have been possible without the help from some of the other staff of the Materials & Environment department. I would like to thank Arjan Thijssen for his help using the ESEM and the long conversations we had every testing day. I would also like to thank John van den Berg for his help in readying my filtration setup in the Microlab. Additionally, I would like to thank Ali Ghaderiaram for helping me set up and create the code for my PM sensor. I am also grateful to the staff at the Hortus Botanicus in Delft, for the care they took with my plants in their experimental set-up outside.

Finally, I want to thank my friends and family for their support during the process of writing my thesis. Thank you, Christine, Ine, and Andie for becoming closer friends than I expected to make during my master's program. Thank you Sophie for being around for all the highs and lows of the past eight years. Thank you to my parents, Anna, and Wiek for always believing in me. I am so grateful that I have had such an amazing student experience here in Delft, and to everyone who played a part in shaping it. I hope my next chapter will be as exciting as this one has been.

E. N. A. (Noor) de Bever
Delft, January 2025

Abstract

Plants can capture particulate matter (PM) on leaf surfaces, helping to reduce PM concentration in the air. In urban areas, limited space is available to increase vegetation cover, but climbing plants require little space to grow. This is why this study investigates the PM capturing capacity of different climbing plants in an urban environment. The PM was collected on the leaves of six plant species and was quantified using two experimental methods. In the gravimetric method, leaves were washed in an ultrasonic cleaner, after which the water was filtered to determine the weight of PM_{coarse}, PM_{10}, and $PM_{2.5}$ that was on the leaves. For the Environmental Scanning Electron Microscope (ESEM) method, images were taken of the leaf surfaces at 125x, 250x, and 500x magnifications and the particles of different size fractions were counted.

The results indicated that there is no statistically significant difference between the amount of PM that *Hedera helix*, *Trachelospermum jasminoides*, *Wisteria sinensis*, *Parthenocissus quinquefolia*, plastic ivy, and *Rynchostegium confertum* captured. They suggest that the epicuticular wax layer of plants plays an important role in long-term PM capture, with *H. helix* and *T. jasminoides* showing trends towards higher PM capture and retention, and that mosses like *R. confertum* have potential for efficient PM collection. A comparison of the two experimental methods indicated that the gravimetric method could be used to determine surface PM retention of different plants, whilst the ESEM method could be used to analyse particles in the wax layer and for more precise analysis of the plant leaves.

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Abbreviations

CiTG Civil Engineering and Geosciences
ESEM Environmental Scanning Electron Microscope
HH *Hedera helix*
LAI Leaf Area Index
PAHs polycyclic aromatic hydrocarbons
PI plastic ivy
PM particulate matter
PQ *Parthenocissus quinquefolia*
RC *Rhynchostegium confertum*
RH relative humidity
SEM Scanning Electron Microscope
TJ *Trachelospermum jasminoides*
WHO World Health Organisation
WS *Wisteria sinensis*

1 Introduction

This research focuses on quantifying the particulate matter (PM) capturing capacity of different species of climbing plants in an urban environment. As more information is uncovered about PM it is becoming of greater concern from a human and environmental health perspective, which has led to a search for ways to mitigate human exposure to PM.

In its 2021 report on global air quality guidelines, the World Health Organisation (WHO) declared air pollution to be the biggest environmental threat to human health because of its contribution to disease burden [1]. It is linked to health complications such as cancer, acute lower respiratory infections, stroke and heart disease, resulting in 4-9 million deaths globally every year [1, 2]. The main components of air pollution which are so detrimental to human health are particulate matter (PM), ozone (O_3), and nitrogen oxide (NO_2) [3]. PM is specifically problematic due to the small size of the particles, which allows them to travel deep into the lungs and cause these aforementioned air pollution-related health complications [1]. It is also dangerous because most of the population is exposed to high concentrations of PM in their daily lives, with 90% of the global population living in areas where the WHO guidelines for maximum PM exposure (10 µg/m^3) are exceeded [1].

Particulate matter (PM) is the name given to tiny solid or liquid particles suspended in the air [4]. The identifying characteristic of these particles is their size, as defined by the particle diameter, with the most common size fractions in research being PM_{coarse} (10-100µm), PM_{10} (≤10µm) and $PM_{2.5}$ (≤2.5µm). The reason why the size of the particles is so important in defining PM is that there are many different sources which emit the particles into the air, and therefore the particles all have different chemical compositions. PM_{coarse} usually has biological origins [5], for example, this can be soil which is blown up by wind or as a result of mining and agriculture activities [6]. Smaller PM fractions usually have anthropogenic origins related to the combustion of fossil fuels and industrial emissions [5, 7]. The different sources of PM result in it being a mix of metals, soil particles, acids, organic chemicals, and biological material [7]. Besides making it difficult to define PM composition, this variation also makes it difficult to target PM particles for removal from the atmosphere.

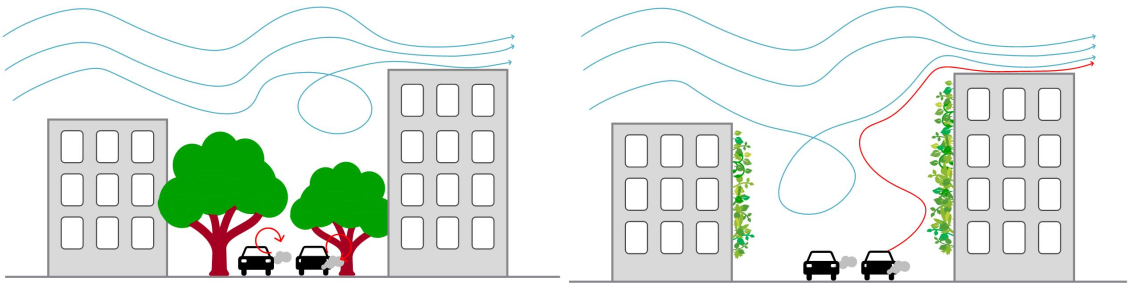
The most successful measure that can be taken to reduce PM concentrations in the air is restricting their emission in the first place. Governments can introduce stricter emission standards, the industry can upgrade their material, filters can be installed on chimneys and exhaust pipes, and mitigating measures can be taken in the mining and agricultural sectors [8, 9]. For example in China, these types of interventions helped to reduce the average $PM_{2.5}$ concentration in the air by 40% over 5 years [10]. It is important to note that when these measures were implemented in 2013, China had some of the worst PM pollution in the world, so this could be seen as a relatively easy win. However, this large reduction in PM concentration over a short period of time shows that these types of interventions work. The challenge of these measures is that they are expensive and require people to change their habits or ways of working, making them economically and functionally unattractive [11]. Additionally, adding a filter to an exhaust pipe or upgrading machinery will reduce emissions, but will not reduce them to zero, and with ever-increasing traffic and industry density the total emissions into the atmosphere are not being reduced [12]. At best, these emission reduction activities are mitigation options but they are not solutions to permanently lower PM concentrations in the atmosphere, as there are also emission sources which cannot be mitigated by these types of interventions such as dust and mechanical wear of materials outdoors. This is why it is important to look into measures which can remove PM from ambient air after it has already been emitted.

With this in mind, one measure known to reduce PM concentrations in air is increasing the amount of vegetation in an area. Plants are the most effective surface for capturing PM from the air, which they do by collecting particles on the surface of their leaves [11, 13]. As the PM particles are transported through the air they will sometimes collide with a surface and stick to it, a process which is referred to as impaction [14]. Although in principle this could be any surface, the leaves of plants are able to capture more PM per area than other materials such as concrete because of their greater surface area, and the structures and electrostatic charges on the leaf surface can trap particles to stop them from re-entering the atmosphere [15, 16, 17]. Once the particles are stuck to the leaf surface they can no longer be inhaled, and if enough particles are stuck on leaves the PM concentration in the air can be lowered, reducing the risk of becoming sick.

There is still a risk of particles being resuspended into the air from the leaf surface. This can happen directly when gusts of wind pick the particles up from the leaf surface, or when the particles get washed off the leaf surface by rain and are resuspended from paved surfaces on the ground [18]. When the particles are washed off into open soil they are less likely to be resuspended, and therefore these particles represent the net removal of PM from the air [18]. These processes of wash-off and resuspension affect larger PM_{coarse} particles more than PM_{10} and $PM_{2.5}$ [7]. The smaller particles are more likely to be trapped by surface structures on the plants, preventing them from being removed by rain or wind. Apart from resuspension and wash-off, some components of PM, such as polycyclic aromatic hydrocarbons (PAHs) or nitrogen-containing compounds, can also be absorbed and transformed by the plant leaves or degraded by bacterial communities on the leaf surface [19, 20, 21]. This is an additional way in which plants are known to remove certain PM components from the atmosphere permanently.

Increased amounts of vegetation will help reduce the PM levels in ambient air, but there are many different species of plants which can be used to achieve this purpose. Climbing plants have some characteristics which make them more practical to plant in urban areas than other types of vegetation like trees and shrubs. Climbers are very flexible to place in densely built-up areas, as they require little space on the ground to be planted in and have few growing requirements [13]. Trees need relatively large tree pits to root properly, and as they grow in size the size of the tree pit they need also increases, which can lead to space issues in urban areas [7]. Climbing plants can be planted in a small area of open soil and thrive without needing more space at the ground level over time. Furthermore, there is a large price difference when considering planting trees versus climbing plants. Currently, at Dutch online retailers, trees can easily cost €100 or more, but climbing plants can be found for less than €5 and will generally not be more expensive than €50-60 [22, 23]. Climbing plants also grow much faster than trees, allowing them to be bought small and cover a large area within one or two growing seasons. Another important factor to consider is the circulation of the air. In narrow streets, if the tree canopy covers the width of the street it can trap pollution at the street level, locally increasing PM concentrations and people's exposure to it [13, 16]. Climbing plants are attached, either directly or indirectly, to the facades of buildings lining the street, which means there are fewer obstructions to the airflow resulting in increased dispersion of emitted pollutants as is illustrated in Figure 1.1.

Although climbing plants have these advantages in urban settings compared to other vegetation types, there has been relatively little effort put into studying how much PM they can capture. Most research focuses on the PM capturing capacity of trees and shrubs, with climbers either being left out entirely or only one or two species being included in the study. Certain leaf characteristics like surface roughness and epicuticular wax have been found to improve PM capturing capacity [24, 25], and these findings are expected to be relevant for all vegetation types. Some papers focus on one specific species of climbing plant, usually *Hedera helix* (common ivy), but this produces data which is difficult to compare to other species of climbing plants and vegetation in general. This is a result of another challenge in this field of study, which is that different methods are being used to quantify the PM capture of various plants, resulting in data which cannot be directly compared as it is in different units and gathered under non-identical conditions. Concisely put, there is a lack of data and the data which there is cannot be reliably compared to each other.



(a) Trees

(b) Climbing plants

Figure 1.1: The difference between trees and climbing plants in narrow streets (adapted from Ferranti et al. (2019) [16])

This has led to the main research question for this thesis:

What is the particulate matter capturing capacity of different climbing plants in an urban environment?

To answer this question the following sub-questions were identified:

- What relation can be made between data collected through different methods for quantifying PM collected by plants?
- Which climbing plant characteristics are the most influential for capturing PM?
- Which climbing plant species collects the most PM?
- How much PM can climbing plants capture compared to other vegetation types ?

1.1. Structure

In the following Chapter 2 an explanation will be given on how plants capture PM and what specific characteristics influence this process of particle collection. An overview is given of data collected by previous studies to showcase the range of PM quantities that various plants can capture, and the different methods for quantifying PM capture by leaves will be introduced. Chapter 3 discusses the methodology of this particular project, first explaining the location where the plants were set up and introducing the plant species studied. Following this, the exact sampling procedure and the chosen experimental methods are described. The results of these experiments are presented in Chapter 4. What these results indicate is discussed in Chapter 5, also referring back to what was found in the literature and how the results compare to expectations. This is also where the limitations of this project are explained. Finally, Chapter 6 summarises the findings of this research project and recommends areas for future research.

2

Literature review

2.1. How plants capture PM

As was seen in previous studies, certain leaf and plant characteristics can be linked to a plant's capacity for capturing PM [4, 7, 19, 24, 25, 26, 27, 28, 29]. These characteristics can be broadly divided into three levels; the micro- and macro level, and environmental factors. At the micro level, influential characteristics are related to the leaf surface structure, and certain microstructures can help to trap captured PM so that it stays on the leaf. The macro-level characteristics are the plant structure and leaf shape, which influence the turbulence of passing air and therefore can increase or decrease deposition rates. Finally, the environmental factors show how the weather influences how much PM plants can capture. Combining what is known about the influence that these different characteristics have can potentially help determine what plants are most suited for capturing PM from the air.

2.1.1. Microstructure

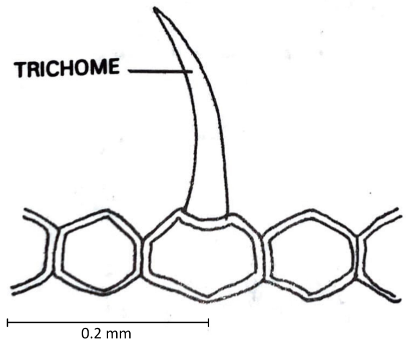
The influence of microstructures on the ability of a plant to capture PM comes down to how rough or smooth the leaf surface is. Research has shown that rough leaf surfaces capture PM more efficiently than smooth surfaces and that there is a positive correlation between the number of particles retained and the roughness of a leaf's adaxial (top) surface [25, 26]. When a leaf has more microstructures on its surface, its texture is rougher. Some examples of these structures are ridges or grooves, hair-like outgrowths called trichomes or villi, stomata, and epicuticular wax [7, 19]. Areas with these structures tend to be optimum particle deposition zones as the structures can trap the particles, which also stabilises them on the leaf surface [26, 27].

Ridges and grooves

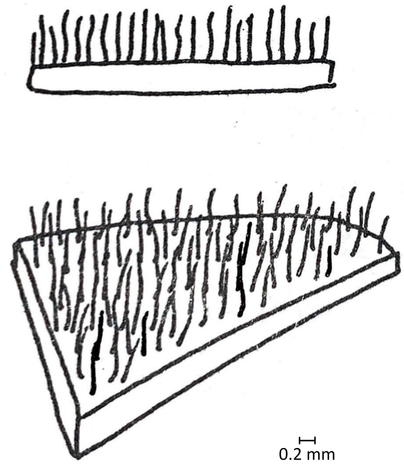
There are different words used to describe the structures that influence the roughness of the leaf surface; furrows, ridges, grooves, throughs, wrinkles, crypts, and folds to name a few. Many of these refer to similar raised or recessed areas on the leaf surface. It is the width, depth, and frequency of these structures that influence the PM capturing capacity of the leaves [19]. For example, a leaf with bigger ridges will be better at capturing larger particles than a leaf with small ridges [4]. Along with the width, the depth of these structures influences how easily particles can be resuspended after settling on the [4]. Shallow and wide-spread structures will not help to retain particles during heavy precipitation or in strong winds as the particles are easily blown or washed out [4]. However, when particles are of a similar size as complex structures they will get a stronger attachment to the leaf surface and are less likely to be resuspended into the atmosphere [26].

Hairs

Trichomes are hairs or hair-like outgrowths of the outermost layer of leaf cells, as shown in Figure 2.1a [30]. They improve PM capturing capacity as their presence increases the surface area of the leaf creating more opportunity for particles to collide with it [7], and they can prevent particles from being resuspended by wind or rainfall by trapping them around their base [4]. Villi are also hair-like structures, but they are long, soft, and shaggy compared to trichomes (see Figure 2.1b) [30]. More so than other microstructures, villi can easily capture fine PM smaller than 2μm as they are more flexible structures [26]. Although most studies agree that the presence of different types of hairs on leaves improves the particle-capturing capacity, some studies have also found a negative correlation between leaf hairs and PM capture [7]. This is likely due to the large variety of types of hairs that can cover the leaf surface, but current research has not found a definitive ranking of which types are the most beneficial or counterproductive.



(a) *Trichome*



(b) *Villi*

Figure 2.1: Hair-like structures on leaf surface [30]

Stomata

Another important leaf structure are the stomata. These are pores, usually in the abaxial surface on the bottom of the leaf, which allow gaseous exchange in the leaf [30]. The pore is flanked by two guard cells and gives texture to the leaf surface. The stomata can open and close depending on environmental factors such as relative humidity, although no significant relationship was found between particle retention and the open or closed status of the stomata [26]. Yan et al. (2018) found that PM accumulation decreased when the stomata density was <94 stomate/mm^2, but it increased when the stomata density was higher than this [29]. Another study found that the stomatal density only correlated to PM capture when the leaf surface around the stomata happened to have the ideal size and shape to match the captured particles [19]. A possible explanation for this is that at a density lower than 94 stomata/mm^2 the distance between the stomata is too large to effectively capture even the larger fractions of PM, but at higher densities, the distances between the stomata's guard cells become small enough to capture PM of different sizes between them.

Epicuticular wax

Some plant species also have a layer of epicuticular wax covering the leaf surface which can add to the roughness of the leaf surface. The main function of this layer is to prevent excessive water loss from the leaf tissue, however, it has secondary protective functions including protection against UV radiation, heat, mechanical stress, and pollution [31]. Some studies have found that the wax quantity can be an important predicting factor for PM accumulation generally [25], although others found that species with the most epicuticular wax do not necessarily collect the most PM [24]. This is because the composition and ultrastructure of the wax layer vary greatly across different plant species, and only considering the quantity of wax does not encompass either of these factors [7, 21]. For leaves with a wax layer, the amount of PM that can be sequestered in the wax layer can range from 40-80% [24, 25]. Once PM is trapped in the wax layer the risk of it being resuspended by wind or precipitation decreases as the PM is at least temporarily immobilised and cannot be released until the wax layer decays [7]. This can happen due to damage by mechanical forces and chemicals from air pollution which degrade the wax, or due to natural degradation of the leaf. Some plant species are able to replenish their wax layer, although others cannot, and this affects the plant's ability to immobilise PM over the long term [28].

Leaf wettability

As it is difficult to quantify the total roughness of a leaf surface, some studies have used leaf wettability as a proxy to compare the surface roughness of different plant species. The leaf wettability refers to how hydrophilic the leaf surface is [32], and it is influenced by many of the same factors that influence PM deposition. Notably, trichome density, wax content, the microstructure of the leaf surface, and stomatal density have been found to also influence the leaf wettability [28, 32]. Previous research has shown that a high leaf wettability implies a higher capacity for PM deposition on the leaf surface [2, 7, 28]. However, other studies have found that the same structures which can capture PM make the leaf less wettable [28]. Leaves with a higher wax content, which can increase the amount of PM that is immobilised on the leaf surface, are also less wettable [32]. One reason for this could be that on average particles are smaller than most water droplets so where the PM can get trapped in surface microstructures, the larger water droplets will stay on top of them due to the surface tension holding them together. During precipitation events, this would hinder the PM removal by rain [7]. However, other wetting properties of the leaf can also increase the removal of PM due to rain as some particles on the leaf surface will dissolve in the water and run off onto the ground [7, 28].

2.1.2. Macrostructure

The macrostructure of a plant or tree can influence its capacity to capture PM in two main ways; the plant structure can influence the turbulence of the air flowing past to result in increased deposition, and the leaf shape can increase this effect and help to trap particles.

Leaf Area Index

One aspect of the plant structure that can impact PM deposition is the leaf density of a plant, which can be represented by the Leaf Area Index (LAI) [2]. The LAI is a measure of the leaf area per unit of area that is covered by the plant on the ground. However, for climbing plants and living wall systems the LAI is usually calculated per unit of vertical area covered by the plant [33]. Plants with a higher LAI have a higher leaf density, which indicates that there is more leaf surface area for the particles to encounter and stick to. The higher leaf density also allows the creation of air pockets within the crown of the plant where the atmosphere is less turbulent [34], allowing more particles to settle on the leaf surfaces.

Growth form

Another way in which leaves can capture PM is when the particles randomly collide with the leaf surface. For this process increased air turbulence around the plant is important and the growth form of a plant plays a significant role in this. For example, more complex tree crowns with many small leaves on a large number of branches have been shown to more efficiently capture PM due to the increased turbulence they create through the crown [7, 14, 34, 35, 36]. Plants with average leaf surfaces smaller than $10cm^2$ have a higher capacity for capturing PM than those with a surface area larger than $100cm^2$ [34]. The reasoning for this is that plants and trees with small leaves usually have a more dense arrangement of them, which results in a greater influence on the airflow [34]. However, there is a point at which the leaves can become too densely packed, preventing the air from flowing through the plant structure and reducing the PM capturing capacity [34]. Another factor which can influence the airflow is the total size of a tree or a barrier covered in plants, as a larger total leaf surface gives particles more opportunities to encounter a leaf surface to settle on or collide with [2, 37].

Adaxial vs abaxial side

A difference has also been found in the quantity of PM that leaves can collect on their abaxial versus their adaxial side (see Figure 2.2). In general, leaves are able to capture more PM on their adaxial surfaces [19, 26, 37]. The differences found in the number of particles per side of the leaf ranged from having two to seven times as many particles on the adaxial surface [26, 37]. Gravity plays a role in this, as one study found that particles larger than 10µm were only found on the adaxial surface [37], and the effect of gravity is larger on larger objects. Another study suggests that the relative smoothness of the abaxial surfaces of most leaves also plays a role [26], as smooth surfaces tend to capture less PM.

Leaf shape

A leaf’s shape can also influence the turbulence of the air flowing past it. Leaves with more complex shapes can have better PM capturing and retention rates, possibly because they can create more

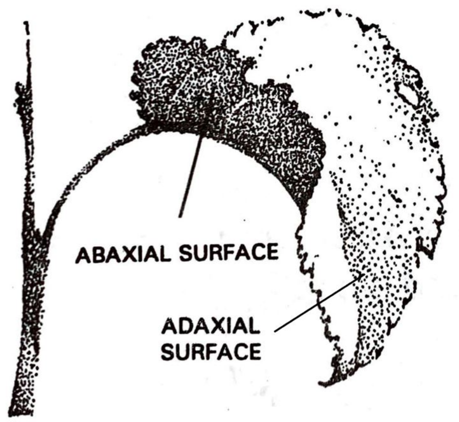


Figure 2.2: Abaxial vs. adaxial leaf surface (adapted from Harris & Woolf-Harris (2001) [30])

turbulent airflow [7]. One study found that from 16 plants studied the most to least effective leaf shapes for PM capture are lanceolate > obovate > elliptic > needle-like > linear (see Figure 2.3) [38]. This difference in PM capture is thought to be due to how erratically the different leaf shapes flutter in the wind, reasoning that if the leaf flutters more, particles cannot settle on the surface [38]. When looking at the entire leaf shape, leaves with narrower bases will flutter more, which is why the lanceolate leaves that are wider below the middle flutter less, and therefore capture more PM [38].

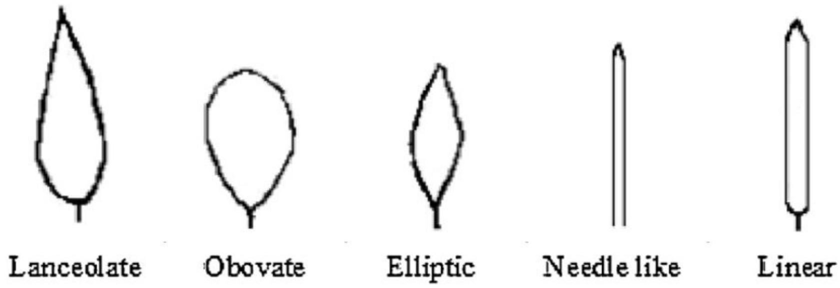


Figure 2.3: Best leaf shapes for PM capture (adapted from Leonard et al. (2016) [38])

Multiple other studies concluded that trees with rigid, needle-shaped leaves capture the most PM compared to other leaf shapes [11, 34, 35]. This ability of needle-shaped leaves is attributed to the higher Stoke's number, which describes the relationship between the stopping distance of a particle and the characteristic dimension of an object, in this case, the leaf. Broadleaved species have a lower Stoke's number, indicating that the particles can flow along and around the leaf's surface relatively easily helped along by the 'fluttering' effect, and therefore the particles are less likely to be trapped on the leaf surface [11]. As the particle size decreases this effect becomes more pronounced, and the effectiveness of large leaves starts decreasing once the particle diameter becomes smaller than 30μm [6].

2.1.3. Environmental factors

Although the plant species has a large influence on how much PM can be captured, there are location-dependent factors which are also important to consider. The most influential environmental factors that play a role in the PM-capturing capacity of plants are wind, PM concentration, rainfall, temperature, and humidity.

Air turbulence

Air turbulence has an important influence on how much PM can be deposited. As was mentioned in Section 2.1.2, when the air is calm within the plant structure this enables the settling of particles, but more turbulent airflow around the outside of the plant enables impaction. At a larger scale, impaction is the more important process, so increased turbulence is more important to achieve as this mixes the air and allows more particles to come in contact with the plant surface, increasing PM deposition on leaves [25]. Specifically in trees, the large structure of the crowns influences air movements [25]. This principle works the same for shrubs and other vegetation types, but trees are considered to be the most effective as they have the largest crowns [39], allowing them to have the largest influence on the airflow around the vegetation.

When there is a higher green coverage rate there is a more significant reduction in PM concentration, as the vegetation has a greater influence on the average wind velocity in the area and can capture more PM [7]. However, the wind can also remove particles from the leaf surface and re-suspend them in the air. This happens during gusts of wind and at higher wind speeds, whilst lower wind speeds correlate to higher PM deposition rates [40]. This has to do with the optimum deposition velocity of particles onto plant leaves. It is difficult to determine this optimum, however, as it is different for each individual plant species and also depends on other environmental factors such as the PM concentration in the air [14].

PM concentration

Plants in locations with high PM concentrations in the air will collect the most PM [7, 25], as more particles can come into contact with the leaf surface. It can therefore be more effective to place plants close to PM emission sources like factories and roads as the concentrations are higher and the plants can prevent the particles from spreading far from the source [37]. The PM concentration is strongly influenced by the particle dispersion through the air after emission. For example, in narrow streets PM emitted from the exhaust pipes of vehicles will come in closer contact with vegetation that is planted there, as there is only a limited amount of space where the exhaust fumes can go [40]. On the other hand, in a vast open area with high wind speeds PM is dispersed more easily and plants will collect fewer particles as they are less likely to come into contact with each other [7].

Although a high PM concentration allows plants to collect more particles, there are negative consequences associated with this for plant health. Depending on the specific composition of the PM it can destroy the protective wax layer on the leaf surface. This is specifically known to affect conifers' needle-shaped leaves, where once the leaf's outer layer is destroyed its ability to sequester PM also decreases [11].

Precipitation

Precipitation can remove PM from the leaf surface, in a process referred to as wash-off [7]. The water on the leaf collects some of the particles when travelling across the leaf surface, and it takes these particles with it when it drops to the ground. The PM which is washed off the leaves is considered the net-PM removal from the atmosphere that plants influence [7]. However, precipitation does not remove all PM from the leaf surface [4]. In a study in which leaves were washed in a process similar to the effect of rainfall on leaves, on average only 23-45% of the particles were removed from the leaf surfaces [4]. A different study found that rainfall has no significant effect on the amount of PM particles retained on the leaf surface [5]. The main reason for this is that the effect rainfall has on removing PM from the leaf is influenced by the surface micro-structure and characteristics of the rainfall such as intensity and duration [4]. When particles are lodged more securely in the surface microstructures they are less likely to be removed, which is why mostly PM_{coarse} is removed [7], and if there is very light rain the chances that water droplets drag along the particles also decreases. Some plant species partially regain the capacity to capture PM after precipitation events when space is created where particles can come into direct contact with the leaf surface again [2].

Temperature and humidity

The temperature and humidity are also known to influence PM capture by plants. Air temperature is negatively correlated to dry deposition velocity, so there is less PM capture when the temperature is high [7]. The humidity is related to the functioning of the leaf elements, as it affects cuticle hydration and the functioning of the stomata [26]. The combination of high temperatures and low relative humidity can result in the shrinking of cuticles and closing of stomata, both of which inhibit the ability of the particles to enter the leaf and reduce the surface roughness [7].

2.1.4. Overview of influential factors

An overview of the different influential factors on PM capture by plants is given in Figure 2.4.

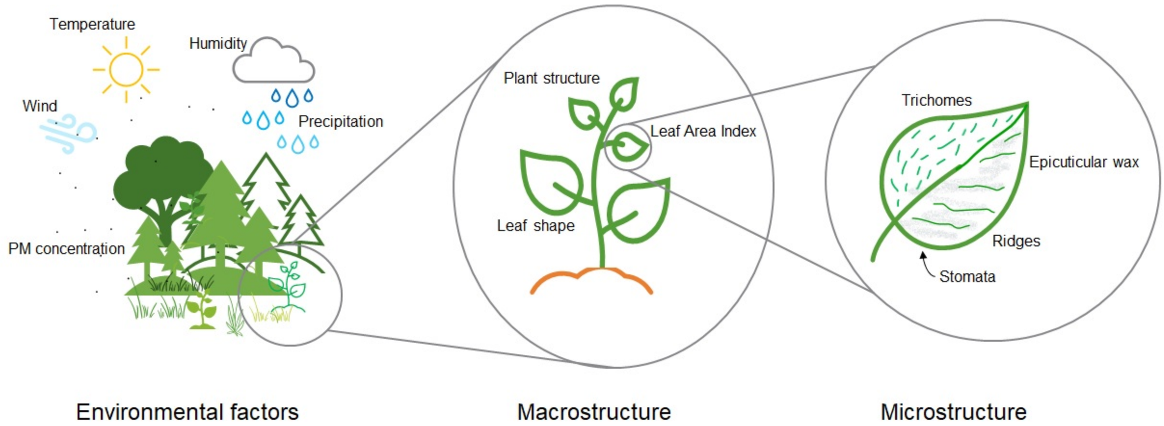


Figure 2.4: Factors influencing PM capture by plants

2.2. Which plants capture the most PM

Research on the topic of PM accumulation by plants generally focuses on the different factors which can influence PM accumulation, instead of finding one single plant species which can capture the largest amount of particles. This is because there are simply too many different plant species, so finding one species with the absolute highest capacity for capturing PM in all the different global climates is nearly impossible. By determining which characteristics influence PM capture, estimates can be made regarding the ability of untested plants to capture PM.

In Figures 2.5 and 2.6 data from 12 different studies has been combined [4, 11, 13, 19, 25, 26, 27, 28, 34, 39, 41, 42]. The data was collected using two different experimental methods, which is why Figure 2.5 shows the data as weight μg/cm^2, whilst Figure 2.6 shows the data in number of particles #/mm^2. It is important to consider that in these graphs the data from different experiments is being compared directly, and has been normalised to be presented in the same units. This has been done to present an overview of both plants that have previously been studied, and what range of PM capture can be expected of different types of plants. However, the experiments in the different studies were conducted under different climactic conditions at different times, and this does influence the results.

In Figure 2.5 the top five species which captured the most PM are *Pinus tabulaeformis*, *Sophora japoinca*, *Salix babylonica*, *Sabina chinensis*, and *Berberis thunbergii* [4, 34]. These first four species were all studied in the paper by Liu et al. (2018) [4], which used an adapted version of the experiment that the other researchers used. This plays a part in why these results show a much higher PM capture compared to other species, and why two of these species show negative PM$_{coarse}$ capture. These negative PM captures showed that the amount of PM on the leaves decreased when there was no rain [4]. This is possibly due to the resuspension of the particles by wind, although the researchers cited no definitive causes [4]. With the exception of *B. thunbergii* these top 5 species are all trees. Two of them have needle-shaped leaves, and the *S. babylonica* is a species of willow, which has long, narrow leaves.

There are five species of climbing plants included in Figure 2.5; *Campsis grandiflora*, *Hedera helix*, *Parthenocissus quinquefolia*, *Parthenocissus thomsonii*, and *Parthenocissus tricuspidata*. They are marked with green arrows in Figure 2.5. Out of these *H. helix* captured the most combined PM with approximately 88μg/cm^2 in the study by He et al. (2020) [34]. It is interesting to note that this is due to the comparatively large amount of PM$_{2.5}$ that *H. helix* collected.

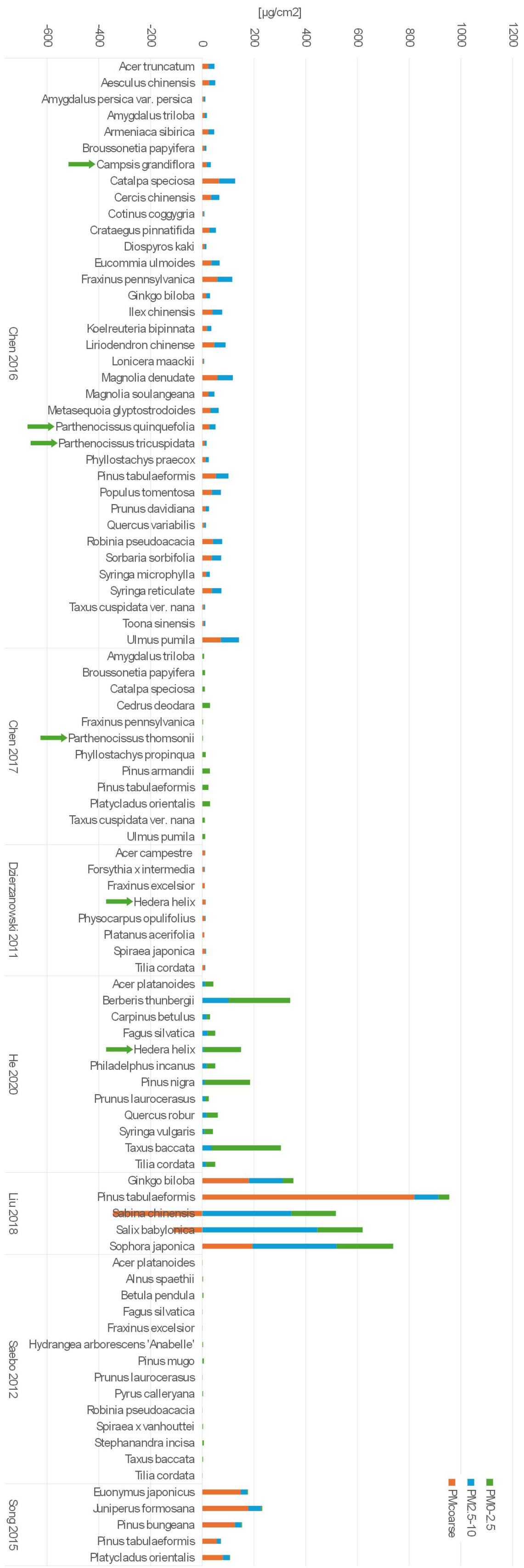


Figure 2.5: PM capture data [µg/cm^2] [4, 11, 13, 25, 27, 34, 39]

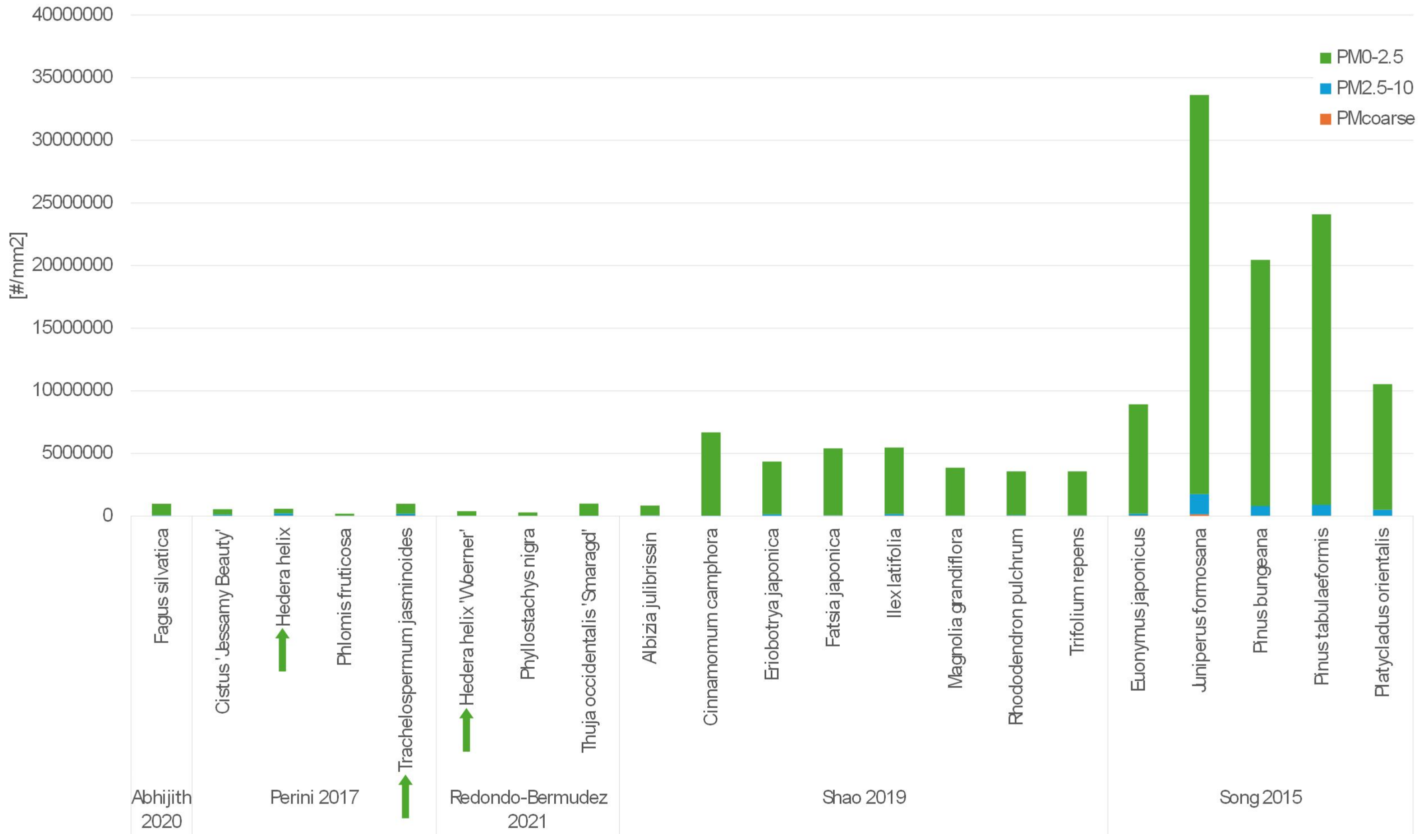


Figure 2.6: PM capture data [#/mm^2] [19, 26, 27, 41, 42]

In Figure 2.6 the best performing plants are *Juniperus formosana*, *Pinus tabulaeformis*, *Pinus bungeana*, *Platycladus orientalis*, and *Euonymus japonicus* [27]. All five of these plants were studied in the same research by Song et al. (2015) [27]. Three of these have needle-like leaves, and *P. orientalis* has very narrow leaves. All five of these species were also included in studies shown in Figure 2.5, but in that case only *P. tabulaeformis* stood out in PM capturing capacity.

In Figure 2.6 only two species of climbing plant are included; *Hedera helix* and *Trachelospermum jasminoides*. They are labelled with green arrows. Out of these two *T. jasminoides* captured more PM, even in the same experimental study by Perini et al. (2017) [42].

Overall one of the biggest differences between Figures 2.5 and 2.6 is the distribution of particles captured in different PM size fractions. Where in Figure 2.5 the size distribution of particles collected changes per plant species and per study, in Figure 2.6 the larger PM fractions PM_{coarse} and PM_{10} are barely visible and any significant differences in PM capture are due to differences in $PM_{2.5}$ capture. This is in large part due to the different experimental methods used to collect the data, which are further explained in Section 2.3.

The results from these various studies indicate that certain plant characteristics are more beneficial to capturing PM than others. Studies including conifers showed that these types of trees have the highest capacity for PM capture due to the leaf shape and arrangement which allows for more frequent impaction of particles on the leaves [11, 25, 34].

Species with trichomes or villi on the leaf surfaces also showed higher PM capturing capacities in multiple studies, specifically increasing the capture and retention of particles with smaller diameters [4, 11, 25, 26, 27, 34]. In contrast, Perini et al. (2017) found that hairy leaves are less effective at capturing particles than leaves with a waxy surface, and concluded that they are therefore a less suitable option to use for reducing PM concentrations in the air [42]. Many of the other studies agree that the wax layer on the leaves plays a role in the PM capturing capacity of the plants [19, 25, 26, 34], but they did not conclude that either hairs or wax were more influential. Dzierzanowski et al. (2011) did not comment on the influence of hairs on PM capture but did determine that there was no significant relationship between the wax quantity and the amount of PM_{coarse} or PM_{10} captured by the plants [39]. A possible explanation for these contrasting findings is that Dzierzanowski et al. (2011) and Perini et al. (2017) used different experimental methods to quantify the PM capture by plants [39, 42].

There is also an agreement between most of the studies that surface roughness influences the PM capture, but that this is very dependent on the relative sizes of particles compared to the furrows, ridges, and grooves on the leaves [4, 11, 19, 26, 27]. However, contrary to this, Sæbø et al. (2012) found no correlation between PM accumulation and leaf surface roughness at all [25]. Different sampling periods and environmental factors may be the reason for this diverging conclusion, as the same experimental methods were used in previously cited studies.

Finally, there is a trend across the cited studies that trees captured more PM than shrubs and climbers, although Chen et al. (2016) and Sæbø et al. (2012) are the only ones to definitively conclude that trees are the most efficient [13, 25]. The reason given for this is that trees promote air turbulence and therefore there is an increased probability of particle impaction on leaf surfaces [13].

2.3. Methods for PM quantification

Over the past two decades different methods for the quantification of PM on plants have been established. The three most cited methods are a gravitational method using filters, using electron microscopy to count particles, and using sensors to determine changes in atmospheric PM around plant barriers.

2.3.1. Gravitational method

This method is based on research done by Dzierzanowski et al. (2011) and has been updated by different researchers over the years [39]. The premise of this experiment is to sample leaves, rinse them in water, and filter this water, to finally determine the weight of PM that was on the leaves by measuring the weight change of the filters. The water is filtered consecutively through a mesh sieve with a pore size of 100µm, and filters with retentions of 10µm, 2.5µm, and 0.2µm in that order [39]. This results in three size fractions of PM that can be determined; PM_{coarse} (10-100µm), PM_{10} (2.5-10µm), and $PM_{2.5}$ (0.2-2.5µm). After completing this process, it is repeated again with the same leaf samples, however, this time chloroform is used instead of water to determine the quantity of PM trapped in the wax layer of the leaves [39].

One step of this method that has been approached differently by other researchers is the process of rinsing the leaves. Dzierzanowski et al. (2011) placed the sampled leaves in a beaker with 250mL of water and agitated it for 60 seconds to remove the particles from the leaf surface [39]. As this was followed by repeating the process with chloroform most of the PM that the leaves had collected was accounted for during the experiments. However, there are environmental health concerns regarding the use of chloroform, which meant that this step had to be skipped in other studies [2, 13].

Liu et al. (2018) compared three different methods for cleaning PM from the leaf surface; water cleaning, brush cleaning, and ultrasonic cleaning, on two conifers and three broadleaf tree species [4]. These steps were applied consecutively, and the removal effect of each step was determined before completing the next step by analysing the PM left on the leaf surface using electron microscopy [4]. The water cleaning process is the same as the process in Dzierzanowski et al. (2011) [13, 39]. This process removed on average 23-45% of PM from the leaf surface, which is within the same range of PM that can be removed by rainfall [4]. The brush cleaning included the extra step of scrubbing the leaf surfaces with a nylon brush to a state of ”apparent cleanliness” of PM particles [4, 13, 15]. In this step, another 20-46% of PM that previously remained on the leaf surface was removed [4]. The most thorough step uses an ultrasonic cleaning machine to agitate the leaves in a beaker of water at 500W for 3 or 10 minutes, for broadleaf and needle-leaf samples respectively [4]. Another 29-46% of particles were removed in this step [4]. Each step also managed to remove a larger amount of smaller particles, with the ultrasonic cleaning removing the most particles $\leq$2.5µm by weight [4]. As the different cleaning techniques were applied to the same leaf samples consecutively it could not be determined whether or not the ultrasonic cleaning was worse at removing large PM particles, or if most of these had simply been removed from the leaf surface in the earlier steps already. The conclusion of this comparison was that adding the ultrasonic cleaning step to the existing cleaning process removed PM from the leaf surface ”almost completely”, removing around 70% of the particles on average, and that it is a necessary step to add to the experimental process [4].

2.3.2. ESEM method

This method for PM quantification was first used by Ottelé et al. (2010) and uses an Environmental Scanning Electron Microscope (ESEM) to take magnified pictures of the leaf surface in order to count the number of particles on the leaf [37]. Although previous research had made use of the Scanning Electron Microscope (SEM) to determine surface structures on leaves, particles could not be counted with the SEM as it requires samples to be covered in a heavy metal coating which also covered up the particles on the leaf surface [43]. However, in the ESEM it is possible to view the samples without coating them as the vapour pressure in the microscope’s chamber can be heightened to prevent the samples from drying out and deforming [37, 43].

The ESEM is used to make microphotographs at magnifications of 125x, 250x, and 500x to count particles with diameters >10μm, 2.5-10μm, and 0.2-2.5μm respectively [37]. To analyse the microphotographs the ImageJ software was used [37]. The biggest challenge in this analysis is accurately separating the particles from the background to create a binary image, a process referred to as thresholding [37]. After counting the particles at each magnification level, a weighting factor is applied to compensate for the zoom effect, caused by each magnification level photographing a smaller area [37].

2.3.3. Sensor method

The third method of quantifying PM collection by vegetation is through the use of sensors which measure PM concentration in the ambient air [2]. By placing PM sensors on two sides of a piece of green infrastructure such as a hedge the difference in ambient PM concentration can be determined, which is concluded to have been captured by the structure [2, 41]. An example of the sensor placement is shown in Figure 2.7 by the yellow and red stars. This method requires a relatively larger amount of vegetation to determine how much PM a specific species of plant can capture, or alternatively, it can determine the PM capturing capacity of a mixed vegetation structure without specifying how much each different included species contributed to PM removal from the air.

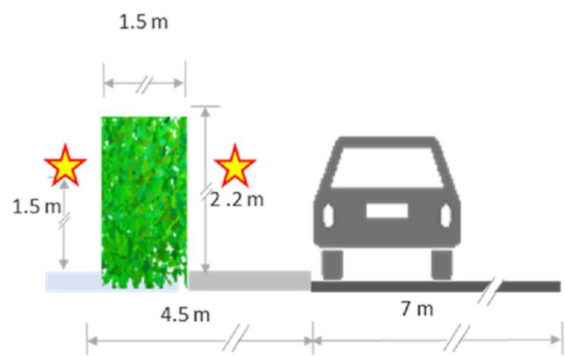


Figure 2.7: Sensor method sensor locations (adapted from Abhijith & Kumar (2020) [41])

2.3.4. Advantages and disadvantages

There are advantages and disadvantages to each of these experimental methods. The biggest advantage of the gravimetric method is that it is the most direct method and it provides data based on multiple leaves and a larger leaf area [41]. It is relatively easy to increase the volume of leaves sampled without significantly increasing the time it takes to complete the experiments. However, there is no absolute size segregation of the particles, only giving results in larger PM size ranges [2]. This makes it more difficult to directly relate the captured PM to specific emission sources. There is also a possibility that some soluble ions in and on the leaf can affect the results as the leaves are cleaned with water [27]. Besides this, the amount of PM collected in the leaf’s wax layer cannot be determined with water as the only rinsing liquid. Although this can be determined by repeating the process with chloroform, there are certain health and environmental concerns related to its use and it can dissolve some particles which would affect the results [2, 41].

Electron microscopy provides a complete particle size distribution and insights into leaf micromorphology, which is an important factor in determining PM retention by plants, and there is no danger of particles dissolving and disappearing from the results [2, 26, 41]. There is also the added benefit that as the leaves are being assessed in the ESEM, there is little to no extra effort required to gather information on the leaf micromorphology [41]. However, this method is more time-consuming, specifically the analysis of the microphotographs, and to draw any conclusions a statistically significant number of micrographs should be taken as only a tiny area of the leaf can be analysed in each image [2, 41]. This is also why some argue that the data from research which employs this method has a relatively low accuracy [26].

The main benefit of using PM sensors to quantify PM capture by plants is that it provides information about how the ambient air is affected by the presence of the vegetation. Most research concerning the PM capture of plants is motivated by a goal to reduce the PM concentration in ambient air as too much exposure is harmful to human health [12, 44, 45]. By directly measuring the PM concentration this method could be seen as having the most useful data output. However, unless the sensors are placed around a large volume of one specific species of vegetation it is impossible to link any of these findings to specific plants or leaf traits. The sensor placement is also very specific, needing an emission source on one side of the vegetation so that a difference in PM concentration can be measured as seen in Figure 2.7 [41]. These two factors can make it challenging to set up this experiment.

A summary of advantages and disadvantages of each method can be seen in Table 2.1.

	Gravimetric method	ESEM method	Sensor method
Pros	Direct method Data representative for the entire plant	Complete particle size distribution Insights into leaf micromorphology	Information about the ambient air quality
Cons	No absolute particle size segregation Soluble ions can be overlooked Particles in wax layers cannot be quantified if only using water	Inaccurate thresholding Need a statistically significant number of images	Needs large homogeneous areas of green barriers Needs a very sepecific setup to get useful results

Table 2.1: Overview of the pros and cons of each method

3

Methodology

3.1. Plant setup

3.1.1. Location

The studied plants were placed at the Hortus Botanicus of the Technical University in Delft. They were put on a balcony on top of the entrance to the botanical gardens (indicated by the red circle in Figure 3.1), next to the intersection of the Julianalaan and the Mijnbouwstraat on the southeast side of the building. The Hortus is located between the Schie River, an important part of the inland shipping routes north of the Port of Rotterdam, and the A13 highway. This location was chosen as it allowed the plants to be placed outside in an area where they would not be disturbed by the public, and the location next to a busy intersection results in adequate concentrations of PM in the air for the plants to capture.

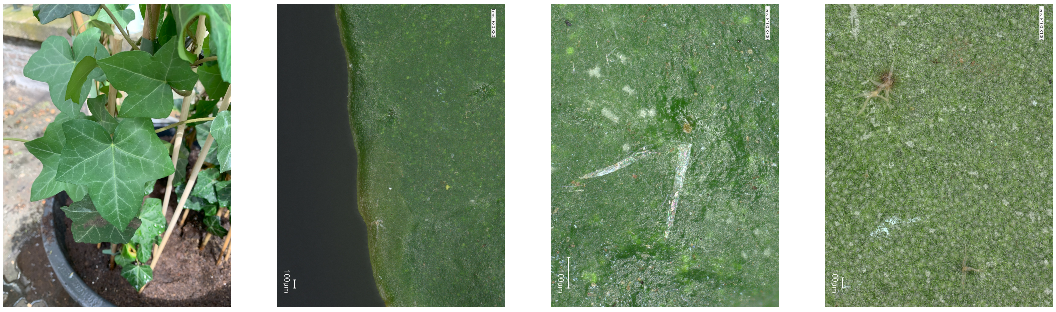
Figure 3.1: Map of the location of the Hortus Botanicus in Delft (adapted from Google Maps [46])

3.1.2. Selected plant species

Four climbing plant species, one moss species, and a plastic climbing plant were selected for these experiments. The climbers are *Hedera helix* (HH), *Trachelospermum jasminoides* (TJ), *Parthenocissus quinquefolia* (PQ), and *Wisteria sinensis* (WS). The moss used is *Rhynchostegium confertum* (RC), and the plastic climbing plant is a version of ivy (PI). These species were chosen because they offer a variety of leaf characteristics and they are either commonly found in the Netherlands or they have been used in previous research so there is data available to compare the findings to. The chosen set of plants includes two species with prominent wax layers on the leaf surfaces, and two without. There is also a difference in the hairs on the leaf surfaces, one species has villi, and the other three climbing plant species have trichomes of varying arrangements. There is a range of leaf arrangements, with two climbing plant species having compound leaves, and the moss having an entirely unique macrostructure.

Hedera helix

H. helix is also known as ivy and is native to the Netherlands where it is often used to cover noise barriers next to highways. It is an evergreen woody plant which uses its roots to attach to walls or frames [47]. The leaves have a deep green, leathery and glossy surface, and are palmately lobed with 3-5 lobes (see Figure 3.2a) [48]. The leaf edges are smooth all the way around the leaf. On both the adaxial and abaxial surfaces small trichomes can be found, sometimes arranged in a star-like figure, or by themselves. In research by Dzierzanowski et al. (2011), *H. helix* collected the highest quantity of PM_{10} particles on the leaf surface, but the smallest amount of $PM_{2.5}$ [39]. However, analysis by Ottelé et al. (2010) the opposite was found to be true [37]. It is important to note that these two papers used different methods for quantifying the PM.

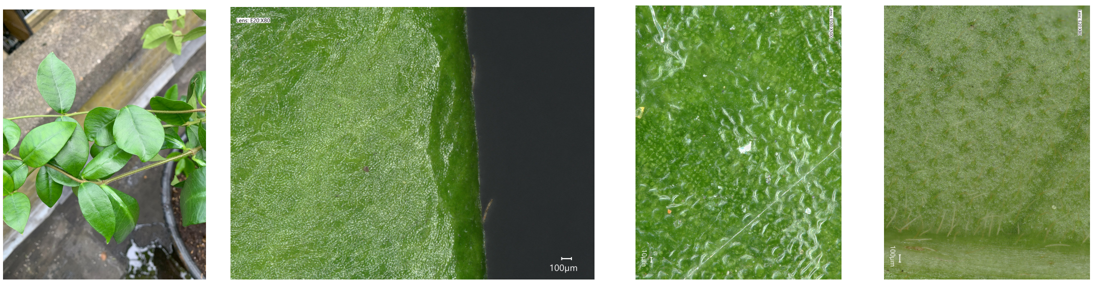


(a) Leaf **(b)** Leaf edge **(c)** Adaxial surface **(d)** Abaxial surface

Figure 3.2: *Hedera helix* (HH)

Trachelospermum jasminoides

T. jasminoides is more commonly known as star jasmine and is an evergreen woody liana. It is a part of the Apocynaceae family, whose plants are characterised by 'milky latex' which leaks from the plant when it is cut or broken [47]. This plant is native to Asia, although it is a popular garden plant in Europe because of the small scented flowers that it produces [49]. The leaves are ovate-shaped and have a smooth waxy surface, as seen in Figure 3.3 [42, 50]. The edges of the leaves have trichomes sticking out from the leaf at regular intervals. Although the adaxial surface showed no trichomes, the abaxial surface had intermitted trichomes which were more concentrated around the nerves of the leaf. In the research done by Perini et al. (2017), *T. jasminoides* collected the highest number of particles compared to three other plants in a vertical green system, which also included *H. helix* [42].

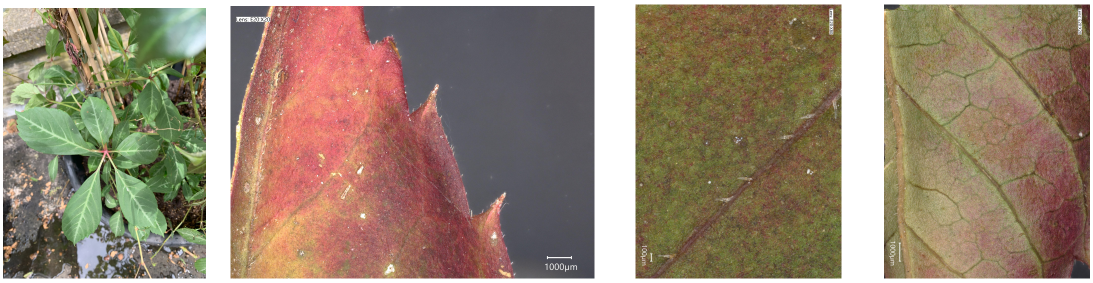


(a) Leaf **(b)** Leaf edge **(c)** Adaxial surface **(d)** Abaxial surface

Figure 3.3: *Trachelospermum jasminoides* (TJ)

Parthenocissus quinquefolia

P. quinquefolia has been introduced to Europe from North America and is also referred to as Virginia creeper [51]. The climber has adhesive discs at the ends of each of the highly branched tendrils, and for the leaves, five leaflets are palmately distributed (see Figure 3.4a), meaning that the leaflets are distributed around the petiole in a way that resembles the palm of a hand. These leaflets' edges are serrated, with sharp teeth along the outside. The adaxial side of the leaves is generally smooth, but there can be some long, soft, straight hairs on the abaxial side [30]. Inspection of the leaves showed that there were trichomes on the nerves of the adaxial surface of the leaves as well (see Figure 3.4c). Out of three liana species compared by Chen et al. (2016), *P. quinquefolia* was the most effective in accumulating PM_{10}, $PM_{2.5}$, and total suspended particles (TSP), reaching levels equal to some of the tree species that were also included in the study [13].

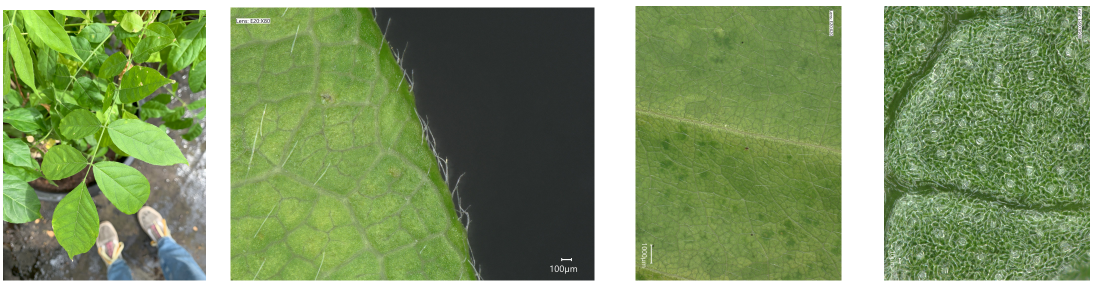


(a) Leaf **(b)** Leaf edge **(c)** Adaxial surface **(d)** Abaxial surface

Figure 3.4: *Parthenocissus quinquefolia* (PQ)

Wisteria sinensis

W. sinensis is a deciduous woody climber also known as Chinese wisteria. It is not native to Europe, but due to its colourful flowers, it can be found in gardens and along the front façades of houses. The leaves are compound, with 7-13 leaflets in an odd-pinnate structure [30, 52], as seen in Figure 3.5a. The leaves are sparsely covered in small, silky hairs also known as villi on both the abaxial and adaxial sides of the leaf. These villi also cover the edges of the leaves, which are otherwise smooth (see Figure 3.5b).

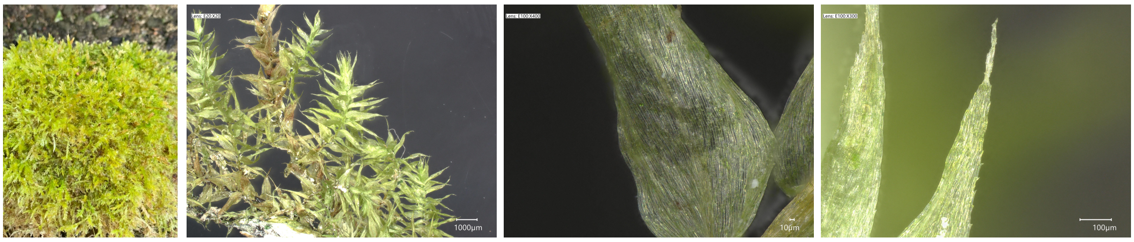


(a) Leaf **(b)** Leaf edge **(c)** Adaxial surface **(d)** Abaxial surface

Figure 3.5: *Wisteria sinensis* (WS)

Rhynchostegium confertum

R. confertum is a moss species that commonly grows on both wood and stones and can be found on man-made structures that are not too acidic [53]. It has small egg-shaped leaves which are attached to longer branches or stems (see Figure 3.6b). The leaves themselves are very thin and have jagged edges. A moss species is included in this research for comparison with the climbing plants as they have similar benefits when it comes to spatial requirements. Currently, research is being done into bio-receptive concrete, which looks at the possibility of creating concrete surfaces that moss can easily grow on in order to increase the greenery in urban areas. This is being done under some assumptions that the benefits of moss are similar to those of other types of vegetation, which will be tested by including a common urban moss species in this research.

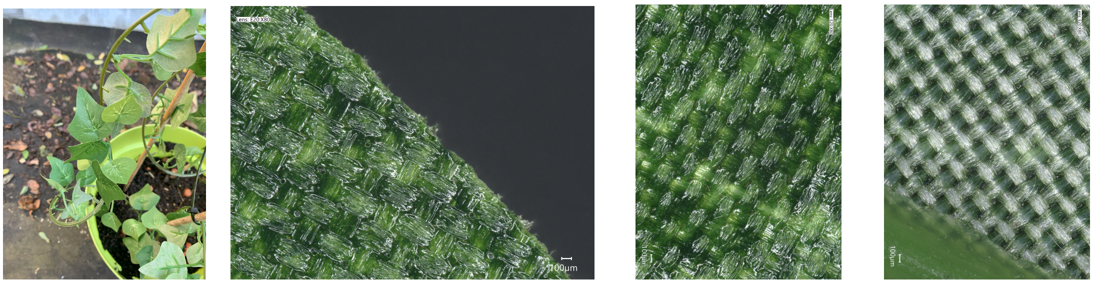


(a) Moss on concrete **(b)** Moss structure **(c)** Cells in moss leaves **(d)** Edges of moss leaves

Figure 3.6: *Rhynchostegium confertum* (RC)

Plastic ivy

The plastic ivy garland was purchased at the Xenos department store in Delft. It is 260cm long and made of woven polyester leaves which are stuck to a plastic 'stem' [54]. The leaves range in size from around 3-9cm^2. The woven structure of the leaves can be seen on both the adaxial and abaxial surface, although on the adaxial surface, another printed layer of plastic covers the woven structure (see Figures 3.7c and 3.7d). The edges of the leaves have been cut and at some points, small polyester threads stick out from the sides (see Figure 3.7b). This plant was included to investigate how important living plant characteristics are to PM capture. Plants do not proactively attract PM, particles happen to encounter a leaf surface and stick to it. Including the plastic ivy will shed light on the importance of plant characteristics when it comes to PM capture, as the macrostructure and environmental conditions will be similar for the plastic and living plants.



(a) Leaf **(b)** Leaf edge **(c)** Adaxial surface **(d)** Abaxial surface

Figure 3.7: Plastic ivy (PI)

Overview of selected plants' leaf characteristics

An overview of the characteristics of each of the chosen plants is given in Table 3.1.

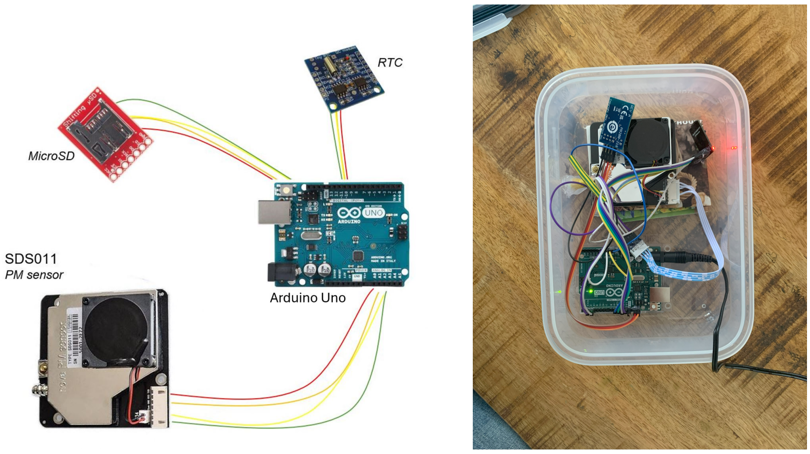
		H. helix	*T. jasminoides*	*P. quinquefolia*	*W. sinensis*	*R. confertum*	*Plastic ivy*
Microstructure	Trichomes/villi	Trichomes	Trichomes	Trichomes	Villi		
		Star-like arrangement	Along edge & on abaxial side	Along edge & veins	Adaxial & abaxial side		
		~0.2mm long	~0.27mm long	~0.19mm long	~0.68mm long		
		~6/cm2	~1600/cm2	~0.6mm spacing	~157/cm2		
	Stomata	116/mm2	296/mm2	93/mm2	275/mm2		
	Visible wax layer	Yes	Yes				
Macro structure	Leaf shape	palmately lobed	ovate	palmately compound	odd-pinate	ovate	palmately lobed
	Leaflet shape			ovate	obovate		

Table 3.1: Overview of leaf characteristics of studied plants

3.1.3. Sensors

In this research sensors are not used to determine the PM capturing capacity of the plants, but they are used to monitor the local climate where the plants were placed. The environmental effects that are most influential for PM capture are the PM concentration in the air, precipitation, wind speed, temperature, and humidity. To monitor these circumstances two devices were used; an Alecto WS-5500 weather station and the Nova Fitness SDS011 PM sensor in combination with an Arduino Uno.

To measure the PM concentration the Nova Fitness SDS011 sensor was used (see Figure 3.8). The sensor uses laser scattering to determine concentrations of $PM_{2.5}$ and PM_{10} in µg/m^3. It does so with an accuracy of $\pm$15% or a maximum of $\pm$10µg/m^3, and a resolution of 0.3µg/m^3 [55]. The sensor was placed on a ledge on the balcony at a similar height to the tops of the plant pots, and next to the wall to allow the sensor to be plugged into a wall socket inside the office that the balcony is connected to. The data from this sensor was recorded at 5-minute time intervals and recorded on an SD card.



(a) Schematic of PM sensor **(b)** PM sensor setup

Figure 3.8: PM sensor

The other environmental conditions were monitored using the Alecto WS-5500 personal weather station. The station measures the temperature, relative humidity, rainfall, and wind speed at 5-minute time intervals. The temperature is measured with an accuracy of $\pm$1°C and a resolution of 0.1°C [56]. The relative humidity is measured with an accuracy of $\pm$5% [56]. The wind speed is measured with a range of 0-50m/s, at an accuracy of $\pm$1m/s at windspeeds <5m/s, and $\pm$10% at windspeeds >5m/s [56]. The precipitation is measured with an accuracy of $\pm$10% and a resolution of 0.1mm when the total rain event was <1000mm [56]. However, earlier research into this specific personal weather station showed that the tipping bucket system used to measure rainfall could not reliably report at this resolution, although for amounts >0.254mm the results are reliable [57]. The weather station was mounted on a tube which was secured inside the plant pot containing *P. quinquefolia*, as seen in Figure 3.9. The data is uploaded to and stored on the open data platform 'Weather Observations Website' (WOW), which was created by the UK Met Office and contains data from personal weather stations across Europe [58].

Figure 3.9: Alecto weather station

3.1.4. Indoor plant setup

As a control group a second *H. helix* plant was placed indoors in an office at the Faculty of Civil Engineering and Geosciences (CiTG) of the TU Delft. The environmental factors are more controlled inside as there is no precipitation, limited air turbulence, and a more constant temperature and humidity. As these factors are relatively stable indoors they were not monitored for the indoor location. A second SDS011 PM sensor was set up indoors to monitor the PM levels between the sampling periods.

3.2. Sampling

The plants were placed outside at the Botanical Garden on the 13^{th} of June 2024. Sampling of the leaves took place at three different moments throughout the year, once in July and twice in October. The sampling process was revised after July to be more detailed in October.

For the first set of samples in July, leaves were picked randomly from all over each plant. The leaves for the gravimetric experiment were picked to make sure that there was a variety of individual leaf sizes and a mix of young and mature leaves. For the ESEM experiment, four leaves were picked off each plant at random, before two of the four were randomly selected for analysis in the ESEM. In July only *H. helix*, *P. quinquefolia*, *W. sinensis*, and *T. jasminoides* were sampled and tested.

Figure 3.10: Division of plant resulting in 8 quadrants to sample from

In October the sampling process had been reviewed and specified further and samples were also taken from the plastic ivy and *R. confertum*. For the samples for the ESEM experiment two mature leaves were selected from the outermost leaf layer of each plant, one being taken from the top of the plant, and the other being sampled from a height equivalent to the edge of the pots in which the plants were planted. The *R. confertum* was sampled from the middle and the outside edge of the moss tuft. For the gravimetric experiment, the leaves were sampled from all over the plant equally. The plant was divided into eight equal parts as shown in Figure 3.10 and an equal number of leaves was taken from each eighth of the plant. Care was taken to still sample a variety of young and mature leaves with different leaf surface areas. The *R. confertum* was sampled by cutting an area of about 5cm^2 from the edge of the tuft.

In October the plants were sampled twice, the first time on the first dry day after 8 consecutive days of rain on October 2^{nd}, the second time three dry days later on October 5^{th}. This was done to see how much PM the various plants would be able to collect when no resuspension or wash-off due to rainfall took place.

Indoor plant

As it does not rain indoors artificial rain had to be created for the indoor plant setup. The amount of 'rain' for the indoor plant was determined as the average amount of daily rain on the 8 rainy days before the outdoor plants were sampled in October. This was on average 10.9mm of rain per day. The artificial rain was created using a shower, where the lowest flow rate from the shower head was 258mL/minute.

Based on this, the plant was sprayed with water for 5:21 minutes to achieve a total simulated rainfall amount of 10.9mm to reflect the average precipitation that the plants located outdoors encountered per day in the week before sampling.

3.3. Choosing an experimental method

In this research, two experimental methods were used to quantify the amount of PM that climbing plants can remove from ambient air. The first is the gravimetric method based on Dzierzanowski et al. 2011 [39], and the second is the ESEM method based on Ottolé et al. 2010 [37]. These two methods were selected as they give direct results of the amount of PM on the leaf surfaces, whilst on the other hand, the sensor method can only conclude that there is a change in PM concentration in the air in front of and behind a body of vegetation without being able to confirm whether or not the PM has settled on the plants. Furthermore, full-grown plants in a solid barrier are required to employ the sensor method, which removes the control over the choice of plant species studied, given that the time frame of this project did not allow for growing an entire hedge of climbing plants.

3.4. Gravimetric method

The first quantification method that is used is the gravimetric method, based on the research done by Liu et al. (2018), Chen et al. (2017) and Dzierzanowski et al. (2011) [4, 11, 39]. The principle of this experimental method is to wash the PM from the leaf surfaces with water and to filter the water through filters with different pore sizes to determine how much weight of PM is left behind on the filters. For this around 200cm^2 of leaves were collected from each plant. These leaves were stored in sealed plastic boxes in a refrigerator at $\pm 4^\circ$C until the experiments were conducted.

Materials:

- 200 cm^2 leaves
- Demineralised water
- Sieve with pore size 100µm
- Whatman type 93 filter (pore size 10µm)
- Whatman type 42 filter (pore size 2.5µm)
- Whatman Cat No. 7060-4701 filter (pore size 0.1µm)
- 1000mL beakers
- Büchner flask
- Büchner funnels to fit the filter diameters
- Vacuum pump
- 105°C oven
- Ultrasonic cleaner
- Petri dishes
- Watch glasses
- Tweezers
- Scales
- Camera
- Ruler
- Funnel
- Rubber bung

Figure 3.11: Gravimetric method filter setup

All materials that were used were washed with tap water, then rinsed with demineralised water, and then dried with pressurised air, before being used. All materials were handled exclusively with clean tweezers or whilst wearing gloves.

Steps:

1. Soak filters in demineralised water for 2 hours.
2. After soaking remove the filters from the water with tweezers and place them in clean Petri dishes. Cover each Petri dish with a watch glass.
3. Put the covered Petri dishes in an oven at 105°C for 3 hours.
4. Remove the Petri dishes from the oven, keep them covered, and let them acclimatise in the weighing room for 13-24 hours.
5. Once the filters have acclimatised, pre-weigh them and record the weights.
6. Take the leaves out of the box and photograph each one against a light background with a ruler next to it. Keep the contact to a minimum and touch as little of the leaf as possible.
7. After taking the pictures, put the leaves in a beaker and cover them with demineralised water.
8. Put the beaker in the ultrasonic cleaner and turn it on for 3 minutes.
9. Using the funnel, pour the water covering the leaves into a beaker through the 100μm sieve.
10. Once the beaker is empty, pour in more demineralised water to rinse it out. Pour this water through the sieve as well.
11. Using tweezers, take the leaves and shake the water off their surface before removing them from the sieve.
12. Set up the vacuum pump with the Büchner flask and funnel and an appropriate size rubber bung, put the 10μm filter in the funnel and put some clean demineralised water through it to stick the filter to the bottom of the Büchner funnel.
13. Start filtering the water that was used to clean the leaves through the filter. If the water level in the Büchner flask gets too close to the tube which connects it to the vacuum pump, turn off the pump and pour the water into a second beaker before continuing the filtration.
14. Once all the water has been filtered, rinse the beaker that it was poured out of with demineralised water and put this through the filter as well.
15. Carefully remove the filter from the Büchner funnel using tweezers and place it into a Petri dish. Immediately cover it with a watch glass.
16. Repeat steps 12 to 15 for the filter with pore size 2.5μm, and after that again for the filter with pore size 0.1μm.
17. Once the water has been filtered through all three filters, place the covered Petri dishes containing the filters in a 105°C oven for 3 hours.
18. After the three hours, remove the Petri dishes from the oven and let the filters acclimatise in the weighing room for 13-24 hours.
19. After acclimatisation weigh the filters again, and record the weights.

After completing the experiment the ImageJ software (Version 1.54g) was used to determine the leaf surface area from the photographs that were taken [59]. To do so first the scale was set for the image using the ruler in the image, after which the image was made binary. Once a binary image was created, the program could determine each leaf's area. This process is shown in Figure 3.12. Dividing the collected weight of PM by the total leaf surface area will give a result of PM collected in weight per unit area, which can be converted to the units of μg/cm^2.

3.5. ESEM

The second method for quantifying the PM captured by plant leaves uses electron microscopy. It is based on a method developed by Ottelé et al. (2010) [37]. An electron microscope can magnify images to a much higher degree than other microscopes, which allows the PM to become visible. The sampled

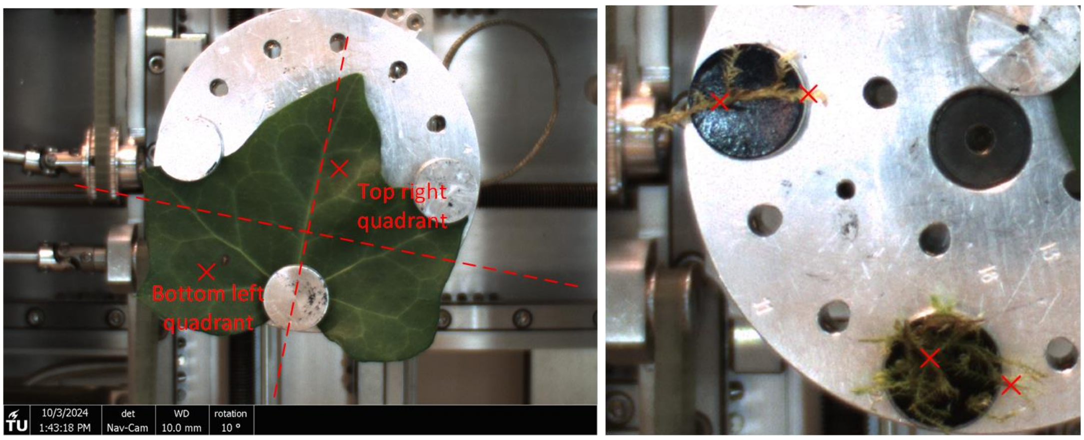
(a) Original image **(b)** Binary image

Figure 3.12: Image of *T. jasminoides* leaves to determine their surface area

leaves are placed in an Environmental Scanning Electron Microscope (ESEM) and the resulting images are analysed using software to count the particles of the different size fractions. This results in a particle density per unit leaf area.

From each plant species, two leaves were taken per sampling date. They were collected using gloves and clean scissors touching only the petiole or the very bottom of the leaf blade. The cut leaves were secured onto the bottom of a plastic box using tape to prevent the adaxial surface from coming in contact with anything during transportation to the lab. For some of the sampling dates the leaves were only able to be analysed a week after the sampling took place. The leaves were stored in a refrigerator at ±4°C until 24 hours before being analysed when they were removed from the refrigerator and acclimatised to room temperature.

The experiments were carried out at the Microlab of the CiTG faculty using the FEI Quanta FEG 650 ESEM. Each leaf was attached to the platform using pins as seen in Figure 3.13. Once the leaf samples were placed in the ESEM they were analysed on low vacuum mode with a high voltage of 15kV. Per leaf, two locations on the adaxial side of the leaf were examined, once in the bottom left quadrant of the leaf, and once in the top right. An area of the blade was selected that contained no large veins and that was not located right at the edge of the leaf. For the moss, a spot was chosen at the top end of the stem and about halfway up the stem to analyse. Approximations of the sampling locations can be seen in Figure 3.13. At each location three micrographs were taken, magnified 125x, 250x, and 500x. In this research, only the adaxial side of the leaves was examined, as previous research has shown that more than twice as much PM is collected here than on the abaxial side, and particles >10µm are only found on the adaxial side [37].



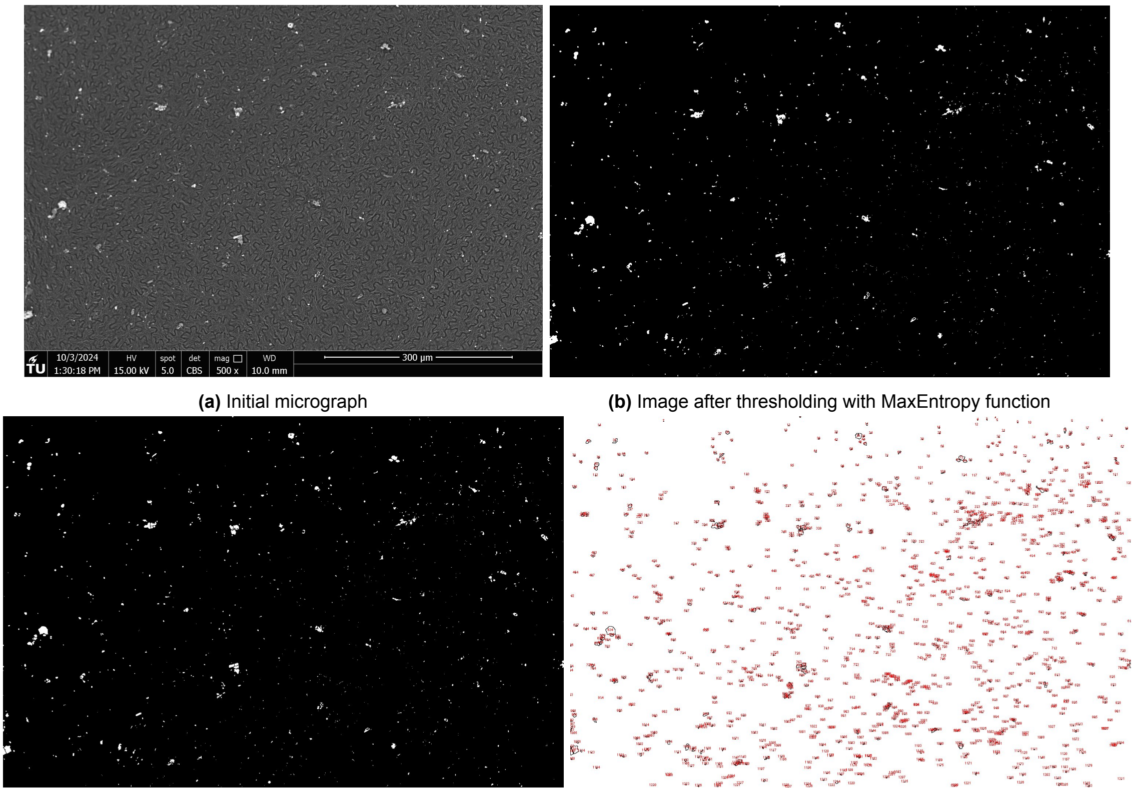
(a) *H. helix* leaf **(b)** *R. confertum* stems

Figure 3.13: Indication of where ESEM micrographs were taken

After the micrographs were taken the images were analysed using the ImageJ software (version 1.54g) for Windows [59]. This process consisted of the following steps after opening the image:

1. Set the scale in mm.
2. Select the area to be analysed and duplicate it. Record the area of this total image.
3. Convert the image to greyscale by changing the type to 16-bit.
4. Threshold the image to select only the particles. When possible the MaxEntropy function was used. When necessary this thresholding was corrected manually.
5. Convert the image to a binary image.
6. Separate the particles using the watershed function.
7. Analyse the particles with the circularity set to the full range (0-1).
8. Save the data output to be processed.

The MaxEntropy function for thresholding works by maximising the inter-class entropy, so it looks for the maximum differences between pixels. This makes it useful when analysing images with relatively few bright objects on dark backgrounds [60]. The watershed function is used to separate the images of particles that are likely overlapping. It does this by creating a distance map from the centre of each object and separating them when two of these distance maps connect [61]. An example of how these steps change the image can be seen in Figure 3.14 where the image of one of the *H. helix* leaves is analysed.



(a) Initial micrograph

(b) Image after thresholding with MaxEntropy function

(c) Image after applying the watershed function

(d) Result of particle analysis

Figure 3.14: Steps for analysing the ESEM micrographs of a *H. helix* leaf

3.6. Statistical Analysis

To determine whether or not there were statistically significant differences in the amount of PM collected by the different plant species across the different PM size fractions, statistical tests were applied to analyse the data using IBM SPSS Statistics (Version 29). Due to the small sample size the Shapiro-Wilk test was used to check if the data on the amount of PM captured by each plant is normally distributed. Following this, Levene's test was used to determine the homogeneity of the variances of the data. As most of the data did not have a normal distribution, the non-parametric Kruskal-Wallis test was used to determine if there were any statistically significant differences between the PM capture of the different plant species that were located outside.

The Kruskal-Wallis test compares the different plant species by ranking the results and comparing the medians of each species' results to see if any groups were statistically different from the rest. When this was the case Dunn's Test with the Bonferroni adjustment was used to determine which two species are statistically different from one another. This information was used to create groups of species that collected statistically similar amounts of PM.

4

Results

4.1. Environmental conditions

Between the sampling dates on October 2nd and 5th the environmental conditions at the plants' location were recorded using an Alecto WS-5500 weather station and a Nova Fitness SDS011 PM sensor.

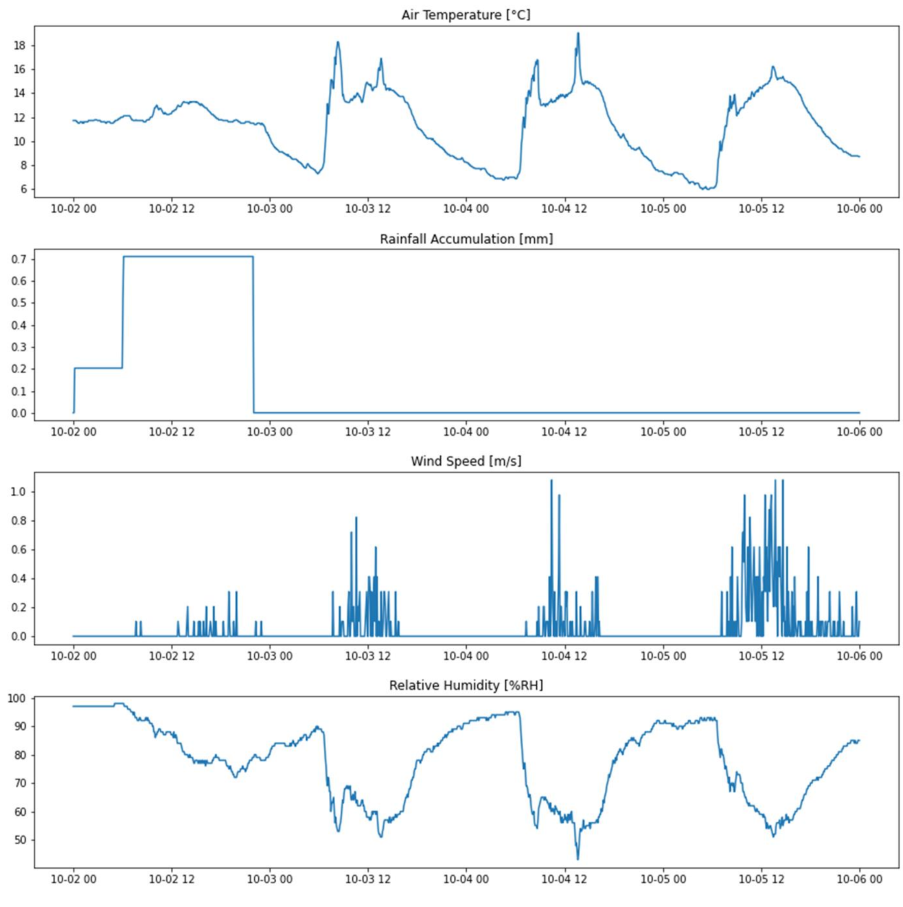
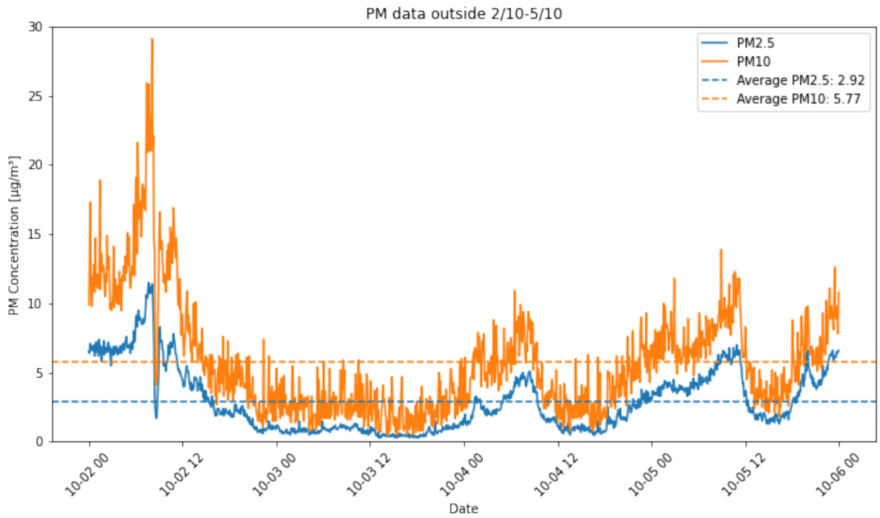


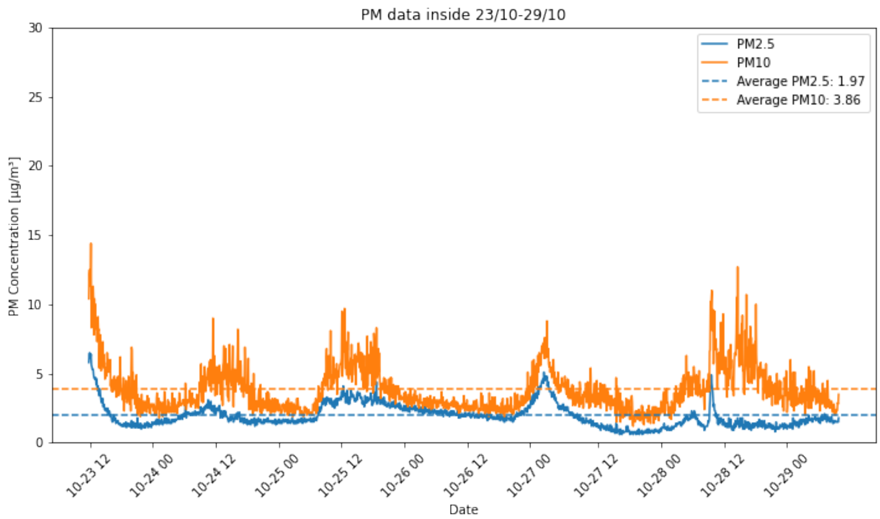
Figure 4.1: Environmental conditions measured at the Hortus Botanicus from October 2nd to October 5th

Figure 4.1 shows the measurements of environmental factors other than the PM concentration which can influence PM capture by plants. All measurements were recorded at 5-minute intervals. During the first day, there was still some precipitation and there was less variation in air temperature, wind speed, and relative humidity. Once the precipitation stopped, all three measures seem to show daily cycles, with the air temperature and wind speed dropping during the night, and the relative humidity decreasing during the daylight hours.

Figure 4.2a shows the PM concentrations that were measured in the air. The PM_{10} and $PM_{2.5}$ concentrations were measured at 5 minute intervals in µg/m^3. Figure 4.2b shows the PM concentrations that were measured indoors in the office where one of the *H. helix* plants was located. As there was an issue with the sensor's SD card, the data for that plant during the sampling period was not recorded. For this reason, Figure 4.2b shows the PM concentrations measured in the week after the samples were taken. This was done to have a reference measurement for comparing the PM levels indoors and outdoors, to see if this corresponds to the amount of PM the respective plants collected. For both datasets the mean PM_{10} and $PM_{2.5}$ were calculated, these are shown by the horizontal lines across the graphs.



(a) PM concentration measured at the Hortus Botanicus from October 2^{nd} to October 5^{th} [µg/m^3]



(b) PM concentration measured inside from October 23^{rd} to October 29^{th} [µg/m^3]

Figure 4.2: Measured PM concentrations in the air

As can be seen in Figure 4.2a the measured PM_{10} concentration in the air is always higher than the $PM_{2.5}$ concentration. This is also reflected in the average PM concentrations of the two size fractions, of which the PM_{10} average concentration (5.77µg/m^3) is just under twice as high as the $PM_{2.5}$ average concentration (2.92µg/m^3). When averaged over the total time that the PM sensor ran (September 30^{th}

– October 15^{th}) a similar difference was calculated with an average PM_{10} concentration of 6.15µg/m^3, and an average $PM_{2.5}$ concentration of 2.41µg/m^3. The gravimetric results show almost the same ratio of PM_{10} to $PM_{2.5}$ collected by the plants. The average PM_{10} collectively accumulated by all the plants was 22.36µg/cm^2, whilst an average of 10.49µg/cm^2 of $PM_{2.5}$ was captured.

4.2. Experimental results

4.2.1. Gravimetric method

In Figure 4.3 the results from the filtering experiment are shown. The bars represent the weight of PM that was collected on the filters, and the weights have been normalised to be displayed in µg/cm^2. The full numerical results can be found in Appendix A.

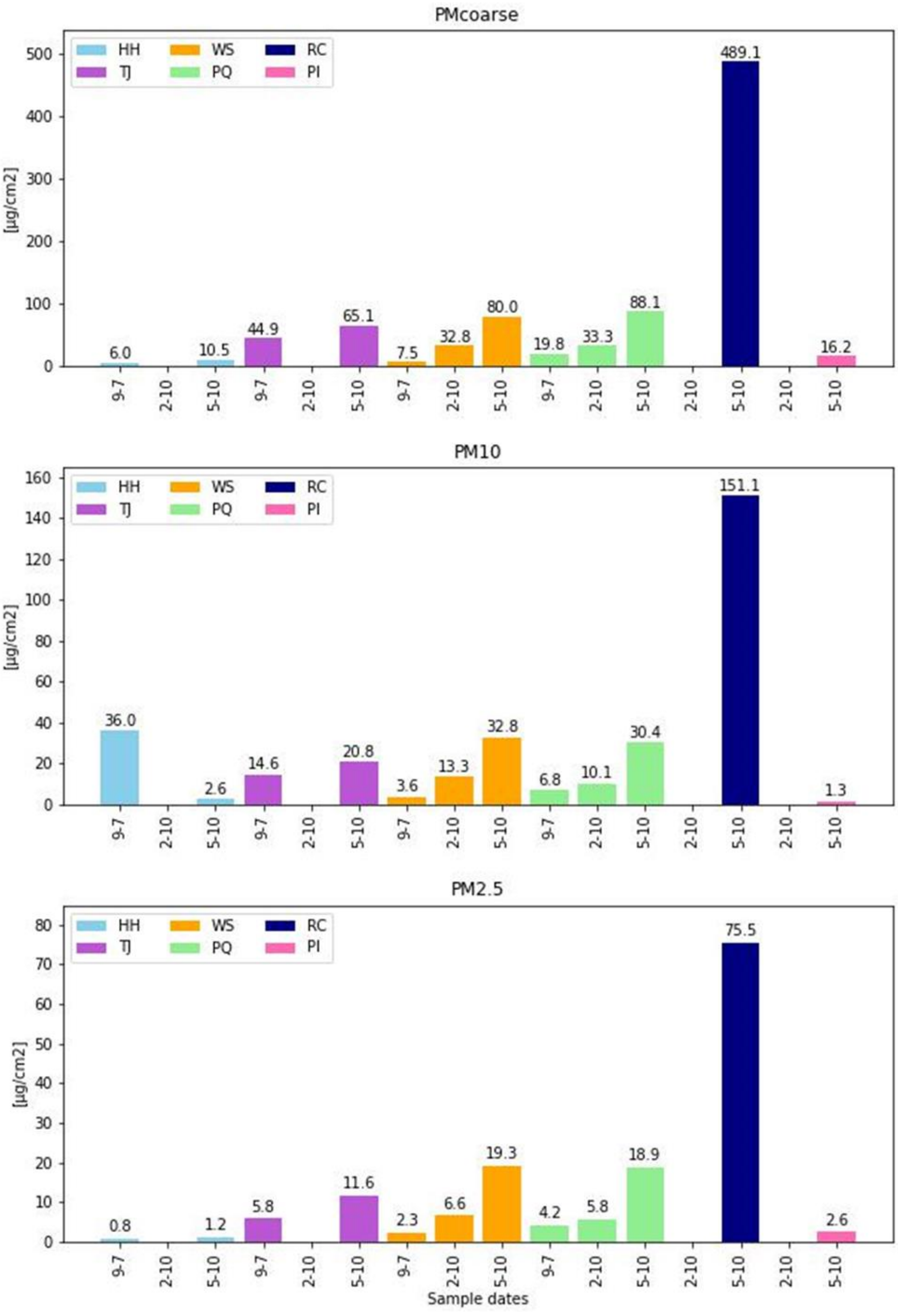


Figure 4.3: Weight of particles collected per sampling date [µg/cm^2]

Although experiments were conducted on all the samples taken on each sampling date, multiple results had to be discarded. During the preparation of the filters for the samples taken on 2 October, some of the filters were dried in aluminium trays instead of in Petri dishes. This likely caused inconsistent drying of the filters and resulted in negative weights of PM being recorded, even though particles were visible on the filters. As only one set of leaves was sampled on each date this means that there is no data for *H. helix*, *T. jasminoides*, *R. confertum*, or the plastic ivy on October 2^{nd}. Furthermore, during the ultrasonic cleaning of the *W. sinensis* leaf samples taken on 5 October, some of the leaves were broken down by the vibrations. It is unknown if this plant matter was removed by the sieve or if it is included in the weight of PM that was measured on the filters. Due to these challenges, and taking into account the length of time that the plants had been placed outside, the most representative data from the gravimetric results is the data from the 5^{th} of October.

As the dataset generated by this experimental method is too small, with only one data point per plant species per sampling date, no statistical analysis could be conducted on these results.

Considering the data from 5 October, *R. confertum* captured the most PM, followed in decreasing order by *P. quinquefolia* and *W. sinensis*, *T. jasminoides*, and finally *H. helix* and the plastic ivy. An important reason for the large difference between the amount of PM per unit leaf area captured by *R. confertum* and the other plants is the different way in which the total leaf area of the sample was determined. Where for the climbing plants the weight of PM captured was determined per unit area of leaf surface, for *R. confertum* it was determined per unit area of ground covered. Correcting the results for this would result in mosses collecting much less PM per unit leaf area than climbing plants do. Comparing the data across all the sampling dates shows that, with the exception of *H. helix*, all the plants that were sampled on multiple days collected an increasing amount of PM over time.

4.2.2. ESEM method

Figure 4.4 shows the amount of PM that the different plants captured as number of particles captured per mm^2 of leaf surface area. Per sampling date, particles were counted at two locations on each leaf, with two leaves being sampled per plant. One of these leaves was sampled from the top of the plant, and the other from along the edge of the pot that the plant was growing in. The full numerical results can be found in Appendix A.

Per sampling date, statistical analysis was done to compare the amounts of each PM size fraction captured by the different plant species. A significance level of p = 0.05 was used. The Kruskal-Wallis test found no statistically significant different groups in any of PM size fractions for the five species sampled on the 19^{th} of June; PM_{coarse} (H = 8.204, p = 0.084), PM_{10} (H = 7.964, p = 0.093), $PM_{2.5}$ (H = 7.418, p = 0.115).

In the samples taken on July 7^{th} there were no significant differences found between the species for PM_{10} (H = 4.247, p = 0.236) or $PM_{2.5}$ (H = 2.934, p = 0.402), however there was for PM_{coarse} (H = 9.398, p = 0.024). After applying the Bonferroni correction the plants could be split up into two groups, with group A having captured more PM_{coarse} particles; A = HH, TJ, PQ, B = TJ, PQ, WS.

The samples taken on 2 October showed no statistically significant difference between how much PM_{coarse} (H = 2.913, p = 0.713) and $PM_{2.5}$ (H = 7.080, p = 0.215) the different plant species captured. There was a significant difference in the amount of PM_{10} (H = 15.120, p = 0.010) that was captured by the different plant species. From this result, the species could be split up into the following groups, again with group A capturing larger amounts of particles: A = HH, PI, TJ, WS, PQ, B = TJ, WS, PQ, RC.

The samples taken on October 5^{th} showed no statistically significant differences for PM_{coarse} (H = 6.653, p = 0.248), or $PM_{2.5}$ (H = 8.260, p = 0.142). There was a significant difference between the number of PM_{10} (H = 11.890, p = 0.036) particles that the different species captured. However, when the Bonferroni correction was applied this difference between the plants was no longer statistically significant.

Over time none of the plants seem to indicate a trend of increasing amounts of PM captured on their leaves. However, the plastic ivy shows a clear trend of collecting less PM over time. When looking specifically at the data from the last two sampling dates (2 and 5 October), *H. helix* and *T. jasminoides*

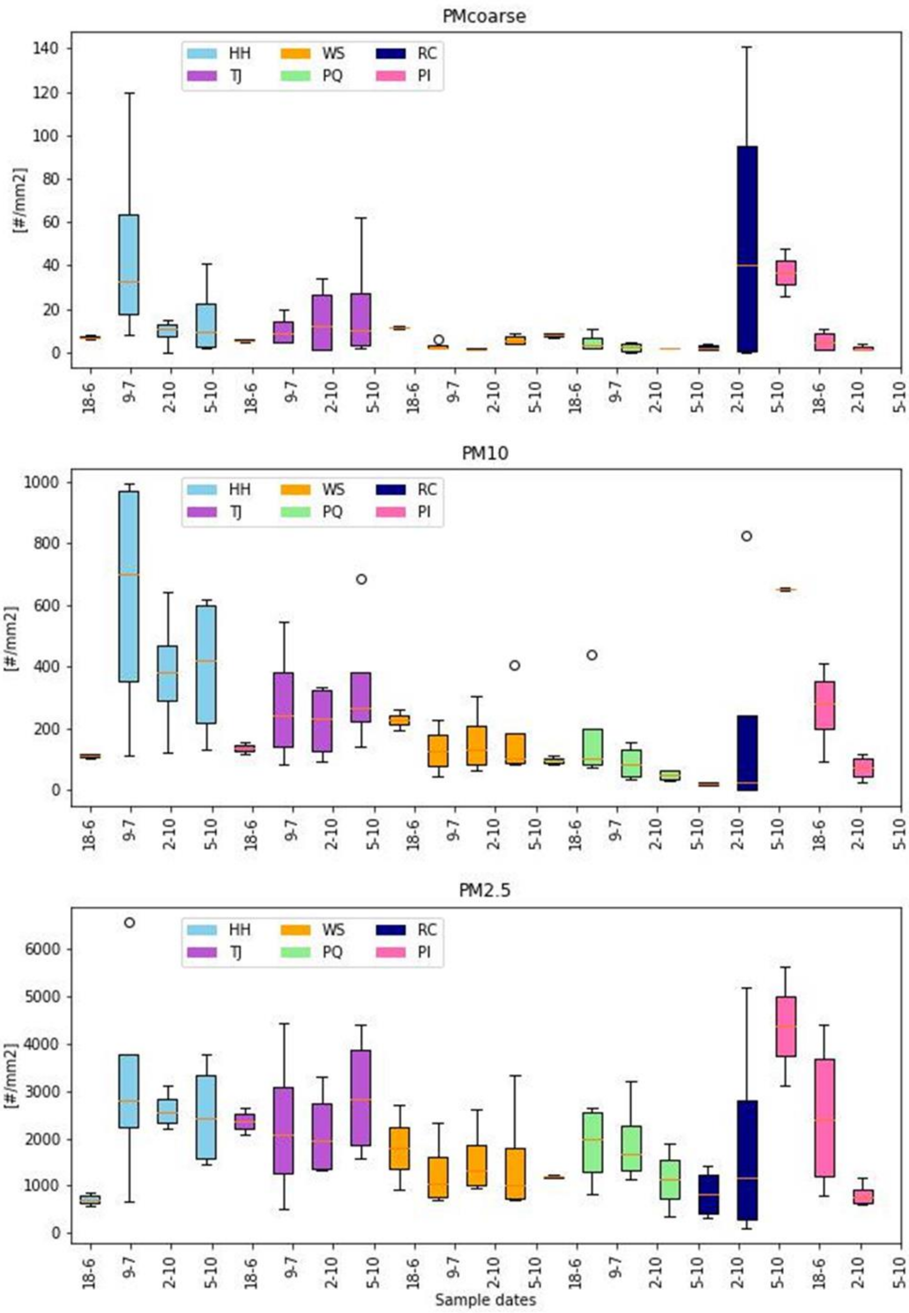


Figure 4.4: Number of particles collected per sampling date [#/mm^2]

show slight increases in the amount of PM captured across the different size fractions.

R. confertum also shows a large increase in captured PM, however, this species was only sampled twice and the standard deviation of the data on the 5th of October makes it difficult to determine whether this is a trend. It is also likely that the amount of PM captured by the moss is underreported in this method, due to how the samples were prepared for the ESEM. For the climbing plants individual leaves were placed in the microscope, whilst for the moss individual stems with multiple leaves were used. Presumably, this led to quite some particles being covered by other moss leaves in the ESEM images, stopping them from being counted.

Indoors vs outdoors

To investigate the influence of environmental conditions on PM capture, one *H. helix* plant was placed indoors in an office. The same experiments were carried out on samples from this plant to compare the results to those of the *H. helix* plant that was located outdoors at the Hortus Botanicus. The ESEM method results of these experiments are shown in Figure 4.5. A Mann-Whitney U test was used to test for any significant differences between the amounts of PM of different size fractions captured by the two plants on both sampling dates. At a significance level of p = 0.05, the only statistically significant result was that the outdoor *H. helix* plant captured more $PM_{2.5}$ than the indoor plant (U = 0, p = 0.029) on the sampling day after the rain event (2-10 and 19-10 respectively). On that same sampling day, there were no significant differences between the amount of PM_{coarse} (U = 14.5, p = 0.059) or PM_{10} (U = 2, p = 0.114) captured by the indoor and outdoor plants. On the second sampling day, following three days without precipitation, no statistically significant differences were found for any of the PM size fractions; PM_{coarse} (U = 11, p = 0.486), PM_{10} (U = 6, p = 0.686), $PM_{2.5}$ (U = 8, p = 1).

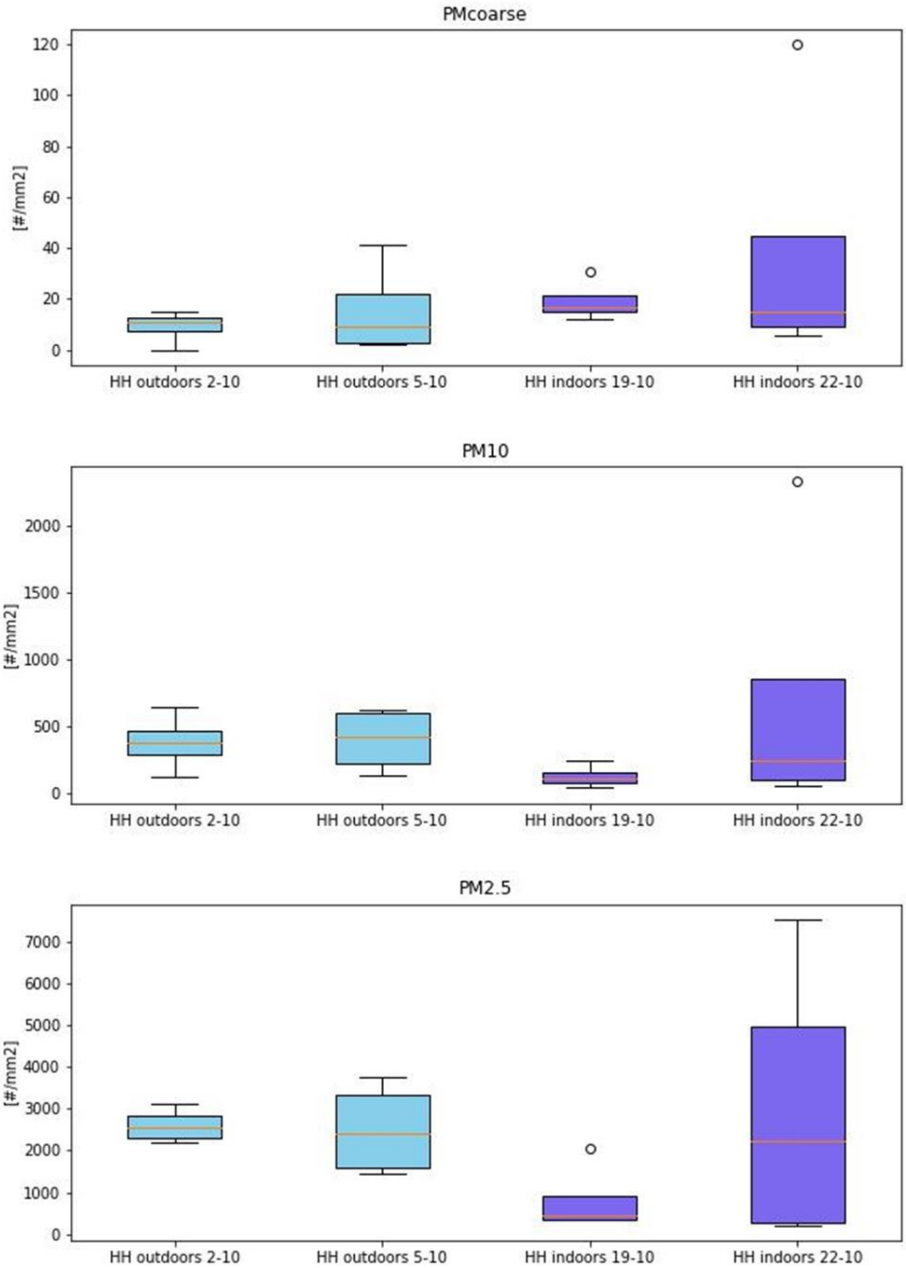


Figure 4.5: Number of particles counted on leaves of *H. helix* located outdoors at the Hortus Botanicus and indoors an office

Figure 4.5 does show for both the indoor and outdoor plants the amount of PM captured on the leaves increased between the two sampling dates. The increase in PM on the indoor plant is larger, but the error is also larger so it cannot be definitively said that this is due to the difference in environmental conditions that the plants were exposed to.

5 Discussion

This research was conducted to determine whether there are differences in the PM capturing capacities of different climbing plant species. Little data exists which directly compares different climbing plant species, so the results from this research provide more data and direct comparison in the same environmental conditions. With this information more informed decisions can be made when considering plant species for urban greening projects. The data was generated through two experimental methods; a gravimetric method and a method using an electron microscope. The study compared *Hedera helix*, *Trachelospermum jasminoides*, *Wisteria sinensis*, *Parthenocissus quinquefolia*, *Rhynchostegium confertum*, and a plastic ivy vine to see if any benefits could be linked to specific microstructures on the leaves.

5.1. How the experimental methods influenced the results

The gravimetric method and the ESEM method produce data in different units which are not interchangeable because PM does not have a set density. The density changes depending on the specific composition of the particles, which depends on the source of the particles. Although the data is not directly comparable, the two methods were expected to show similar trends concerning PM capture by the different plants compared to each other and over time. However, this is not the case. Neither dataset shows any consistent statistically significant differences when the plants are compared per sampling date, but that is where the similarity ends. The trends seen in Figures 4.3 and 4.4 are not similar. There is the inherent discrepancy that the larger particles are going to be heavier, and therefore more weight of PM_{coarse} particles will not necessarily correspond to a larger number of PM_{coarse} particles counted in the ESEM images. The data reflects this, as by absolute amount of weight all plants capture the most PM_{coarse} and the least $PM_{2.5}$, whilst by absolute number of particles counted all plants capture the largest number of $PM_{2.5}$ particles and the smallest number of PM_{coarse} particles. However, trends within PM size fractions were expected to be similar in both datasets, and they are not.

The gravimetric data seems to indicate that there is more PM collected on the leaf surfaces over time, with the plants having more weight of PM on their leaves at the last sampling date in October than they did at the first sampling date in June. This trend is not reflected in the ESEM data. There, the number of particles counted varies per sampling date but there is no trend of the number of particles increasing consistently over time.

Perini et al. (2017) also found that there was no significant change in particles accumulated over time using the same ESEM method [42]. In this data, the only situation where accumulation over time could be seen is in the PM_{coarse} data for *T. jasminoides*, but even here the increase in particles over time is much less pronounced than it is in the gravimetric data. A possible explanation for this is related to the ability of the ESEM method to count the particles trapped in the wax layer of the leaves, whilst the gravimetric method as it was carried out in this research cannot quantify these particles. Sæbø et al. (2012) found that up to 82% of PM captured by leaves can be temporarily immobilised in the surface wax layer [25]. As these particles are counted in the ESEM method the 'baseline' amount of particles is already higher, and therefore increases in the amount of particles which are not trapped in the wax layer are relatively smaller.

Ultrasonic cleaning PM removal ability

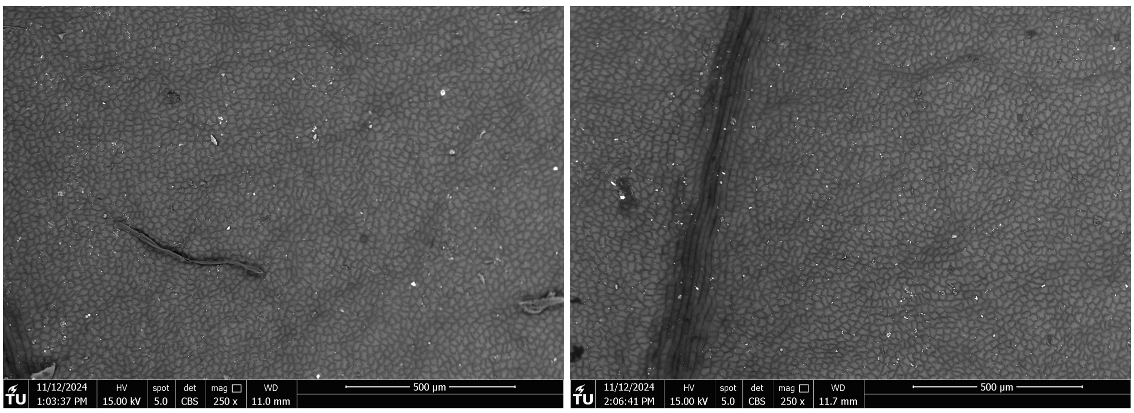
To determine how effective the ultrasonic cleaning in the gravimetric method was, an extra test was performed to check how much PM was removed from the leaf surface by the ultrasonic cleaner. One leaf each was sampled from *T. jasminoides* and *W. sinensis*, as these are the two species with respectively the highest and lowest amount of wax on the leaf surfaces, and it was expected that this was a factor in the (lack of) PM removal by the ultrasonic cleaner. The leaves were analysed at two locations in the ESEM, washed in the ultrasonic cleaner, and subsequently analysed at two locations in the ESEM again. The images were not taken at the exact same locations before and after cleaning, but they were taken in the same quadrant of the leaves as described in Section 3.5. The results are shown in Table 5.1.

Analysis of these images indicated that the ultrasonic cleaning removed around 19% of the particles from the surface of *T. jasminoides*, and around 64% of particles from *W. sinensis*. Figure 5.1 also shows that the *T. jasminoides* leaf remains much dirtier after the cleaning process than the *W. sinensis* leaf does in Figure 5.2. This discrepancy is likely due to the lack of a wax layer on the leaves of *W. sinensis*, which means that the particles can be more easily removed from the leaf surface by water. It would explain why the results from the gravimetric and ESEM experiments suggest that different plants captured the most PM, even on the same date. If the gravimetric method, as it was applied in this research using only water, does not remove all the particles that can be counted in the ESEM method, then the results cannot be directly compared.

	TJ_{before}	TJ_{after}	Δ TJ	WI_{before}	WI_{after}	Δ WI
PM_{coarse}	4.5	6.5	-2	8	3	5
PM_{10}	249	214	35	427.5	95	332.5
$PM_{2.5}$	3595.5	2716.5	879	3230	1602.5	1627.5

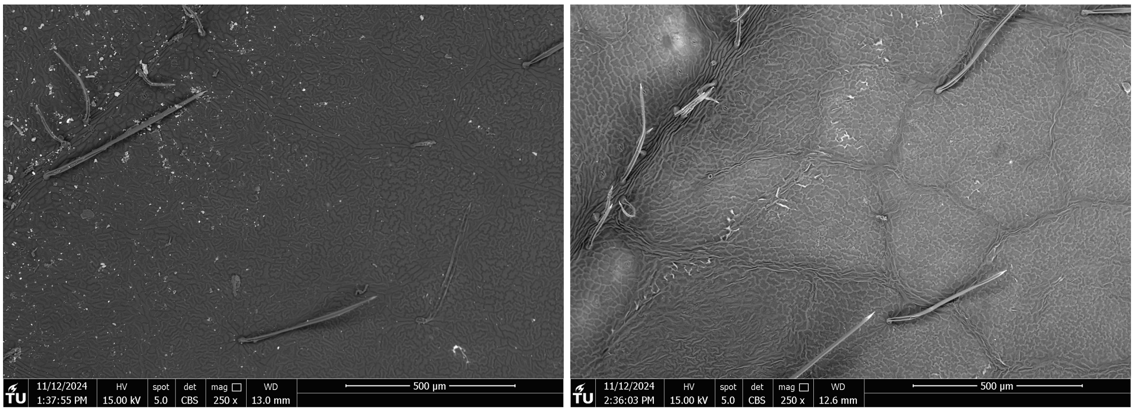
Table 5.1: Average number of PM particles counted before and after ultrasonic cleaning of *T. jasminoides* and *W. sinensis* leaves [#/mm^2]

Another valuable insight to come out of this extra experiment is that the particles are not concentrated around the villi on the blade of the *W. sinensis* leaf. In the top left corner of Figure 5.2a the density of particles is higher, and there are more villi. However, this is also where the main vein of the leaf is located. The villi which are further away from the vein, on the leaf blade, do not show any higher density of particles collected around them. This suggests that villi do not influence the amount of PM that leaves can capture.



(a) Leaf surface before cleaning **(b)** Leaf surface after cleaning

Figure 5.1: *T. jasminoides* before and after ultrasonic cleaning



(a) Leaf surface before cleaning

(b) Leaf surface after cleaning

Figure 5.2: *W. sinensis* before and after ultrasonic cleaning

Benefits and drawbacks of the experimental methods

One of the biggest challenges of using the ESEM method to quantify PM capture by plants is the thresholding of the images. Although automatic thresholding functions exist and were applied for the image analysis (see Section 3.5), they did not always correctly identify all particles and regularly had to be manually corrected. In 56 out of 245 images (23%) manual thresholding of the particles was required, and in other cases, images had to be retouched by hand to block out certain areas that were being counted as particles even though they were not. This was a recurring issue in the images taken of *W. sinensis*, where the tips of the villi were often included in the automatic thresholding, as seen in Figure 5.3, even though there were no particles on them. Similar issues were common in the analysis of *R. confertum*, where the lines of the individual cell walls were included in the thresholding before all the particles in the image were accounted for, as seen in Figure 5.4. These issues made the image analysis of the ESEM data a rather time-consuming and more subjective process, as best judgement had to be used in the manual thresholding and retouching processes. In previous research, the automatic thresholding function was used as well [37, 42], but only one paper mentions having to manually adjust the threshold [5]. This is likely related to the plant species that were tested, as the two which required manual thresholding the most often in this research (*W. sinensis* and *R. confertum*) have not been analysed in previous research.

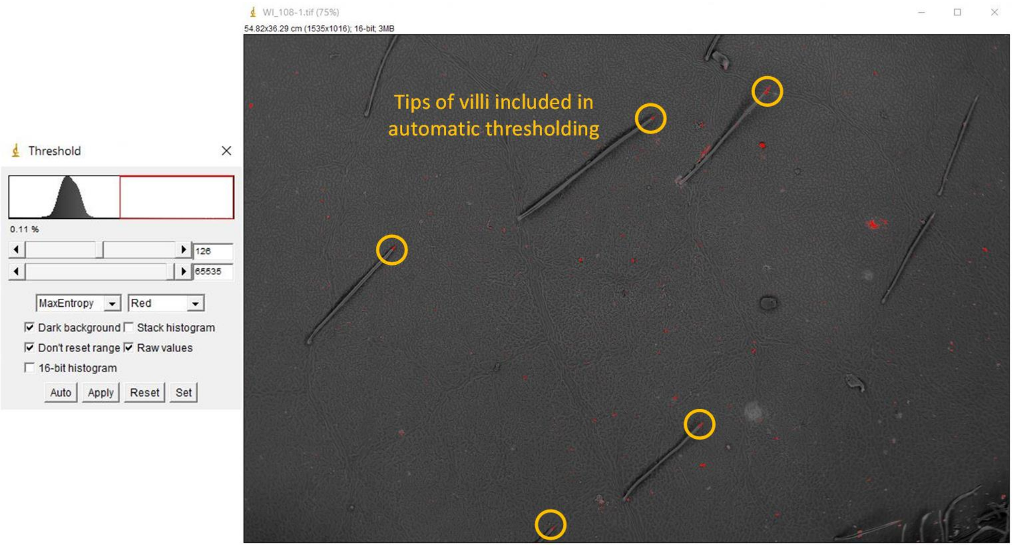


Figure 5.3: Tips of villi on *W. sinensis* being included in the automatic thresholding

The main challenge of the gravimetric method was precisely following the experimental plan. In a shared lab with limited resources, this proved more difficult than expected and led to some of the

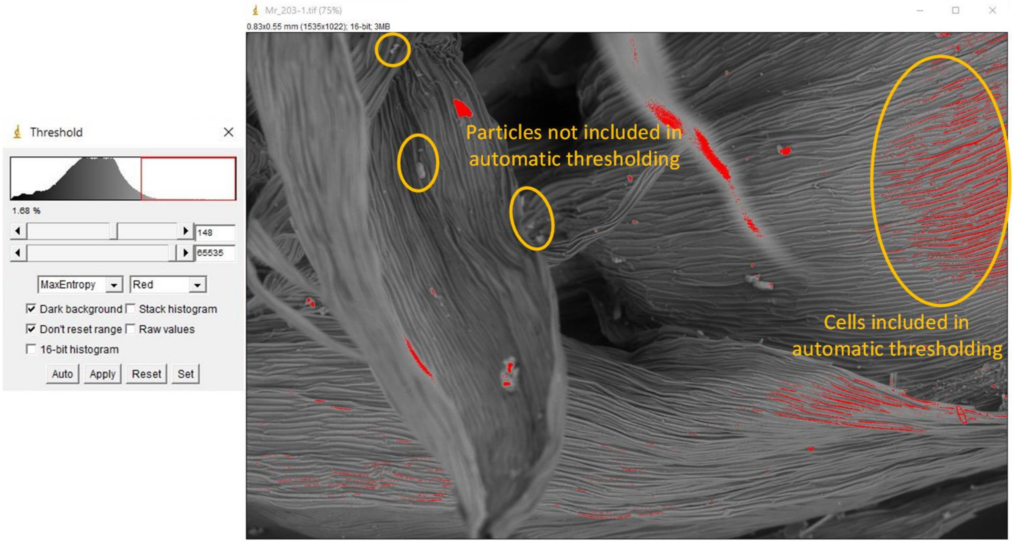


Figure 5.4: *R. confertum* cells included in thresholding before the particles

gravimetric results being discarded. The limited availability of Petri dishes meant that some of the filters were pre-dried in aluminium trays instead, with the results after the filtering showing a negative change in the weight of these filters. It is unknown if this was due to uneven and incomplete drying of the filters or an inadequate closure of the aluminium trays. Additionally, due to limited space in the oven, only two experiments could be completed per day, which meant that some of the leaves were stored for 12 days before being analysed. For *W. sinensis*, this was probably the cause of the destruction of the leaf surface in the ultrasonic cleaner as seen in Figure 5.5, which likely increased the final PM weights that were measured.

Figure 5.5: Damage to *W. sinensis* leaf stored for 10 days after ultrasonic cleaning

Overall, both methods had advantages and disadvantages, which can be more pronounced depending on the research goal of the experiment. One important advantage of the gravimetric method is that very little post-experimental data processing is required to get results. Additionally, one experiment can be considered representative of an entire plant, as multiple leaves have to be sampled to collect discernible quantities of PM by weight on the filters. This makes the gravimetric method a logical choice for research where the aim is to compare many different plant species, as extra time can be spent running experiments on more plant samples instead of on image analysis. The major benefit of the ESEM method is that the results are more detailed. Although more samples have to be analysed to be considered representative of a plant species, when determining the effects of micro- and macrostructure on PM capturing capacity the extra information that the ESEM results provide can be very useful. On the images, it is possible to see whether or not particles are more densely collected around certain microstructures, and it is possible to sample leaves from specific locations on the plants to check whether or not the macrostructure plays a role in PM capture. Where the gravimetric results can be used to make more generalised statements about the influence of certain plant characteristics, ESEM analysis can specifically determine whether such assumptions are correct.

5.2. Factors influencing PM capture of different plant species

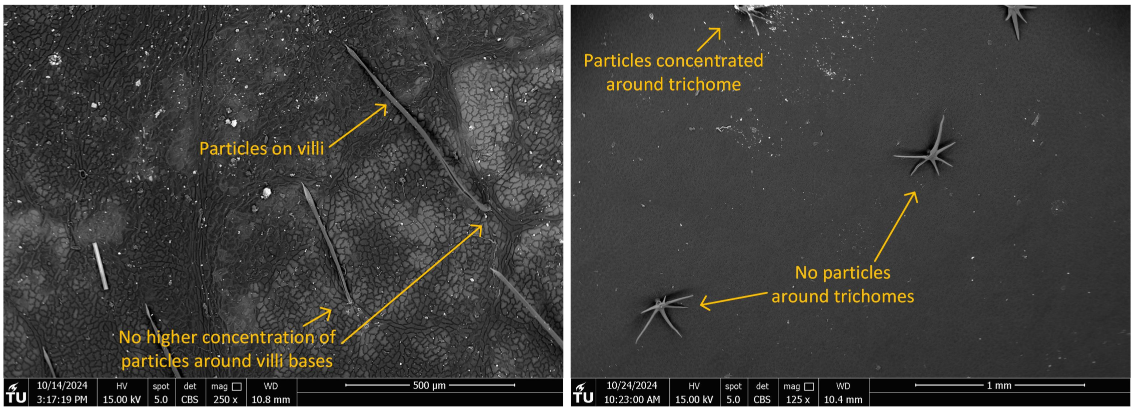
Different aspects of the microstructure of the leaf surface, the macrostructure of the plant, and environmental conditions were found to influence the amount of PM that the plants captured capture.

5.2.1. Microstructure

Some of the microstructures that were found to influence PM capture and retention in this research include the hairs on the leaf surface and the epicuticular wax layer.

Hairs

As was briefly mentioned in Section 5.1, the amount of hair-like structures like trichomes and villi did not have a significant effect on the PM captured by the climbing plants in this research. The expectation was that these structures would help accumulate particles more densely around them, which would lead to overall higher PM quantities captured, as was seen in research by Liu et al. (2018) and Shao et al. (2019) [4, 26]. Although the data does not reflect this, on some of the ESEM images trichomes and villi on *H. helix* and *W. sinensis*, respectively, are visible. Qualitative evaluation of these images shows that in some cases there seems to be a higher number of particles collected around the base of some trichomes, but not always. The villi on *W. sinensis* do not seem to collect more particles around the base, but their value seems to lie more in simply increasing the surface area of the leaf to collect particles on the villi themselves (see Figure 5.6a). This corresponds to the findings of Chávez-Garcia and González-Méndez (2021) that one of the main benefits of hair-like structures is that they increase the surface area of the leaf [7]. For *H. helix* it also does not seem to be the case that more particles are collected around all trichomes. In Figure 5.6b the trichome structure at the top has much more particles surrounding it, but the other trichomes in the image do not seem to have a higher particle density around them. The positive effects of hair-like structures on PM capture can therefore not be corroborated by this research.



(a) Villi on *W. sinensis* **(b)** Trichomes on *H. helix*

Figure 5.6: PM around villi and trichomes

Stomata

As the stomata are located on the abaxial side of the leaf, any effect they have on PM capture can only be checked using the gravimetric data collected in this research. Yan et al. (2018) found that PM accumulation increased when stomatal density was >94 stomata/mm^2 [29]. *H. helix*, *T. jasminoides*, and *W. sinensis* have stomatal densities greater than this threshold, but they did not capture more PM than the other three plants. However, it cannot be definitively concluded that the stomata do not affect PM capture, as any potential effect would only be visible in the gravimetric dataset which is very small. Unlike the effect of the trichomes and villi, the effect of the stomata on PM capture cannot be checked qualitatively either, as no ESEM images were taken on the abaxial side of the leaves where the stomata are located.

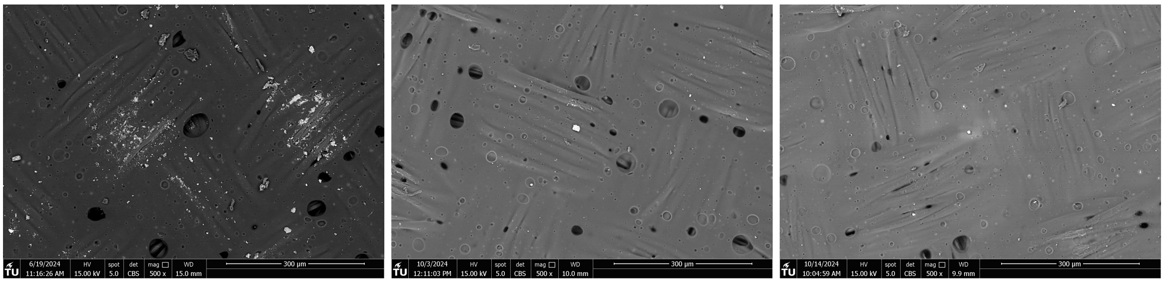
Epicuticular wax

Sæbø et al. (2012) concluded that the epicuticular wax layer can help predict PM accumulation [25], however, the results from this research are more in line with the conclusions made by Popek et al. (2013) that more epicuticular wax does not necessarily correspond to higher PM capture [24]. The two plants with the most epicuticular wax (*H. helix* and *T. jasminoides*) captured similar quantities of PM as the other four tested plant species. Notably, the gravimetric results do not include the particles that are immobilised in the wax layer, whereas the ESEM results do. This could in part explain why the trend in the gravimetric data that PM accumulation increases over time is not reflected in the ESEM data (see Section 5.1).

The additional experiment to test the effectiveness of ultrasonic cleaning indicated that around three times more PM was removed from the *W. sinensis* leaf which has almost no wax layer, compared to the amount removed from the *T. jasminoides* leaf with a visible wax layer. Although this has fewer implications for PM capture when defined as the number of particles on the leaf surface at any given time, it directly affects the ability of the leaf to retain these particles on its surface over longer periods of time in various environmental conditions. This means that when the particles in the wax layer are included, the plants with thicker wax layers will likely show more PM accumulation as more particles are retained.

Plastic degradation

Out of all the tested plants, only the plastic ivy showed a clear negative trend in PM capture over time in all size fractions. As the plants were placed outside, this may be in part due to the degradation of the plastic as a result of exposure to direct sunlight. A comparison of the ESEM images over time, as in Figure 5.7, shows that the texture of the leaves seems to flatten out. If Figure 5.7a the woven fibres of the material and circular holes in the printed plastic top layer can still be seen quite clearly under the collected particles, however in Figure 5.7c these are less defined. Whilst multiple research projects have found that rougher leaf surfaces tend to capture more PM [25, 26, 27], this result supports those conclusions by suggesting that a smoother leaf surface will capture less PM.



(a) Sampled on 18 June **(b)** Sampled on 2 October **(c)** Sampled on 5 October

Figure 5.7: Adaxial surface of plastic ivy leaves over time

5.2.2. Macrostructure

Of the tested plant species, *R. confertum* is the only one with a completely different macrostructure. The individual moss leaves are directly connected to the stems, and they are much smaller than the leaves of the climbing plants. This means that the leaves are much more densely packed, resulting in mosses generally having a much higher Leaf Area Index (LAI) than vascular plants do (6-140m^2/m^2 as opposed to 1-20m^2/m^2) [62]. Even though per unit leaf area *R. confertum* did not outperform the climbing plants, when the LAI is taken into account the moss could likely capture more PM per unit surface area than the climbing plants could. This would also be in line with previous research done on trees and shrubs which found that higher leaf density corresponds to higher PM capture [2, 34], but further research on different moss species would be needed to confirm this.

When considering the results of the gravimetric method for the samples taken on the 5th of October, *W. sinensis* and *P. quinquefolia* had the most PM by weight on their leaves. These are the two tested climbing plant species with compound leaves, making their macrostructure slightly more complex than the single leaves of *H. helix* and *T. jasminoides*. The complexity of tree crowns is known to increase the efficiency of PM capture [14, 34, 35, 36], and these results indicate that this might be true for other growth forms such as climbing plants as well.

5.2.3. Environmental factors

In the data recorded of the outdoor environmental conditions (Figures 4.1 and 4.2a) the highest PM concentration peaks correspond with the peak of rainfall in the last night before sampling took place on October 2nd. After it stopped raining the peaks in PM concentrations started to coincide with increased wind speeds and air temperatures, and decreased relative humidity. This is not entirely surprising, as these peaks indicate daily cycles. As the plants were located near a relatively busy road junction (see Section 3.1.1), where there is usually more traffic during the day than there is at night, the PM concentrations in the air are higher during the day.

PM concentration

Another aspect that is interesting to consider is whether or not the PM concentrations of different size fractions that were measured in the air can be related to the PM quantities that were found on the leaf surfaces. The data from the SDS011 PM sensor can be compared to the gravimetric results, as both of these measurements quantify PM by weight (µg). Doing this shows that, at least by weight, there was around twice as much PM_{10} as $PM_{2.5}$ both in the air and on the leaf surfaces.

Precipitation

To investigate the effect of precipitation on PM accumulation on the leaves samples were taken immediately after a week-long rain spell (October 2nd), and subsequently after three days without rain (October 5th). The expectation was that all the plants would have more PM on their leaves after the three dry days compared to right after the rain ended, but this cannot be definitively concluded from the collected results.

The ESEM results show that *H. helix*, *R. confertum*, *T. jasminoides*, and *W. sinensis* all had an increase in collected particles in at least one of the PM size fractions after the dry days, but both the plastic ivy and *P. quinquefolia* indicate a decrease in accumulated particles, and all these changes were minimal. This corresponds to findings by Ottelé et al. (2011) that rainfall does not significantly affect the amount of PM that is retained on leaf surfaces [5]. However, this research only studied *H. helix* using the ESEM method, which means that likely a large amount of the quantified PM was trapped in the wax layer and therefore would not be removed only by (rain) water.

The only entirely reliable data from the gravimetric method for both sampling dates is for *P. quinquefolia*, which did show a large increase in particles captured between the 2nd and 5th of October (see Figure 4.3). When it comes to the effect of precipitation on surface PM retention, the gravimetric method as it was applied here is more appropriate, as it quantifies the particles that are not trapped in the wax layer and can theoretically be removed by precipitation. Both Liu et al. (2018) and Przybysz et al. (2014) applied the gravimetric method and found that rainfall removed particles from the leaf surface [4, 63]. This would imply that the leaf surface should be relatively 'clean' of particles after a long period of rain and that in the three days without precipitation, there should be a sizeable increase in PM on the leaf surface. This is what the data for *P. quinquefolia* shows. However, as none of the other species have reliable gravimetric results for both days these results alone cannot be used to draw this conclusion.

Indoors vs outdoors

The PM concentrations which are presented in Figures 4.2a and 4.2b indicated that on average the PM concentration was slightly lower indoors than it was outdoors. Consequently, it was expected that the increase in PM accumulated on the indoor plant during the three dry days would be less than the increase in particles accumulated by the *H. helix* plant that was located outside. As the results in Figure 4.5 show, this was not necessarily the case. One possible explanation may be that environmental factors other than precipitation, the wind for example, resulted in the removal of particles from the leaf surfaces of the plant located outdoors. However, it must be noted that the standard deviation for the inside samples taken on October 22nd is larger than the average value because one of the sampled leaves was extremely dirty. This is likely because it was an older leaf which was already on the plant when it was growing outdoors at the plant nursery and at the garden centre before it was placed indoors for this research. The difference in PM accumulated on the indoor plant between the two sampling dates, according to the gravimetric results, is much smaller than shown in the ESEM results. Given that this method used a larger number of leaves and could not quantify the particles that might have been immobilised in the wax layer, the gravimetric results might be a more reliable measure of the amount of PM captured by the indoor plant.

5.3. Comparison of PM capturing capacity of different plant species

Although there were no statistically significant differences between the amount of PM captured by the different plant species, the results do suggest there are some differences between the PM capturing capacities of the studied plants. Over time, plants like *H. helix* and *T. jasminoides* might be able to capture more PM. The particles that get immobilised in the thicker wax layers of these plants are less likely to be affected by changing environmental conditions. In the study by Perini et al. (2017), *T. jasminoides* captured more PM than *H. helix* did based on ESEM results [42]. They reasoned that the superior ability of *T. jasminoides* to capture PM was due to the thick cuticle and wax layer [42], but *H. helix* also has a thick wax layer, and no other attributes influencing PM capture were specified to explain the difference between the amounts of particles captured by the two plant species. This corresponds to the results of this study, where the ESEM results showed that these two plant species captured very similar amounts of PM, and the characteristics of these two species were also found to be very similar.

It was not identified as a statistically significant difference, but it has to be noted that the moss species *R. confertum* had collected a lot more PM according to the gravimetric method than any of the climbing plants that were tested (see Figure 4.3). As was mentioned in Section 4.2.1 this is in large part due to the discrepancy in the area calculations. Where for the climbing plants the weight of PM captured was determined per unit area of leaf surface, for *R. confertum* it was determined per unit area of ground covered. The results from the ESEM method do not show the same difference between the number of particles captured by either *R. confertum* or the climbing plants as the gravimetric results do, although the amount of PM captured by the moss species is likely underreported by this method. Two aspects contribute to this, one is the difficulties with the thresholding as was described in Section 5.1, and the other has to do with the structure of the moss as described in Section 4.2.2. Although these factors make it difficult to compare the PM captured by *R. confertum* to that of the other plants, the findings indicate that potentially moss can capture more PM than climbing plants will when covering the same vertical surface area.

5.4. PM capturing capacity of climbing plants compared to other vegetation types

Although the amounts of PM captured in this research are generally lower than in other papers, they are still within the same order of magnitude. This suggests that the results from this research are a relatively accurate representation of the amount of PM that these plants have captured. It is also to be expected that results from different studies will not always closely match in this type of research, as the environmental conditions of the plant locations can be very influential in how much PM is available for capture, and these conditions cannot be perfectly recreated as most papers take samples from plants that are located outdoors.

As was discussed in Section 2.2, data from previous studies indicated that climbing plants capture less PM than most tree and shrub species [11, 13, 19, 34, 39, 42]. Although this research only tested climbing plants and one moss species, the results seem to confirm this as well.

The benefits of placing climbing plants in urban areas, as opposed to placing trees, are still significant. They take up comparatively small amounts of space, are easy to maintain and usually cheaper than trees. They also grow in size much quicker than trees and shrubs and do not have the associated risk of trapping pollutants at ground level. However, the results from this and previous research show that climbing plants cannot compete when it comes to the amount of PM they can capture. This comparison is also only made per unit leaf area, and the difference in PM accumulation would likely become even more pronounced if the entire plants are compared. The overall advantages of increasing urban vegetation are not limited to removing PM from the atmosphere, but where this is an important factor in decision making climbing plants cannot per definition be considered preferable to trees or shrubs. From the current data, it cannot be said that mosses would outperform other types of vegetation either, but more moss species would have to be studied to definitively ascertain this.

5.5. Limitations

What would have been beneficial for the analysis and comparison of the PM captured by the different plants was determining the Leaf Area Index (LAI). Not having this information made it impossible to directly compare the gravimetric results of the climbing plants to those of the moss in this research, and limited the ESEM comparison to PM capture per unit leaf area even though the biggest advantage of the moss is its high LAI. One of the complicating factors in the determination of the LAI of the climbing plants is that for these types of plants, this is often calculated per unit of vertical surface. However, in this experimental setup, the plants grew individually in pots supported by bamboo sticks, instead of against a vertical surface like a wall. Potentially this affected the amount of PM that the plants were able to capture, as the wind blows differently along a wall than it does in the open air. It could therefore be called into question how representative these results are for vertical green infrastructure attached to façades.

The weather, in combination with the time frame of this project, also influenced certain choices that were made. The initial plan was to have sensor data from the period when experimental data was generated as well, but there were some delays in the delivery of certain parts of the sensors which pushed back the sampling and experiment dates. Once the sensors were set up at the end of September it started raining more frequently, which made it difficult to find consecutive dry days to plan the sampling around. The original plan was to take a two-week dry period to plan the sampling around, but in the end, this was a three-day period. With a longer dry period, the difference between the PM accumulation at the start and the end might well have been more apparent. The time frame of this project also meant that there was no time to re-do the gravimetric experiments that went wrong or to analyse a larger amount of leaves in the ESEM method. If this had been possible, some trends in the data might have been stronger, resulting in more robust conclusions.

A larger dataset would also have made the statistical analysis more robust for the ESEM data, or at least possible for the gravimetric data. For some samples, there was still a large variation in the data (as can be seen in Figure 4.4), which influenced the statistical analysis. The statistical relevance of the results is influenced by the small sample set and the resulting small dataset. If the amount of PM captured by plants follows a normal distribution, it cannot be confirmed by analysing this small data set. Consequently, the non-parametric Kruskal-Wallis test had to be used to determine any potentially significant differences, even though nonparametric tests generally are less likely to identify differences than their parametric counterparts.

6
Conclusion

This research aimed to determine how much particulate matter (PM) different climbing plants can capture in an urban environment. Four species of climbing plants (*H. helix*, *T. jasminoides*, *W. sinensis*, *P. quinquefolia*) were studied, along with a moss species (*R. confertum*) and a plastic plant, to determine which of these would collect the most PM, if there were any specific characteristics which influence PM capture, and if the PM capture of climbing plants is comparable to that of other vegetation types. To quantify the PM capture of the plants two different experimental methods were tested and compared.

The main findings were as follows:

- The gravimetric method, as executed in this research, measures the amount of PM which can be mobilised by water, disregarding the PM immobilised in the leaf's wax layer. The ESEM method gives a good overview of total PM on the leaf but does not give any information on how well this PM is attached to the leaf surface.
- Villi and other hair-like structures are most useful for short-term PM capture, whereas a wax layer on the leaf surface can retain the PM for longer periods of time.
- *H. helix* and *T. jasminoides* showed trends towards higher PM capture with good PM retention, whereas *W. sinensis* and *P. quinquefolia* showed a trend towards lower overall PM capture and poor PM retention.
- Compared to trees and shrubs, climbing plants collect less PM per unit of leaf area, however the moss species *R. confertum* has the potential to be a promising alternative option for vertical greening.

The importance of surface structures in capturing PM on plant leaves is known and was corroborated by the data of the plastic plant, which lost some of the definition of its surface structures over time and also collected less PM over time. The two types of structures that were the most influential in this set of climbing plants were the epicuticular wax layer and villi on the leaves. The influence of the wax layer can be seen in the long-term capture of particles. These particles were trapped in the wax layer and did not get washed off during the gravimetric experiments, but were counted during the ESEM experiments where the *H. helix* and *T. jasminoides* showed higher PM capture than the other plant species. Meanwhile the villi on *W. sinensis* did not seem to influence the amount of PM retained by the leaves, which was very similar to the amounts found on *P. quinquefolia* which has no hair-like structures or significant wax layer on its leaf surfaces. Inspection of the ESEM images also showed no increased particle accumulation around the individual villi on the *W. sinensis* leaves, but there were particles present on the lengths of the villi themselves. This suggests that plants with thicker epicuticular wax layers would be most beneficial in areas where the climate is drier, as the captured PM can be immobilised in the wax layer. In wetter climates plants without wax layers might be favourable, as the particles accumulated on the leaf surface can be washed off onto the ground, contributing to the net removal of PM from the air.

In line with findings from other research, the results from both methods showed that climbing plants capture less PM in the number and weight of particles than trees and shrubs. This is based on quantities of PM captured per unit leaf area, but when the total leaf area per plant is taken into account this difference is amplified even more in both metrics. This does not mean that climbing plants cannot be used to increase vegetation density in urban areas. Climbing plants grow faster than most trees and shrubs, and they require less horizontal space to grow, generally making them easier to place in densely built-up areas. *R. confertum*, the moss that was studied, showed potential for capturing larger quantities of PM. However, due to some challenges in applying moss in the chosen experimental methods, the results could not be directly compared. Overall, if the main goal of placing vegetation is to capture PM from the air, climbing plants might not be the most effective option, but moss could offer a solution which combines higher PM capture with the space-related benefits of climbing plants.

6.1. Future outlook

In this research two different methods for PM quantification were applied and could be directly compared. As it was used here, the gravimetric method measured the PM on the leaf surface which can be washed off relatively easily. This makes it a useful method when researching the maximum capacity for PM accumulation on the leaf surface, as this can be somewhat regenerated when particles are removed by rain or wind. When the added step of repeating the experiment with chloroform instead of water is applied, this method can also quantify the amount of PM stored specifically in the wax layer. This version of the gravimetric experiment can be used to ascertain the respective amounts of PM which is accumulated in and on top of the wax layer and whether this distribution differs across plant species. The ESEM method counts all the particles on the leaf surface, which gives a better understanding of the total PM capture, but it does not differentiate between particles immobilised in the wax layer and those on the surface of the leaf. This makes it more applicable when directly comparing the PM capture of different plants under the assumption that all the particles are removed from the atmosphere, either by immobilisation in the wax layer or by wash-off into the soil. The preciseness with which the leaves for the ESEM experiment can be sampled also makes it more useful if the research is focused on the influence of the plant's macrostructure.

Using these, or other methods, one area that would be valuable to look into in the future is what happens to the PM particles after they settle on the leaf surface. It is known that some particles are resuspended or washed off, but little is known about the particles which remain on the leaf. It would be specifically relevant to know what happens to the particles which are trapped in the epicuticular wax layer. It is possible that they simply remain trapped until the leaf falls off the plant and they are also absorbed by the soil, or they could be broken down by microbes on the leaf. This would also be influenced by the composition of the PM that the plants collect. It would be valuable to establish if different plants or different plant characteristics capture specific types of particles more than others. If this were the case, specific plant species could be matched to known pollution sources to more effectively reduce the spread of PM.

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A

Experimental results

A.1. Gravimetric results

Table A.1 shows the full dataset for the weights of particles collected from the leaf surfaces through the gravimetric experiments.

The **Date** column shows the sampling date of the leaves that were analysed.

The **Species** column indicates which plant species was tested using the same acronyms as the graphs in the results chapter (see Chapter 4): *Hedera helix* (HH), plastic ivy (PI), *Rhynchostegium confertum* (RC), *Trachelospermum jasminoides* (TJ), *Wisteria sinensis* (WS), and *Parthenocissus quinquefolia* (PQ).

The three columns **PMcoarse**, **PM10**, and **PM2.5** show the weight of particles found on the filter surfaces in micrograms per cm^2.

Some of the plants have 'n/a' as a result. These are the experiments where the results had to be discarded, as was explained in Section 4.2.1.

Table A.1: Gravimetric results [µg/cm^2]

Date	Species	PMcoarse	PM10	PM2.5
9-7-2024	HH	5.96	36.018	0.777
2-10-2024	HH	n/a	n/a	n/a
5-10-2024	HH	10.488	2.622	1.165
9-7-2024	TJ	44.909	14.581	5.832
2-10-2024	TJ	n/a	n/a	n/a
5-10-2024	TJ	65.096	20.767	11.582
9-7-2024	WS	7.53	3.601	2.292
2-10-2024	WS	32.767	13.273	6.636
5-10-2024	WS	80.033	32.784	19.285
9-7-2024	PQ	19.774	6.845	4.183
2-10-2024	PQ	33.324	10.098	5.806
5-10-2024	PQ	88.059	30.356	18.87
2-10-2024	RC	n/a	n/a	n/a
5-10-2024	RC	489.123	151.09	75.545
2-10-2024	PI	n/a	n/a	n/a
5-10-2024	PI	16.239	1.282	2.564

Indoor results

Table A.2 shows the gravimetric results for the *H. helix* plant that was located indoors in an office at the Faculty of CiTG at the TU Delft.

Table A.2: Gravimetric results for the *H. helix* plant located indoors [μg/cm^2]

Date	Species	PMcoarse	PM10	PM2.5
19-10-2024	HH indoors	10.098	2.524	0.421
22-10-2024	HH indoors	10.917	2.83	0

A.2. ESEM results

Table A.3 shows the full dataset for the particles counted on all the leaf surfaces during the ESEM experiments.

The **Date** column indicates the date on which the samples were analysed in the ESEM. Samples taken on June 18th, July 10th, and October 2nd were analysed a day later on 19-6, 10-7, and 3-10, respectively. The samples taken on October 5th were analysed 9 days later on 14-10.

The **Species** column indicates which plant species was tested using the same acronyms as the graphs in the results chapter (see Chapter 4): *Hedera helix* (HH), plastic ivy (PI), *Rhynchostegium confertum* (RC), *Trachelospermum jasminoides* (TJ), *Wisteria sinensis* (WS), and *Parthenocissus quinquefolia* (PQ).

Loc on plant refers to the location at which that specific leaf was sampled. A 't' indicates that the leaf was sampled from the top of the plant. An 'r' indicates that it was sampled at the height of the rim or edge of the plant pot. For the moss species RC, one of the locations is 'm', these samples were taken from the middle of the moss tuft, and the 'r' samples were taken from the edge.

As some samples were taken before the revised sampling procedure was implemented, the **Leaf nr** column indicates if it was the first or second leaf analysed on that date.

The **BL vs TR** column indicates at which location on the leaf the ESEM images were taken. 'BL' stands for 'bottom left', meaning that the images were taken in the quadrant close to the leaf petiole on the left side of the main vein. Conversely, 'TR' stands for 'top right', and indicates that the images were taken in the quadrant near the tip of the leaf, to the right of the main vein. A visual of this is shown in Figure 3.13.

The three columns **PMcoarse**, **PM10**, and **PM2.5** show the number of particles counted in number of particles per mm^2.

Table A.3: ESEM results [#/mm^2]

Date	Species	Loc on plant	Leaf nr	BL vs TR	PMcoarse	PM10	PM2.5
19-6-2024	HH		1	BL	6	103	558
19-6-2024	HH		1	TR	8	120	854
10-7-2024	HH		1	BL	120	993	6583
10-7-2024	HH		1	TR	45	965	2769
10-7-2024	HH		2	BL	8	115	658
10-7-2024	HH		2	TR	21	434	2839
3-10-2024	HH	r	1	BL	10	415	2745
3-10-2024	HH	r	1	TR	12	641	3130
3-10-2024	HH	t	2	BL	0	122	2197
3-10-2024	HH	t	2	TR	15	349	2359
14-10-2024	HH	r	1	BL	3	251	1632

Date	Species	Loc on plant	Leaf nr	BL vs TR	PMcoarse	PM10	PM2.5
14-10-2024	HH	r	1	TR	41	592	3205
14-10-2024	HH	t	2	BL	2	130	1452
14-10-2024	HH	t	2	TR	16	618	3777
19-6-2024	PI		1	BL	48	656	3117
19-6-2024	PI		1	TR	26	650	5634
3-10-2024	PI	r	1	BL	1	232	4399
3-10-2024	PI	r	1	TR	1	96	802
3-10-2024	PI	t	2	BL	11	335	1317
3-10-2024	PI	t	2	TR	8	414	3455
14-10-2024	PI	r	1	BL	4	120	850
14-10-2024	PI	r	1	TR	1	97	1163
14-10-2024	PI	t	2	BL	1	27	655
14-10-2024	PI	t	2	TR	2	54	591
3-10-2024	RC	m	1		3	16	321
3-10-2024	RC	m	1		1	20	1406
3-10-2024	RC	r	2		4	28	1174
3-10-2024	RC	r	2		1	24	442
14-10-2024	RC	r	1		1	2	355
14-10-2024	RC	r	1		0	1	107
14-10-2024	RC	m	2		141	52	1989
14-10-2024	RC	m	2		80	824	5204
19-6-2024	TJ		1	BL	6	117	2069
19-6-2024	TJ		1	TR	5	155	2650
10-7-2024	TJ		1	BL	12	545	4432
10-7-2024	TJ		1	TR	5	159	2637
10-7-2024	TJ		2	BL	5	85	501
10-7-2024	TJ		2	TR	20	326	1494
3-10-2024	TJ	r	1	BL	34	325	1376
3-10-2024	TJ	r	1	TR	24	334	3312
3-10-2024	TJ	t	2	BL	1	93	1323
3-10-2024	TJ	t	2	TR	1	142	2541
14-10-2024	TJ	r	1	BL	16	284	1568
14-10-2024	TJ	r	1	TR	62	686	3706
14-10-2024	TJ	t	2	BL	4	249	4405
14-10-2024	TJ	t	2	TR	2	141	1963
19-6-2024	WS		1	BL	11	197	905
19-6-2024	WS		1	TR	12	261	2698
10-7-2024	WS		1	BL	2	230	1350
10-7-2024	WS		1	TR	2	165	2329
10-7-2024	WS		2	BL	2	87	762
10-7-2024	WS		2	TR	6	47	698
3-10-2024	WS	r	1	BL	1	63	1036

Date	Species	Loc on plant	Leaf nr	BL vs TR	PMcoarse	PM10	PM2.5
3-10-2024	WS	r	1	TR	1	90	940
3-10-2024	WS	t	2	BL	2	307	2600
3-10-2024	WS	t	2	TR	2	177	1632
14-10-2024	WS	r	1	BL	4	94	721
14-10-2024	WS	r	1	TR	4	82	710
14-10-2024	WS	t	2	BL	7	112	1279
14-10-2024	WS	t	2	TR	9	405	3349
19-6-2024	PQ		1	BL	9	82	1157
19-6-2024	PQ		1	TR	7	111	1231
10-7-2024	PQ		1	BL	11	440	2639
10-7-2024	PQ		1	TR	2	85	830
10-7-2024	PQ		2	BL	5	122	1466
10-7-2024	PQ		2	TR	2	75	2501
3-10-2024	PQ	r	1	BL	4	158	3205
3-10-2024	PQ	r	1	TR	5	125	1963
3-10-2024	PQ	t	2	BL	0	35	1391
3-10-2024	PQ	t	2	TR	1	46	1122
14-10-2024	PQ	r	1	BL	2	31	359
14-10-2024	PQ	r	1	TR	2	66	843
14-10-2024	PQ	t	2	BL	2	62	1413
14-10-2024	PQ	t	2	TR	2	36	1890

Indoor results

Table A.4 shows the ESEM results for the *H. helix* plant that was located indoors in an office at the TU Delft. This plant was labelled 'bHH' to distinguish it from the plant which was located outdoors.

Table A.4: ESEM results for the *H. helix* plant located indoors [#/mm^2]

Date	Species	Loc on plant	Leaf nr	BL vs TR	PM10	PM2.5	PM0.1
19-10-2024	bHH	r	1	BL	16	131	337
19-10-2024	bHH	r	1	TR	18	91	359
19-10-2024	bHH	t	2	BL	12	43	541
19-10-2024	bHH	t	2	TR	31	245	2042
22-10-2024	bHH	r	1	BL	120	2325	7540
22-10-2024	bHH	r	1	TR	10	364	4118
22-10-2024	bHH	t	2	BL	6	53	311
22-10-2024	bHH	t	2	TR	20	119	212

Ultrasonic cleaning effectiveness

Table A.5 shows the ESEM results for the leaves which were used to test the effectiveness of the ultrasonic cleaner.

In the **Species** column the first two letters represent the plant species (*Trachelospermum jasminoides* (TJ) and *Wisteria sinensis* (WS)), and the following letters indicate whether the results are from before ('b'), or after ('a'), the leaf was cleaned in the ultrasonic cleaner.

Table A.5: ESEM results for the experiment testing the effectiveness of the ultrasonic cleaner [#/mm^2]

Date	Species	BL vs TR	PMcoarse	PM10	PM2.5
12-11-2024	TJb	BL	3	261	4129
12-11-2024	TJb	TR	6	237	3062
12-11-2024	TJa	BL	8	163	3067
12-11-2024	TJa	TR	5	265	2366
12-11-2024	WSb	BL	4	369	3087
12-11-2024	WSb	TR	12	486	3373
12-11-2024	WSa	BL	5	157	2250
12-11-2024	WSa	TR	1	33	955