Role of roadside vegetation as a passive method for urban air particulate matter absorption and its capturing efficiency under different conditions

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Zusammenfassung

Die Umwelt schädigender Feinstaub (*Particulate Matter*, kurz als PM bezeichnet) ist eine Bedrohung für die menschliche Gesundheit und verkürzt die Lebensdauer, weil sowohl respiratorische und neurodegenerative Erkrankungen auf die PM-Verschmutzung zurückgeführt werden als auch die DNA vieler Stadtbewohner durch $PM_{2.5}$ und ultrafeinen Staub geschädigt wird. Mit der Beschleunigung des Urbanisierungsprozesses wurde der vom Straßenverkehr freigesetzte Feinstaub zu einer der wichtigsten Komponenten von PM aus anthropogenen Aktivitäten im Stadtgebiet. Es ist notwendig, eine effiziente Methode zu finden, um die Verschmutzung der Städte durch PM einzudämmen.

Es ist längst bekannt, dass grüne Pflanzen eine wirkungsvolle Phytoremediation zur städtischen Feinstaub-Reduzierung leisten, aber die Forschungen konzentrierten sich auf den PM-Abschwächungsmechanismus von großen Flächen wie Stadtwäldern, städtischen Grünanlagen und Feuchtgebieten. Die Wirksamkeit von kleinen Pflanzenbeständen am Straßenrand, die der Feinstaub-Belastung unmittelbar ausgesetzt sind, wurde jedoch weniger beachtet. In dieser Studie wurden zwölf besonders effiziente Pflanzenarten mit einem besonders hohen PM-Wirkungsgrad ausgewählt und verglichen, die in Hannover, Deutschland, am Straßenrand wachsen. Zugleich ging es darum, die Charakteristika dieser hocheffizienten Pflanzenarten herauszustellen und die inneren und äußeren Ursachen für die unterschiedlichen Wirksamkeiten verschiedener Pflanzenarten zu charakterisieren. Es sollte herausgefunden werden, welche Pflanzenarten am Straßenrand optimale Nutzungsmuster unter ähnlichen urbanen Bedingungen haben.

Aus den Experimenten ergab sich, dass *Taxus baccata, Pinus nigra, Berberis thunbergii* und *Hedera helix* besonders effizient wirken, allesamt immergrüne Pflanzen, überwiegend mit nadelförmigen Blättern. Pflanzenarten mit kleinen Blättern sind effizienter als Arten mit großen Blättern. Pflanzenarten mit rauer Blattoberfläche, tiefen Furchen, Trichomen und Stomata halten am Straßenrand besonders wirkungsvoll PM fest. Auch Wachs auf den Blattoberflächen und Hydrophilie sind wirkungsvoll. Optimal hinsichtlich sowohl PM_{10}- als auch $PM_{2.5}$-Absorptionsfähigkeit unter hohem Verkehrsdruck sind Pflanzen mit nadelförmigen Blättern. Blätter im Höhenbereich von ein bis zwei Metern halten die meisten großen Partikel und Feinstaub in verschiedenen Höhenbereichen fest. Ein komplexes Pflanzmuster aus nadelförmigen und breitblättrigen Pflanzenarten oder eine vertikale grüne Wand ist der optimale Bewuchs am Straßenrand. Diese Form der Vegetation am Straßenrand wäre ein besonders umweltfreundliches Phytosanierungssystem zur Reduzierung von städtischem Feinstaub und kann eine Grundlage für das zukünftige Management einer umweltfreundlichen Straßeninfrastruktur und Stadtplanung sein.

Schlüsselwörter: Feinstaub; Straßenrandvegetation; Blattmerkmale; Grüne Wand; Verkehrsdruck

Abstract

It has been widely discussed that air particulate matter (PM) has become a serious environmental issue which put great threats to human health and life-span. The respiratory and neurodegenerative disease are considered highly related to PM pollution. Most European urban residents are considered under the threat from $PM_{2.5}$, and ultra-fine PM has even been reported to harm human DNA. With the acceleration of urbanization, traffic-related PM is becoming a large portion of anthropogenic PM in the urban area, finding an efficient way to mitigate the urban PM pollution is thus quite imperative.

Green vegetation has been accepted as efficient phytoremediation for urban PM reduction by former researches, but most studies focused on the PM capturing mechanism by vegetation which has large planting area, like city forest, urban green land, and city wetland. The efficiency of roadside vegetation which faces directly to the source of urban PM pollution was, however, rarely reported. This study tries to select the most efficient roadside plants by comparing the PM capturing efficiency of 12 common urban plant species with different leaf traits and leaf surface characteristics in Hanover, Germany; to summarize the similarity of highly efficient plant species; to explore the internal and external factors which lead to the efficiency disparities; and attempts to propose optimal using patterns with efficient roadside plants under different urban conditions.

Among all tested plants, *Taxus baccata*, *Pinus nigra*, *Berberis thunbergii* and *Hedera helix* were found to be the most efficient species; evergreen plants which had needle-shaped leaves were generally more efficient than deciduous species with broad leaves; species with small leaf area tended to possess higher efficiency than species with large leaves. Plant species with rough leaf surface which is resulted from a large amount of existing deep grooves, trichomes and stomata were found quite effective for PM capture. In addition, leaf wax and leaf hydrophilicity were also motivators for high capturing efficiency. In the view of finding optimal using patterns, needle-leaved plants were found efficient for both PM_{10} and $PM_{2.5}$ capture under the high traffic pressure, while broad-leaved species was optimal for $PM_{2.5}$ capture under the light traffic pressure; leaf surface with a height range of 1-2 m was the most effective area for large PM absorption and leaf wax was effective for fine PM reduction at all height ranges. In brief, complex planting pattern which combines both efficient needle-leaved and broad-leaved roadside vegetation, or a vertical green wall which is covered by efficient roadside plant species are recommended by us as optimal using patterns.

This study especially highlights the role of roadside vegetation as eco-friendly phytoremediation for urban PM pollution absorption and is supposed as a theoretical basis for future roadside green infrastructure management and city planning.

Keywords: Urban particulate matters; Roadside plants; Leaf traits; Green wall; Traffic pressure

Abbreviations

A. platanoides	*Acer platanoides*
A. truncatum	*Acer truncatum*
AH	Average plant height
B. thunbergii	*Berberis thunbergii*
B. pendula	*Betula pendula*
B. megistophylla	*Buxus megistophylla*
C. betulus	*Carpinus betulus*
CA	Contact angle
CD	Canopy density
DCA	Drop contact angle system
Dec.	Deciduous
Dibenzo-*p*-dioxins	Dibenzodioxin (molecular formula: $C_{12}H_8O_2$)
EWPA	Elution-weighing-particle size-analysis
EDX	Energy dispersive X-ray spectroscopy
EEA	European Environment Agency
E. japonicus	*Euonymus japonicus*
Evg.	Evergreen
F	Family
F. sylvatica	*Fagus sylvatica*
F. chinensis	*Fraxinus chinensis*
G. biloba	*Ginkgo biloba*
H	Habit
H. helix	*Hedera helix*
LAD	Leaf area density
LPSA	Laser particle size analyzer
LBL	Leaf band layer
LS	Leaf shape
MA	Mean leaf area
N. nucifera	*Nelumbo nucifera*

PM	Particulate matter
PM_{10}	Particulate matter with aerodynamic diameter lower or equal to 10 µm
$PM_{2.5}$	Particulate matter with aerodynamic diameter lower or equal to 2.5 µm
PT	Plant type
PTFE	Polytetrafluoroethylene
P. tomentosa	*Paulownia tomentosa*
P. incanus	*Philadelphus incanus*
P. bungeana	*Pinus bungeana*
P. nigra	*Pinus nigra*
P. tabuliformis	*Pinus tabuliformis*
P. sylvestris	*Pinus sylvestris*
P. occidentalis	*Platanus occidentalis*
P. cerasifera	*Prunus cerasifera*
P. laurocerasus	*Prunus laurocerasus*
Q. ilex	*Quercus ilex*
Q. robur	*Quercus robur*
S	Shrub
S. album	*Sedum album*
S. babylonica	*Salix babylonica*
SEM	Scanning Electron Microscope
SIRM	Saturation isolation remanent magnetization
S. matsudana	*Salix matsudana*
SN	Scientific name
S. vulgaris	*Syringa vulgaris*
T	Tree
T. baccata	*Taxus baccata*
T. cordata	*Tilia cordata*
TSP	Total suspended particle
UFORE model	Urban forest effects model
WHO	World Health Organization

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Chapter 1 General Introduction

1.1 Introduction of particulate matter (PM)

With the sharp increase of the economy and the rapid development of human society, environmental problems are becoming an ever more serious issue in modern society, placing great threats against all human beings, both naturally and socially (Corvalan *et al.* (1999), Kennish 2002, Myers and Patz 2009, Vorosmarty *et al.* 2010, Sheffield and Landrigan 2011, Weber *et al.* 2014). In particular, air pollution is one of the most serious environmental issues, causing extensive concern over the last two decades (Matyssek *et al.* 2015, Kolle and Thyavanahalli 2016). It has been estimated that millions of tonnes of toxic pollutants are released into the atmosphere every year (Rai 2013), especially in developing countries (Wang *et al.* 2008, Gupta *et al.* 2016). As air pollution poses serious problems in more and more countries, it has been widely accepted that finding ways to reduce it should be a key issue among all human activities (Bickerstaff and Walker 2001, Chen and Kan 2008).

Air pollution in urban areas has attracted much attention and has led to significant research in recent years (Grosjean *et al.* 1990, Brauer *et al.* 2008, Han *et al.* 2014). Although urban air pollution is caused by a variety of factors, the pollution caused by particulate matters (PM), especially by PM_{10} and $PM_{2.5}$ have been proven to be notably negative for public health (Davidson *et al.* 2005). The composition of PM includes several different kinds of toxic ingredients which have been proven to cause damage to human cardiovascular and respiratory systems (Schwarze *et al.* 2006), reducing the amount of PM in the air is therefore a key topic for a healthy human society and deserves further studies in the future.

1.1.1 Definition of dust and particulate matter

Dust is a type of solid matter consisting of soil, anthropogenic components of metals and natural biogenic materials (Ferreira-Baptista and De Miguel 2005). Particulate matter refers to a mixture of solid particles or liquid droplets suspended in the atmosphere of the Earth. Particulate matter (PM) in the atmosphere normally has many existing forms, including visible dust, sand,

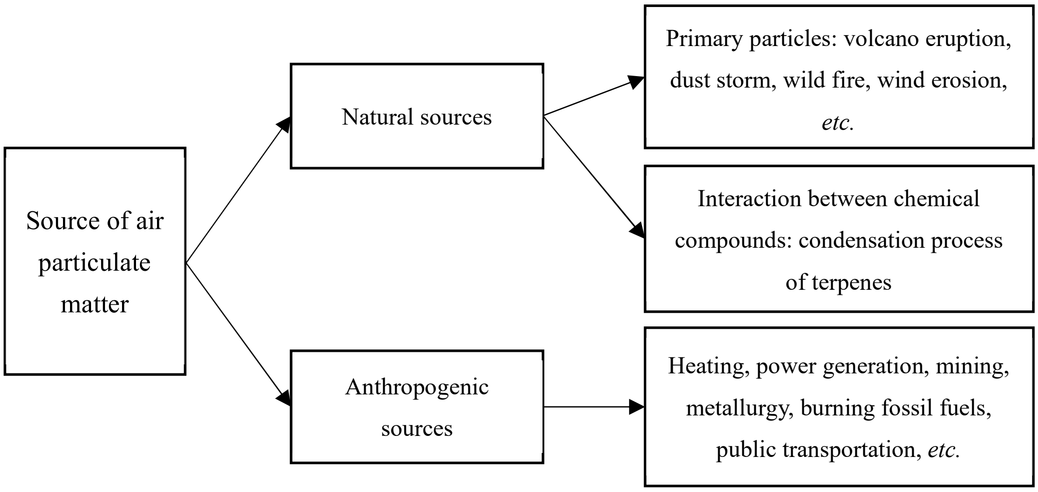


Fig. 1.1 Main source of air particulate matter

and aerosols. These types of PM have many harmful effects on human health, as was shown in London smog.

The pollution level caused by PM is usually assessed by measuring the density of PM with different aerodynamic diameters. Typically, particulate matter with an aerodynamic diameter higher than 10 μm is defined as "Large PM"; particulate matter with an aerodynamic diameter between 10 and 2.5 μm is classified as "Coarse PM"; and particulate matter with an aerodynamic diameter less than 2.5 μm is defined as "Fine PM"; and "Ultrafine PM" is defined as PM with an aerodynamic diameter lower than 0.1 μm. PM_{10} includes particulate matters where the aerodynamic diameter is lower or equal to 10 μm, and $PM_{2.5}$ includes particulate matters where the aerodynamic diameter is lower or equal to 2.5 μm (Zhu *et al.* 2006). All PM with a small aerodynamic diameter has significant negative effects on human health because of their inhalable characters

1.1.2 Sources of particulate matter and its removal process

The particulate matter (PM) in the air is generated from a variety of sources, including both natural and anthropogenic (Fig. 1.1). Natural sources of PM include natural processes such as volcano eruptions, dust storms, wind erosion and wildfires (Zhang *et al.* 2015b). These particles are emitted directly and are the primary particulate matters. In contrast, other PM formed by the interaction between chemical compounds, such as the condensation process of terpenes, are defined as secondary particulate matters (Beckett *et al.* 1998). Anthropogenic sources are those like industrial emissions, mining, heating, public transportation and other human activities (Seinfeld 1975, Suzuki 2006, Matsuda *et al.* 2010, Sawidis *et al.* 2011). The PMs from industrial emissions is those discharged from power generation, mining, metallurgy and chemical industries, these types of sources heavily rely on the burning of fossil fuels as their power source. The burning processes involved in these types of produces a substantial amount of PM in the outskirts of the cities (Bealey *et al.* 2007), however, road traffic is considered to be the main PM source within the inner city. Although natural street dust can also contribute to (large) particles in the air, it poses little risk to the public health (Steinnes *et al.* 2000) because these particles are not as deleterious as the fine particles discharged by city public traffic systems (Veijalainen 1998).

Caborn (1965) described five main sources of particulate matters: 1) transformation of vapor to aerosol by condensation; 2) those generate from the smoke; 3) newly generated particulate matters from the natural chemical reactions between original particles in the atmosphere; 4) the formation of particles by the mechanical disruption and the salt crystals above oceans; 5) the formation of large particles which are combined with small ones by the process of coagulation.

Corresponding to the formation of PM, its removal process is driven mainly by two kinds of deposition: dry deposition and wet deposition. Dry deposition is mainly caused by impaction, interception, turbulence, gravitational sedimentation and thermophoresis. Impaction is when small particles interfacing a big obstacle are not able to follow the streamlines of the flow due to its inertia, it will impact the droplet; Interception is the process where small particles are too close to an obstacle and they may collide and drop from the air stream; Some particulate matter agglomerates themselves into a larger particle and then falls onto the ground due to gravity, this process is known as sedimentation. In some meteorological situations, the turbulence caused by wind also leads to the deposition of PM; this occurs in processes like diffusion. As some particles with a small diameter such as $PM_{2.5}$ could hardly be deposited by their own gravity, turbulence is typically the main factor in the dry deposition process. With stronger turbulence, the small-sized PM is reported to be more easily deposited from the air. Wet deposition consists of two main parts: below-cloud scavenging, and in-cloud scavenging. PM such as nitrate and sulfurous particles can absorb moisture in the air and pass into cloud droplets, which are then brought to the ground surface with raindrops and snow. This process is known as in-cloud scavenging. Below-cloud scavenging occurs when raindrops collide with PM through Brownian diffusion, impaction and turbulent diffusion. The two main procedures can be summarized into seven detailed processes to remove PM from the atmosphere (Pye 1987).

1.1.3 Harmful effects caused by particulate matters

Negative effects of particulate matter (PM) on the urban atmosphere and the residing population can be summarized into two main aspects. Firstly, it causes the reduction of the urban visibility and secondly, it poses serious threats to residents` health condition.

1.1.3.1 Reduction of visibility in the urban area

Particulate matter can severely decrease the visibility in the urban areas by two ways. Firstly, it reduces the visibility by absorbing and by scattering the light. Previous studies have shown that light scattering plays a dominant role in light absorption (Boubel *et al.* 1994). The degree to which the visibility is reduced depends largely on the diameter and the refractive index of the PM. Normally, PM with a diameter between 0.1-1.0 μm, have the greatest effects on visibility, as PM within this diameter range has a similar wavelength to that of visible light. In cities with heavy air pollution, sulfur dioxide and nitric dioxide in the air produce sulfate and nitrate particles. These PM become the nuclei which scatter the light when they meet the appropriate humidity (approximately 67%). This kind of nuclei can also cause haze in cities (Boubel *et al.* 1994). By reducing the emission of SO_2, visibility in Los Angeles has been reportedly been partly improved (Farber *et al.* 1994), while the UK`s haze reduction experiment from 1956 to 1968 came to the conclusion that photo-chemical PM has a notable influence on decreasing visibility in urban areas (Brimblecombe and Bowler 1992).

1.1.3.2 Threats to residents` health

It has been extensively reported that PM has caused great damage to human health in recent years. There is a great amount of evidence supporting a direct causal relationship between human health and the density of PM (Pope and Dockery 2006). Many specific diseases such as asthma, chronic obstructive pulmonary disease, pulmonary fibrosis, cancer, type 2 diabetes, neurodegenerative disease, major depressive disorder, and even obesity have been linked with $PM_{2.5}$ (Brauer *et al.* 2008, Chen *et al.* 2016, Kim *et al.* 2016).

The pathogenicity of PM lays on its inhalable property and its toxic components. Most PM consists of mineral, inorganic and organic compounds, water aerosol, carbon and trace elements. Some of these components will cause serious damages to health (Grigoratos *et al.* 2014). Normally, most illnesses caused by PM are related to the cardiovascular and respiratory systems (Sturm 2010), because the small size of PM allows it penetrate and deposit in the human`s respiratory tract. As previously discussed, PM is classified into coarse particle and fine particle by different aerodynamic diameters. Additionally, fine particles are further divided into two groups: accumulation mode with an aerodynamic diameter lower than 2.5 μm ($PM_{2.5}$) and ultrafine PM with a diameter less than 0.1 μm ($PM_{0.1}$) (Giere and Querol 2010, Guarnieri and Balmes 2014). Because of its small size, $PM_{2.5}$ can penetrate much deeper into the alveoli of lungs than PM_{10}, while the relatively larger surface area provided by the small sized PM allows it to carry more pathogenic microorganisms and aromatic hydrocarbons on its surface (Duan *et al.* 2015). Small-sized PM thus has more deleterious health impacts compared to larger particles (Maher 1991, Cohen *et al.* 2005, Oberdoerster *et al.* 2005, Saragnese *et al.* 2011). Studies have even found that genetic damage can be caused to human DNA by PM (Knaapen *et al.* 2004, Moller *et al.* 2008, Coronas *et al.* 2009). An increasing amount of evidence indicates that ultrafine PM is even more toxic than $PM_{2.5}$ and $PM_{10,}$ and it could cause serious diseases such as hypertensive crisis (Franck *et al.* 2011, Khatri *et al.* 2012, Tang *et al.* 2012, Kurhanewicz *et al.* 2014).

1.2 Process of studies in reducing urban particulate matter

1.2.1 Background

As particulate matter (PM) poses great risks to residents` health and has caused serious damages to human society, effective solutions to mitigate the pollution brought by PM are urgently needed. The discussion focusing on lowering the density of PM in urban areas have taken place in three main stages. In the early 20th century, researchers like Hennebo (1955) found the positive effects of urban greenbelts in lowering the concentration of urban air pollution and provided some suggestions for urban tree planting. Kratzer (1956) discussed the function of gardens and parks in PM filtering and provided more evidence for the cleaning effects of plants. Guderian (1975) highlighted that greenbelts settled close to sources of pollution sources would demonstrate better performance as a pollution filter. Building more parks and gardens were thus recommended as a preliminary solution to purify urban air in many types of research (Hennebo 1955, Kratzer 1956, Guderian 1975, Moller *et al.* 2008). In the second stage, as more and more stringent legislation came into force (Sanderson 1961), the PM pollution come to remission. Wet cleaning of streets and a restriction on the numbers of vehicles allowed in urban areas were thought to be the most effective way to reduce PM at that time. However, these methods depend highly on manufacturing technology improvement and environmental legislation, the public later reached the consensus that instead of focusing on parks and gardens, common urban vegetation would also be a suitable substitution for the PM capture and could improve the air quality in urban areas (Litschke and Kuttler 2008). Recent studies have realized that vegetation has significance in both rural and urban ecosystems (Pott 2005), unlike previous studies which have focused mainly on the cleaning effects of parks, green land and industrial technical improvement, Researchers have recently turned their attention back to the plants themselves, and the PM capturing efficiency of roadside vegetation, particularly that located next to the biggest urban PM source: streets (Rai 2013). More and more modern studies are analyzing the role of urban roadside vegetation as an efficient and eco-friendly solution for PM capture from various angles.

1.2.2 Efficiency of plant species for urban PM absorption

As road traffic is considered to be the main source for PM pollution in urban areas, and vegetation would be adjusted to the human intervention (Burrichter and Pott 1988), settling vegetation barriers close to the source of pollution is considered the most effective way to reduce the convergence of air pollution and reduce the concentration of PM in the ambient environment (Guderian 1975).

The way in which vegetation removes air PM can be divided into two parts: the direct mode and the indirect mode (Wu *et al.* 2012). The direct mode refers to the retardation effect caused by leaves and branches which are exposed to the atmosphere. A large area covered by green vegetation reduces the wind speed and PM of a relatively large size can fall with gravity.

Additionally, when the wind passes through the branches, greater turbulence was caused and the sedimentation rate of small-sized PM like $PM_{2.5}$ is accelerated (Matsuda *et al.* 2010). Due to the promotion of airflow, small-sized PM like $PM_{2.5}$ can be inlaid or adhered to the humid leaves which leaf surface is relatively rough. In some special cases, PM can also be captured by electrostatic interaction between the particles and the leaf surface, but this absorption process is rare under natural conditions. Some ultra-fine PM has also been reported to be directly absorbed by plants through their stomata (Zhao *et al.* 2005). The indirect mode refers to that vegetation can build up an appropriate environment for PM capture. Through transpiration and decreasing temperature, vegetation can regulate the local climate and avoid conditions which would be negative to the sedimentation of particulate matters. Some chemical reactions are also restrained by the low temperature, and thus secondary pollution is also avoided (Nowak *et al.* 2006). In addition, planting vegetation can also reduce energy consumption in summer and restrain sources of pollutant (Zhao *et al.* 2005).

According to previous studies, using plants as an effective PM filter has been widely accepted. Trees are considered as an effective filter for particulate matter in the city area as they can reduce the wind speed in the street canyon and also weaken the air exchange between the roof of a building and the street canyon. This results in the accumulation of PM inside the street canyon (Gromke and Ruck 2007, Kumar *et al.* 2008, Buccolieri *et al.* 2009). In addition, a mass of branches of trees decreases turbulent kinetic energy, and the air in the tree canopy becomes more stable. The PM carried by turbulence therefore has a stable condition in which to deposit onto the leaf surface (Jeanjean *et al.* 2017). Because of the strong shear stresses when wind passes through trees, urban vegetation not only causes extra mechanical turbulence, but also reduces turbulence kinetic energy and provides a suitable condition within the tree canopy for PM absorption (Abhijith *et al.* 2017). Lohr and Pearson-Mims (1996) also reported that PM concentration in rooms where 2% of the total area is occupied by plants is much lower than in rooms without plants, and Maher *et al.* (2013) tested the PM concentration inside a row of houses alongside a main street and reported significant differences is found between areas with and without plants. Plants thus are considered to have significant reduction capacity for both indoor and outdoor PM pollutants.

Although plants have a notable ability to decrease PM concentration, the capturing efficiency between different plant species varies (Przybysz *et al.* 2014). Wang *et al.* (2015c) compared the deposition capability among 13 plant species in Beijing and notable differences are found between species. The species with the highest capacity is *Buxus megistophylla* while *Salix babylonica* is the least effective species. Moreover, size fractions of deposited PM between species are also various. Wang *et al.* (2015c) claimed PM with large size fractions tend to have an advantage in being deposited than those with small size fractions. Leaf traits including the size of the microstructure and the density of stoma are reported to be key factors for PM accumulation. Species with an intensive stoma and deep grooves and wrinkles usually exhibit higher deposition efficiency (Wang *et al.* 2015c). In addition, Tallis *et al.* (2011) assessed the PM capturing ability of trees in London by using the UFORE model and found that an expansion of urban vegetation coverage results in significantly positive effects on PM reduction. Conifers exhibit the highest potential for PM_{10} reduction in the area with heavy air pollution. Zhang *et al.* (2015b) made a further advancement in this field by comparing the PM absorption capacity of leaves from six common plant species in Beijing and found the following sequence about the PM deposition capability: *Pinus tabuliformis* > *Pinus bungeana* > *Salix matsudana* > *Acer truncatum* > *Ginkgo biloba* > *Populus tomentosa.* In general, needle-leaved tree species tends to have a higher capacity than broad-leaved tree species for PM capture. This result is consistent with Qi`s findings in their study conducted in Zhengzhou, China (Qi *et al.* 2009).

The differences in PM capturing efficiency between different plant species is correlates to different leaf surface morphological traits. The morphological traits of leaves which have great effects on PM reduction capacity can be concluded to three parts: blade profile, leaf hair density and stoma density. Fan *et al.* (2015) compared 26 broad-leaved species in Beijing, and found that different plant blade profiles lead to different PM capturing efficiency. Hwang *et al.* (2011) claimed that species with a large leaf area tend to be more effective in decreasing PM density; the results from Qi *et al.* (2009) also confirmed this tendency. Needle-leaved plants are found to be highly effective for PM capture due to their large leaf area in total. Simultaneously, former studies have found that leaf surface which is eriophyllous and hairy is far more efficient in capturing and to retaining, PM and leaves with a long and thin pubescence can effectively prevent PM from escaping from the leaf surface (Chen *et al.* 2006, Tallis *et al.* 2011). The density of stoma and the level of leaf surface roughness have also been considered as a major factor. Wang *et al.* (2008)

and Mo *et al.* (2015) found species with high stoma density and deep grooves are far more effective in capturing and holding PM as there is sufficient storage space. Their finding is consistent with the results of Zhang *et al.* (2015b), who found that a high density of stomata on the leaves of *Pinus tabuliformis* accelerates its PM capturing capacity compared to those with fewer stomata, such as *Populus tomentosa* and *Ginkgo biloba.* In conclusion, needle-leaved species which has a hairy surface, high stomata density and deep grooves and wrinkles are reported to be highly effective for PM capture. Meanwhile, a large volume of leaf hair and stomara increases the roughness of leaf surface and provides sufficient space for PM to be stored.

Former studies have also compared the PM capturing efficiency between shrubs and arbors, herbs and woody plants. According to Pyatt (1973), herbs collectes more PM than woody plants, but later Weber *et al.* (2014) claimed no obvious difference is found.

Although leaf traits play an important role for PM capture, dust content in the atmosphere and other external factors such as wind, the traffic density and the distance between plants and PM sources are also reported to have great effects on PM reduction efficiency (Baldauf *et al.* 2008, Tong *et al.* 2016). Weber *et al.* (2014) compared the PM capturing ability between herbaceous species and other roadside plants in Berlin, finding traffic density had significant effects on the PM reduction efficiency of plants. The PM density was found to be much higher on leaf surfaces near the roads with high traffic density than those with low traffic pressure. Brantley *et al.* (2014) assessed the efficiency of tree barriers to reduce the density of traffic-related PM and found that a mature tree barrier can notably improve air quality near the road. In addition, leaves at different heights showed notable diferences for PM capture, leaves above 15 cm from the ground accumulated more PM than leaves growing at a lower position, tall vegetation also collected more PM than dwarf species (Weber *et al.* 2014). Researches have also tried to understand the consequences of wind on PM capture. Brantley *et al.* (2014) took wind directions as an influencing factor and promoted the understanding of roadside vegetation as an urban PM filter under various complicated wind conditions.

1.2.3 Efficiency of roadside plants for indoor PM reduction

The ability of roadside plant species to reduce indoor PM has also been reported by former studies. Maher *et al.* (2013) measured the PM concentrations of PM inside a row of urban houses by using both PM monitoring and magnetic measurements. Results based on both methods showed indoor PM concentration declines by over 50% in houses behind roadside trees. Though scanning electron microscope observation, a significant agglomeration of PM is found around the leaf surface hair of roadside trees. Additionally, by measuring magnetic remains on the leaf surface, the amount of captured PM between road-proximal and road-distal plants are found to be almost equal (Maher *et al.* 2013). Roadside plants showed a notable ability to reduce PM both indoors and outdoors.

Although PM concentration indoors is greatly decreased by roadside vegetation, former studies have focused mainly on the plants` capturing abilities for PM with a diameter over 10 μm or between 2.5 μm to 10 μm. As further evidence has indicated that PM with a diameter smaller than 2.5 μm could cause more serious threats to human health (Liu *et al.* 2018), the role of roadside plants to reduce indoor fine PM has also become an important issue. However, studies on this topic are still rare.

1.2.4 Interdisciplinary methods to assess PM capturing efficiency of roadside plants

Compared with traditional methods to assess the efficiency of roadside plants for PM reduction in urban areas, interdisciplinary methods have recently received a lot of attention. One of the most inspired methods is the environmental plant magnetic biomonitoring approach

Biomonitoring is an efficient tool for particle detection (Gibbard *et al.* 2010). The advantage of using plants as a monitor relies on the wide distribution area, where there are sufficient monitor sites. Some species (such as evergreen species) provide the researcher with more leaves to monitor throughout the year compared to deciduous species. Biomonitoring can thus be operated for a longer time and more captured pollutants on leaves can be detected (Hansard *et al.* 2011). This method also uses leaves as a PM collector and pollutants which consist of magnetic particles can be detected and measured directly. Magnetic monitoring has many advantages that traditional measurements cannot match (Hansard *et al.* 2011).

Previous studies have shown a clear correlation between PM concentration and magnetic susceptibility (Blaha *et al.* 2008). Fly ash samples from a power plant burning black coal was tested, comparing the grain-size (0.5-300μm) of the bulk sample and the grain-size spectra from magnetic extracts (1-186.5μm). Strongly magnetic particles were found, mainly with a fractions range less than 63μm (Blaha *et al.* 2008). Road dust samples from Seoul have also been measured using thermomagnetic and electro-microscopy methods. Carbon-bearing iron-oxides are found to be the main component, suggesting that most anthropogenic particles are derived from the burning of fossil fuels (Kim *et al.* 2009). When the samples have a weak magnetic feature, Saturation Isothermal Remanent Magnetization (SIRM) is claimed as a good alternative; SIRM has been claimed to have a close correlation with PM and acts as an agent for PM monitoring (Muxworthy *et al.* 2003). As air pollution in urban areas is largely caused by road traffic, the magnetic property of leaf samples which is exposed to the field in the urban area can indicate the strong correlation between PM density and its magnetic concentration (Matzka 1997).

In conclusion, the magnetic properties of leaves from roadside vegetation could be used as an indicator for the detection of urban PM pollution (Rai 2013). Although biomagnetic monitoring is still a new method, it could become an important solution for PM monitoring and reduction in the future with the development of environmental magnetism technology.

1.3 Research objectives and structure of this thesis

1.3.1 Structure of the thesis

In the frame of the investigation, three different experiments were carried out. The first experiment was conducted to understand whether efficiency differences existed between different roadside plant species with various leaf traits for traffic-related PM capture. Twelve roadside plants were selected as tested material and significant differences in PM capturing efficiency between plant species were found. The similarities of roadside plants with a relatively high PM capturing efficiency were explored and it was found that leaf shape and leaf surface traits would, to a great extent, affect the PM capturing efficiency of one species in particular. It was also found that roadside plants with needle-shaped leaves or with small broad-shaped leaves normally possess a higher capturing efficiency. *Taxus baccata*, *Pinus nigra*, *Berberis thunbergii* and

Hedera helix were found to be four highly efficient species in this study, while *Prunus laurocerasus* was the most inefficient. More detailed results and discussions for the first experiment are elaborated upon in Chapter 2.

Although the PM capturing efficiency of different roadside plants was explored in the first experiment, their efficiency was still unknown during winter months where the capturing efficiency of deciduous plant species declined significantly, and the PM concentration in the air is relatively high when compared to summer. In the second experiment, four common roadside evergreen species were selected and their PM capturing efficiency during winter was evaluated. Each plant species demonstrated different efficiency in each of the winter months. The needle-leaved species *T. baccata* and *P. nigra* were, in general, the most efficient species, while *P. laurocerasus,* like its performance in summer, remained to be the most inefficient species also during winter. Detailed results and discussions for the second experiment are elaborated upon in Chapter 3.

In order to have a better evaluation of how roadside plants react to different traffic pressures in different city blocks, two efficient species with different leaf shapes (*T. baccata* and *H. helix*) were tested in the third experiment. The two tested species were found to react differently under different traffic pressures when absorbing PM with different size fractions. A green wall covered with *H. helix* was also studied to understand the spatial distribution features of different sized PM and to try to develop a good use pattern of efficient roadside plants for PM reduction. More details and discussion for the third experiment are presented in Chapter 4.

At last, a general discussion is written to have a overall understanding of the role of different roadside plants species in traffic-related PM reduction under different conditions in the urban area (Chapter 5). And prospective study directions are raised to discuss the deficiency of this study and possible direction for future study (Chapter 6).

In order to have a better understanding and discussion, detailed objectives and hypotheses were put forward in each chapter.

1.3.2 Research objectives

As vegetation and plants play an important role in air pollution mitigation, numerous studies have previously been conducted. Most studies focused on the absorption efficiency of plants for particulate matters coming mainly from complex and diverse pollution sources such as industrial discharge. However, the efficiency of roadside plants for PM reduction in the urban area, especially in areas where the public transportation system is the primary PM pollution source, has been rarely reported. The main objectives of this study included three aspects: 1). Discover which common roadside plant species are efficient by comparing the PM capturing efficiency of different plant species; 2). Seek both internal and external factors which accelerate a plant`s PM capturing efficiency by comparing different characteristics of highly efficient roadside plants; 3). Explore the best use pattern of the efficient roadside plant species under various external conditions.

To approach the overall research objectives, nine detailed objectives were selected and discussed in each chapter:

1. To select urban roadside plant species which possess a high PM capturing efficiency, twelve common roadside species were tested and their PM absorption efficiency (for both PM_{10} and $PM_{2.5}$) was compared alongside one main street in Hanover, Germany (Chapter 2).

2. To evaluate the commonality of urban roadside species which have similar PM capturing efficiency, twelve tested roadside plants in this study were classified into species groups by their leaf shapes and leaf surface area. The PM reduction efficiency (for both PM_{10} and $PM_{2.5}$) of each species groups were tested. (Chapter 2).

3. In order to understand the reasons which results in the interspecific efficiency difference for PM capturing (for both PM_{10} and $PM_{2.5}$), leaf surface structural characteristics of the tested roadside plant species were observed by optical microscope (Chapter 2).

4. To evaluate the PM capturing efficiency (for both PM_{10} and $PM_{2.5}$) of roadside species during winter (when most deciduous plants lose their leaves and therefore their capturing ability), four common roadside evergreen plant species were selected, and their PM capturing efficiency was tested in each winter month (from November to March) (Chapter 3).

5. To gain a further understanding of the reasons which lead to the interspecific efficiency differences in PM capture, the leaf surface micro-morphological characteristics of four

evergreen species was observed by Scanning Electron Microscope (SEM) (Chapter 3).

6. To discuss the relationship between leaf surface hydrophilicity and its PM capturing efficiency, the leaf surface contact angle (CA) of four evergreen species was tested and the correlation between leaf surface contact angle and PM capturing efficiency was evaluated (Chapter 3).

7. To explore the variation in PM capturing efficiency of roadside plants under different traffic pressures, two relatively efficient plant species with different leaf shapes were selected. Their efficiency to capture PM with different size fraction was measured under three different traffic pressures (low, middle and high pressure) (Chapter 4).

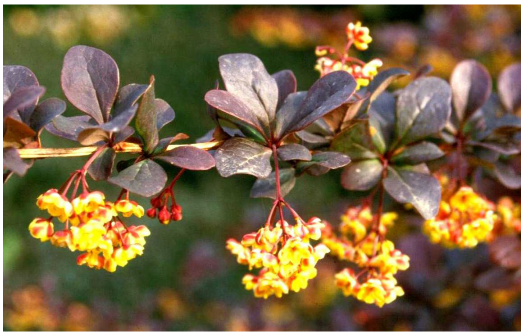
8. To understand the variation in PM capturing efficiency of roadside plant species at different height ranges, the climbing species: *Hedera helix* was selected. The PM capturing efficiency of its leaf surface and its leaf wax were tested respectively at four testing zones, which were defined by different height ranges above from the ground (Chapter 4).

9. To explore a good use pattern of roadside plants as a PM filter, a green wall covered by *Hedera helix* alongside an urban street was selected and the spatial distribution characteristics of different sized PM at different height ranges were measured (Chapter 4).

1.4 Brief introduction to the tested roadside plant species in this study

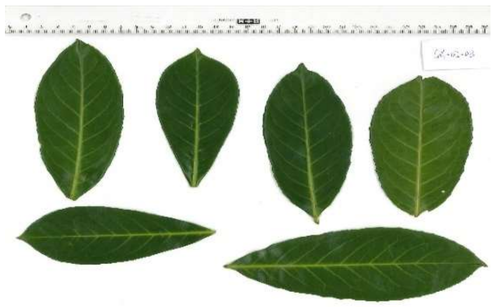
In order to test the PM capturing efficiency of roadside plants, 12 common roadside species in Hanover, Germany, were chosen as the tested plants. Detailed descriptions of each species are introduced below. On the left side, an overview of the tested plants can be found and on the right side, photos of leaves of each tested species are displayed.

1.4.1 *Berberis thunbergii*



Family: *Berberidaceae*; also known as Japanese barberry. A small deciduous shrub which is approx. one meter tall. Its branches are angulate and dark red in color; its shoots are reddish-green, glabrous and the spines on the branches are simple and 5-15 mm long. The leaves are thin, papery and very small, 1-2 cm long and 0.5-1.2 cm broad. The leaf color is reddish or purple and the leaf shape is obovate or rhombic-ovate. Both leaf surfaces have indistinct reticulate veins and the leaf margin is entire. The flowers are pale yellow and are produced in drooping 1-2 cm umbrella-shaped clusters of 2-5-flowers. Its berry is shiny, red, ellipsoid or spherical, approx. 9-10 mm long, juicy and solid. It also contains 1-2 brown seeds. (Flora of China 2019).

1.4.2 *Prunus laurocerasus*



(Köhler 1887)

Family: *Rosaceae*; also known as cherry laurel. An evergreen shrub or small-sized tree, growing upto 5 to 15 meters tall and with a trunk up to 60 cm broad. The leaves are dark green, leathery and shiny, 6-18 cm long and 3-7 cm broad. The petiole is 5-15mm, glabrous and eglandular, and the blade shape is elliptic to obovate; the leaf margin is remotely serrulate or nearly entire. The inflorescence is 26-32 flowered racemes and its white flowers are with petals 3-4 mm long, and the petals are obovate or elliptical. The drupes are deep purple-red, ovoid to conic-ovoid and 13-17 mm long. (Rushforth 1999, Flora of North America 2019).

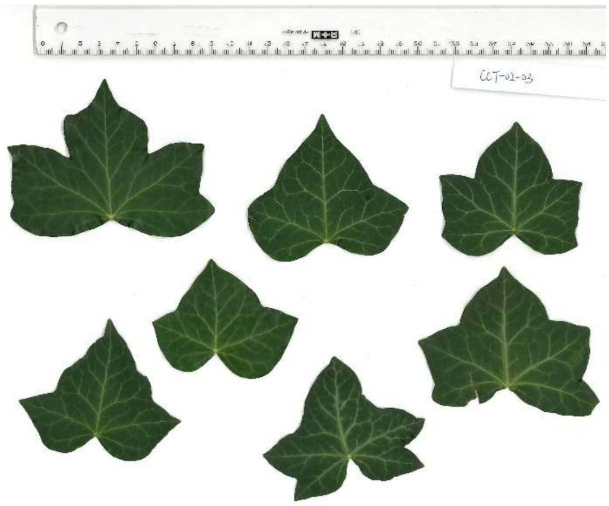
1.4.3 *Philadelphus incanus*

Family: *Hydrangeaceae*; also known as hairy mock orange. A shrub which is 1.5-3.5 m tall. The color of the branchlets from the previous year is gray-brown and the color of those from the current year is brown or purple. The petiole is 5-10 mm long; the shape of the leaf blade is ovate, 6-12 cm long and 8-10 cm broad. Dense white villus is found at abaxial of the leaf, and adaxially bristly hairs are appressed. The leaf margin is sparsely serrate; the inflorescence is racemes. The petals color is white and its shape is ovate or suborbicular; the length of the petals is 1.3-1.5 cm long with and the breadth is 0.8-1.3 cm (Flora of China 2019).

1.4.4 *Syringa vulgaris*

Family: *Oleaceae*; also known as common lilac, originationg as a floral element from sourthern Europe which has been cultivated since the 16th century (Pott 1995). It is a large shrub which grows up to 6 m high. The color of its bark is grey to grey-brown. Its leaf is subcoriaceous, 5-10 cm long and 2-6 cm broad with a mucronate apex. The leaf shape is oval to cordate, the leaf margin is entire and the leaf color is bright green; the inflorescence is panicle. Flowers are often scented and are coloured lilac, white, azure, or red. The fruit is a slightly compressed, loculicidal capsule. Two seeds are in each locule and the seed is flat and narrowly winged. (Flora of Pakistan 2018).

1.4.5 *Hedera helix*



Family: *Araliaceae*; also known as English ivy. A climbing evergreen vine which grows up to 20-30 meters on a suitable surface. Its leaves are evergreen, leathery, glossy and entire 3- 5 lobed. The leaf shape is broadly egg-shaped to triangular, and the leaf length is about 4-10 cm. The inflorescence is terminal and globose compound umbel. The color of the petals is greenish-yellow. Its fruits are bluish-black berries which are 6-9 mm long and have 2-5 seeds (Douglas *et al.* 1998-2002).

1.4.6 *Taxus baccata*

Family: *Taxaceae*; also known as yew. A conifer and a midium-sized evergreen tree which grows 10-22 m tall, with a trunk up to 2 m in diameter. The color of the bark is brown. The leaves are small, flat, strait needles with a pointed tip. The color of its leaf is dark green, the leaf is normally 1-4 cm long and 2-3 mm broad and it grows spirally in two rows on either side of the stem. *Taxus baccata* is dioecious, its male flowers are insignificant white-yellow globe-like structures; its female flowers are bud-like, scaly and green when young but become brown and acorn-like with age. *Taxus baccata* does not actually bear its seeds in a cone. Each seed is 4-7 mm long and enclosed in a red, fleshy, berry-like structure (known as an aril) which is open at the tip (Rushforth 1999).

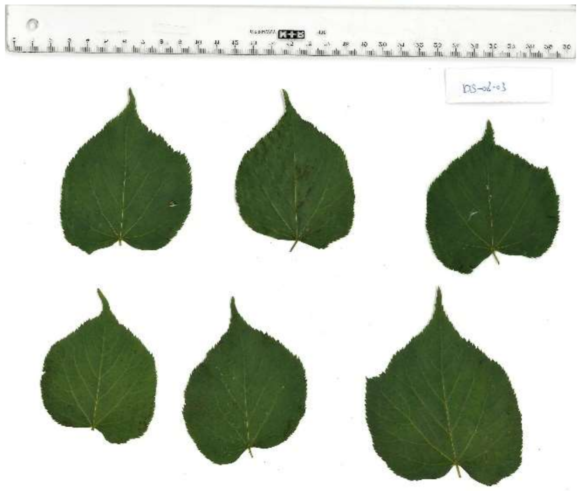
1.4.7 *Pinus nigra*

Family: *Pinaceae*; also known as black pine. It is regarded as a tertiary relict of a circum-Mediterranean clan (Pott 1996). It is a large coniferous evergreen tree which grows up to 50 m tall. The color of its bark is gray or dark brown and its branchlets are pale brown or orange-brown. The leaf blade is needle-shaped, straight or curved; each bundle has two needles and the leaf color is pale or dark green. Each needle is 4-19 cm long and 1-2 mm broad. The seed cones are subsessile, yellowish or pale brown in color, shiny, 3-8 cm long and 2-4 cm broad. (Flora of China 2019).

1.4.8 *Quercus robur*

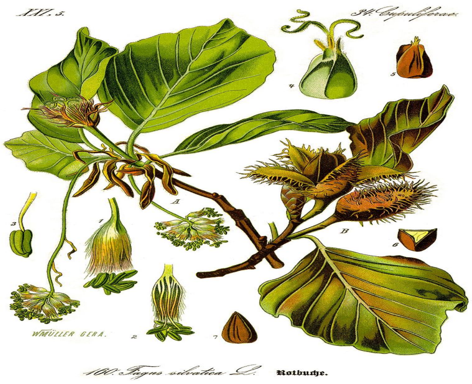
Family: *Fagaceae*; also known as European oak. A large deciduous tree which grows up to 30 m tall. The color of its bark is light grey. The leaf petiole is 3-6 mm long, and the leaf shape is obovate to narrowly elliptic or narrowly obovate. The leaf is 7-15 cm long and 3.5-8.5 cm broad, and leaf margin is moderately or deeply lobed. The abaxial surface color of the new leaf is light green, glabrous or sparsely pubescent. Leaf is glabrous at its maturity, color of adaxial mature leaf surface is deep green to light green or gray, dull or glossy (Flora of North America 2019).

1.4.9 *Tilia cordata*



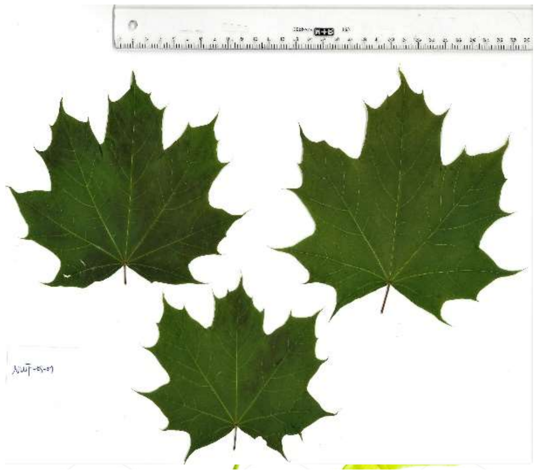
Family: *Malvaceae*; also known as linden, a deciduous tree growing to 20–30 m tall with a trunk up to 1 m in diameter. Its young bark is smooth and grayish whiel the older bark is firm with vertical ridges and horizontal fissures. The crown is rounded in a formal oval shape to pyramidal. Its branching is upright and increases in density with age. The leaves are alternately arranged and are rounded or triangular-ovate in shape. Leaves are 3-8 cm in lenghth and width; the leaf surface is hairless. The inflorescence is drooping panicles with up to 12 yellow single flowers. The flowers are monoecious, hermaphroditic and very fragrant. The buds are alternate, pointed egg-shaped and have red scales; it has no terminal bud. The fruit is a dry nut-like drupe which is 6–7 mm long and 4 mm broad, containing one to two, brown, smooth seeds (Upham Smith 1969, Rushforth 1999).

1.4.10 *Fagus sylvatica*



Family: *Fagaceae*; also known as European beech. A deciduous tree which grows up to 50 m tall with a 1.5 m trunk. The leaf shape is ovate, 5-10 cm long and 3-7 cm broad. On each side of the leaf, there are 6-7 veins, and the leaf margin is entire or with a slightly crenate. Its leaves are light green in spring and become middle green later. The leaves remain on the tree in winter instead of fall off; this process is called Marcescence. Its male flowers are borne in the small catkins which is a hallmark of *Fagales*. The nuts are triangular, 15-20 mm long and 7-10 mm wide at the base, two nuts are found in each cupule. (Wühlisch 2008) .

1.4.11 *Acer platanoides*

Family: *Sapindaceae*; also known as Norway maple. A deciduous tree which grows 20-30 m tall with a trunk which is up to 1.5 m in diameter. The color of its bark is grey-brown and the bark has shallow grooves. The petiole is 8-20 cm long, the leaf arrangement is opposite, and the shape of the blade is palmately lobed; The leaves are 7-14 cm long and 8-20 cm broad, and the leaf margin is incised. Inflorescences is 15-30 flowered corymbs, and petals are 3-4 mm long with a color of yellow-green. Its fruit is double samara with two winged seeds. The wings are 3-5 cm long, glabrous and widely spread. (Gilman and Watson 1993, Douglas *et al.* 1998-2002, Rushforth 1999).

1.4.12 *Carpinus betulus*


Family: *Betulaceae*; also known as European hornbeam. A small to medium sized deciduous tree which is 20-25 m high. The bark is smooth and steel-grey in color. The leaves are alternate, with prominent veins and a distinctive corrugated texture. The leaf shape is obovate with the leaf margins is serrated. The leaf length is 8-10 cm and the leaf color is light to dull green.The flowers are unisexual, and the inflorescences is pendulous catkins. The male catkins are 6 cm long and the female catkins are up to 15 cm long. Its fruits are 6-8 mm long nutlets (achene) which are clustered in 8 pairs (Komarov 1970, Mitchell 1974, Johnson and More 2006, Dixon *et al.* 2013, Savill 2013).

Chapter 2 Reduction of urban airborne particles: Leaf trait matter

2.1 Background and hypotheses

With rapid global economic growth and urbanization, environmental pollution, and air pollution in particular, poses an increasing threat to people, resulting in both social issues and public health issues worldwide (Kennish 2002, Myers and Patz 2009, Gupta *et al.* 2016). Most air pollution in urban areas is caused by air particulate matter (PM), which comes in different forms such as visible dust, sand and aerosols. Air PM is from both natural sources such as the eruption of volcanoes, dust storms, wildfires and wind erosion (Zhang *et al.* 2015a) and anthropogenic sources such as heating, mining, the burning of fossil fuels, industrial discharge and other human activities (Seinfeld 1975, Matsuda *et al.* 2010). Because of their small sizes, heavy metal ingredients and toxic components, air PMs, especially PM_{10} and $PM_{2.5}$ have notably harmful effects to human cardiovascular and respiratory systems and even damage human DNA (Knaapen *et al.* 2004, Coronas *et al.* 2009, Sturm 2010).

Cities present critical scenarios. Due to the large amount of vehicles in urban areas, traffic-related PM is believed to be the main cause of air pollution in cities. As an example, in recent years Beijing had more than 5 million vehicles (Yearbook 2014) and in 2013 the $PM_{2.5}$ air quality index reached 154 (Chen *et al.* 2015a). Air pollution caused by road traffic systems in cities seriously threatens inhabitants' health. Therefore, reasonable strategies to reduce PM in the urban atmosphere and to protect the public health from PM pollution are urgently needed.

Two main approaches have been considered so far. The first focuses on PM source restriction through the implementation of environmental laws aimed at reducing toxic emission from factories nearby cities, changing the energy resource structure and limiting the amount of vehicle. The other strategy explots the capacity of plants to capture PM from air onto their leaf surface (Litschke and Kuttler 2008). Because of its role of multifunctional interface between a plant and its environment, leaf surface will have an impact on both biological and ecological processes, and the topography can directly affect the microhabitat availability and suitability of plants for PM deposition (Zhang *et al.* 2017b).

Studies showed that about 0.71 million tons of air pollutant (including PM_{10}) is removed in one year by urban trees in the USA (Nowak *et al.* 2006). McPherson *et al.* (1994) suggested that the amount of PM_{10} removed by urban vegetation in Chicago could grow up to 234 tons in one year if 11% of the urban area is covered with trees. McDonald *et al.* (2007) claimed that local trees can decrease PM concentration by 2-10% if the vegetation coverage increases to 25%. The mechanism through which different roadside plant species capture urban PM has been widely studied (Chen *et al.* 2017). Leaf surface traits like wrinkled surface, grooves and ridges, stomata, trichomes and even secreted grease and mucus have been considered largely extend the efficiency of plants for PM capture (Hwang *et al.* 2011, Lin and Khlystov 2012, Sæbø *et al.* 2012, Rasanen *et al.* 2014, Mo *et al.* 2015, Zhang *et al.* 2015b). In addition, high hydrophilicity of leaf surface - which could be quantified by a low leaf surface contact angle - has also been claimed to lead to a high amount of captured PM onto leaf surface (Wichink Kruit et al. 2008, Koch et al. 2009, Kardel et al. 2011). However, little is known about the impact of leaf shape and leaf area for PM capture. Moreover, numerous studies have been conducted in regions where the industrial contamination is the main source of urban air pollution (Wang *et al.* 2016, Zhang *et al.* 2017b, Venkataraman *et al.* 2018), but little attention was paid to the areas, where road traffic is the main cause of air pollution. In addition, most former studies focused only on the efficiency of plants from city gardens and city forests, but the efficiency of roadside plants, which normal face directly to the urban streets, has been rarely considered. Nevertheless, only by optimizing species selection based on leaf`s PM capturing efficiency and by providing species-specific information for the design of vegetation landscape alongside streets in urban areas, the benefits of urban vegetation in reducing city air pollution and purifying urban air could be fully maximized.

The main objectives of this chapter are:

1. to select highly efficient plants among common roadside plant species in areas where traffic-related PM is the main contaminant;
2. to summarize the common traits of highly efficient plant species
3. to preliminarily evaluate the factors which led to the differences of PM capturing efficiency among different roadside plant species.

To obtain a comprehensive understanding of the PM-reduction mechanisms based on leaf traits, the following hypotheses are posed in this chapter:

(1) there are significant differences between roadside plant species in PM capturing efficiency, which are related to their leaf traits;

(2) needle-leaved species are more effective at capturing both PM_{10} and $PM_{2.5}$ than broad-leaved species;

(3) urban roadside plant species with large leaf surface area has higher PM capturing efficiency than species with small leaf surface area.

To verify these hypotheses, twelve common urban roadside plant species were selected alongside one main street in Hanover, capital of State of Lower Saxony in Germany. As the Hanover industrial zone is located on the outskirts of the city, urban traffic-related contaminant from automobile exhaust, brakes and asphalt (Grigoratos and Martini 2015) could be considered as the main PM source. This chapter provided scientific views for the reduction of urban air pollution depending on city roadside plants.

2.2 Materials and methods

2.2.1 Study field description

The study in this chapter was conducted in Hanover, Germany. As the capital city of state Lower Saxony, Hanover is one of the largest cities in northern Germany. The annual average temperature is from 5.2 ℃ to 13.3 ℃, wind direction in September is northwest and annual total amount of rainfall is 641.2 mm. Like most big cities, Hanover suffers from different levels of air pollution (Hannover 2011).

The sampling area was set along the street “Nienburger Straße” in Hanover (Fig. 2.1), from the tram station of “Schneiderberg/Wilhelm-Busch-Museum” to the tram station of “Appelstraße” (52°23'05.6" - 52°23'27.8"N, 9°42'15.7" - 9°42'45.8"E). It is a two-way street with two metro tracks running down one side. The street used for sampling was about 1 km long and about 5 m wide. This street connects the university campuses “Schneiderberg” and “Herrenhausen” and is also important constitute part of public traffic system in Hanover, because it connects the city center to the peri-urban highway system. Along the street locate university campuses of Leibniz University, residential areas and two large city gardens ("Georgengarten" and "Herrenhäuser Gärten"). The number of vehicles running on the street was counted manually three times from 8:00 am to 06:00 pm on a mid-week day. The average car number was 1100 per hour. With no industrial facilities around and relatively high traffic flow, PM captured on leaf surface alongside this street can be considered as mainly from the road traffic system.

Plant leaves were sampled from roadside trees and shrubs which located about 5 to 7 meters away from the road curb, and no barriers exist between the plant and sampling street. Sampling

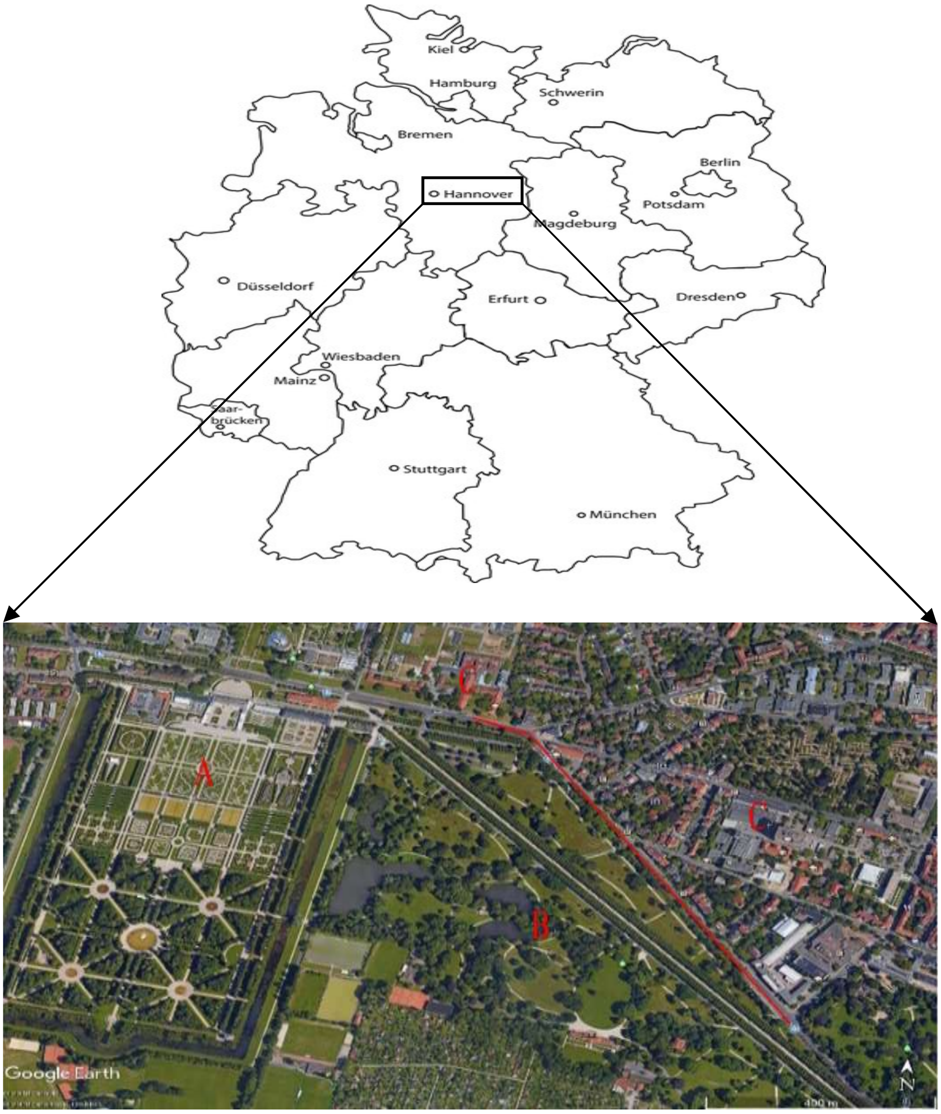


Fig. 2.1 Location of the study area in Hanover. The red line: the street for sampling in this study; A: "Herrenhäuser Garten " ; B: City park "Georgengarten"; C: University campus. (based on the map from: www.google.com/intl/de/earth, changed)

was conducted in September to ensure that plant leaves were in the best condition after a growing period from spring to summer for PM capture, all leaves were at their best growth condition and were fully extended.

2.2.2 Plant species for testing and sampling method

2.2.2.1 Plant species for testing

In order to evaluate the efficiency of roadside species with various leaf surface traits (shown in Tab. 2.1) for air born particles capture, leaves of *Berberis thunbergii, Prunus laurocerasus,*

Table 2.1 Traits and characteristics of tested plants alongside sampling site

SN	F	H	PT	LS	MA	AH
Berberis thunbergii	*Berberidaceae*	S	Dec.	Oval and broad	2.76	0.6-2.5
Prunus laurocerasus	*Rosaceae*	S	Evg.	Leathery shiny broad	54.90	5-15
Philadelphus incanus	*Hydrangeaceae*	S	Dec.	Oval and broad	30.91	1.5-3.5
Syringa vulgaris	*Oleaceae*	S	Dec.	Broad	50.44	6-7
Hedera helix	*Araliaceae*	S	Evg.	Five-lobed juvenile broad	27.87	20-30
Taxus baccata	*Taxaceae*	T	Evg.	Needle	0.79	10-20
Pinus nigra	*Pinaceae*	T	Evg.	Needle	5.05	22-50
Quercus robur	*Fagaceae*	T	Dec.	Lobed broad	48.54	4-12
Tilia cordata	*Malvaceae*	T	Dec.	Ovate and broad	48.67	20-40
Fagus sylvatica	*Fagaceae*	T	Dec.	Slightly crenate broad	29.22	15-24
Acer platanoides	*Sapindaceae*	T	Dec.	Palmately lobed broad	149.35	20-30
Carpinus betulus	*Betulaceae*	T	Dec.	Corrugated texture broad	49.99	15-25

Notes: SN: Scientific name of plant species; F: Family; H: Habit; PT: Plant type; LS: Leaf shapes; MA: the mean leaf area (cm^2 $leaf^{-1}$); AH: Average plant height (m); S: Shrub; T: Tree; Dec.: Deciduous; Evg.: Evergreen.

incanus, Syringa vulgaris, Taxus baccata, Pinus nigra, Carpinus betulus, Quercus robur, Tilia cordata, Fagus sylvatica, Acer platanoides and *Hedera helix*, which are commonly grown in Hanover, were selected as tested plant species.

2.2.2.2 Sampling method

Twelve plant species were selected for sampling. For each species, three sampling points were randomly set alongside the sampling street and plants on each sampling point were 5 to 7 meters away from the curb. Leaves from different species were gathered randomly from the outermost layers of the canopy which faced directly to the street at each sampling points. All samples were harvested in September, five days after a continuous rainfall with accumulated precipitation of 15 mm, as leaf surface from outermost layers of the canopy can be considered as totally cleaned (Pal *et al.* 2002, Wang and Li 2006, Wang *et al.* 2015a). All samples were gathered from the same street to avoid disturbance caused by different traffic volume. For broad-leaved species, twelve blades were collected and for each needle-leaved species, fifty blades were randomly harvest within a sampling area which was 1.5-2 m above the ground. In total, 660 leaves were gathered for the PM deposition measurement on the same day. All sampled leaves were from plants which were in similar growing condition and they were all healthy without disease or pests. In order to prevent contamination during sampling, disposable gloves were used and all leaves were harvest by pinching petioles. Leaf samples of each plant species were then put into a valve bag to prevent them from being polluted by further PM in the air. After being labeled with species name and serial number, all samples were brought back to the laboratory without big tremors to prevent the PM on leaf surface from dropping out and all samples were stored in a clean lab refrigerator with a temperature of 8 °C for next measurements.

2.2.3 PM analysis methods

2.2.3.1 Leaf surface washing and turbid solution preparation

By the original methods conducted by Dzierzanowski *et al.* (2011) and by Sæbø *et al.* (2012), PM with three size fractions (large: $PM_{>10}$, coarse: $PM_{10\text{-}2.5}$ and fine: $PM_{<2.5}$) were obtained at last. Improved "weight difference measurement" by patent of Liu *et al.* (2014) was applied to quantify the amount of PM_{10} and $PM_{2.5}$ which was captured on the leaf surface directly. Leaves from each sample were dipped in a glass beaker with 200 mL distilled water for 5 min and a non-depilatory brush was used to scrub both sides of each leaf to ensure that all particulate matters on the leaf surface were dropped into distilled water. Then another 200 mL distilled water was used to flush leaf surface for three times. All 400 mL turbid solution was collected in the beaker and was weighed by a balance (0.001g), the weight of all 400 mL turbid solution was recorded as M_{ST}. The turbid solution was then stirred with a stirring plate for 5 minutes, and then 50 mL turbid solution was transferred into a pre-dried and pre-weighed plastic test tube with a pipette. Then the plastic test tube was weighed and the weight of the 50 mL solution was recorded as M_{S50}. The solution in the plastic tube was then dried with a Vacuum Freeze Drier (Alpha 1-2 LD plus Entry Freeze Dryer Package, Martin Christ, Australia) for 72h until all solution in the tube was totally dried out. The weight of particulates left in the test tube was recorded as M_{SP}.

2.2.3.2 PM classification and turbid solution filtration

Turbid solution from last step was passed through an extraction filtration apparatus which equipped with a 47 mm glass filter funnel connected to a vacuum pump (KNF Neuberger, USA). The first filter was nylon hydrophilic membrane filter (HNWP04700, Millipore, Ireland, 2017) with a bore diameter of 10 μm. After the first filtration, the grain diameter of the PM obtained on the fiber membrane filter was greater than 10 μm and the grain diameter of the PM in the first filtrate was less than or equal to 10 μm.

The first filtrate was filtrated by the extraction filtration apparatus again with a filter paper (CAT-1442-047, Whatman Labware Products, UK, 2017) which bore diameter was 2.5 μm. After the second filtration, the grain diameter of the PM obtained on the filter paper was greater than 2.5 μm but less than or equal to 10 μm, the grain diameter of the PM in the second filtrate was less than or equal to 2.5 μm.

All fiber membranes and filter papers were put in a drying oven with a temperature of 60 °C for 2h until all fiber membranes and filter papers were totally dried. After being dried, all fiber membranes and filter papers were reserved in a polytetrafluoroethylene desiccator under a vacuous and constant temperature condition for 1h until their temperature reached room temperature to avert electrostatic interference during the next weighing process. All fiber membranes and filter papers were weighed using a scale sensitive to 0.0001g. By comparing the weight differences of dried fiber membranes before and after filtration, the weight of the PM which grain diameter is greater than 10 μm was calculated and recorded as $M_{PM>10}$. Filter papers were disposed with the same process and PM left on it after the second filtration was those with a diameter between 10 μm to 2.5 μm, its weight was recorded as $M_{PM2.5\text{-}10}$. The amount of captured PM_{10} and $PM_{2.5}$ were then calculated by the following formula.

All fiber membranes and filter papers used above were pre-dried by a dry oven with a temperature of 60 ℃ for 2h. The original weight of blank filter paper and membranes were also recorded. The efficiency of different roadside species for PM capture was expressed by the amount of captured PM by unit leaf area.

2.2.3.3 Formula for the calculation of the amount of captured PM10 and PM2.5

The following formulas claimed by Liu *et al.* (2014) were used to calculate the amount of captured PM_{10} and $PM_{2.5}$ by leaf surface of different plant species.

$$MT_P = M_{SP} \times \frac{M_{ST}}{M_{S50}}$$

$$MT_{PM>10} = \frac{M_{PM>1}\ \times M_{ST}}{M_{ST}\ \ M_{S50}}$$

$$MT_{PM2.5-10} = \frac{M_{PM2.5-10} \times M_{ST}}{M_{ST} - M_{S50}}$$

$$MT_{PM\ \ .5} = MT_P - MT_{PM>1}\ \ - MT_{PM2.5-10}$$

$$MT_{PM10} = MT_{PM2.5} + MT_{PM\ \ .5-10}$$

Where MT_P is the weight of total particulate matter including $PM_{>10}$, PM_{10} and $PM_{2.5}$; $MT_{PM>10}$ is the weight of total particulate matter which grain diameter is greater than 10 μm; $MT_{PM2.5\text{-}10}$ is the weight of total particles which grain diameter is between 2.5 and 10 μm; $MT_{PM2.5}$ is the weight of total $PM_{2.5}$; MT_{PM10} is the weight of total PM_{10}; M_{SP} is the weight of particles contained in the 50 mL turbid solution; M_{ST} is the weight of the whole turbid solution; M_{S50} is the weight of the 50 mL solution which was transferred into plastic test tube; $M_{PM>10}$ is the weight of PM which grain diameter is greater than 10 μm; $M_{PM2.5\text{-}10}$ is the weight of PM which grain diameter is between 10 μm and 2.5 μm.

2.2.3.4 Measurement of leaf surface area

Leaves from broad-leaved species were first scanned (MP C3004exS, Ricoh, Tokyo, Japan). The scanned images were then transformed into black and white images in which the scanned leaf area was black against a white background. Then the leaf surface area was calculated by the image processing program Image J (Version 1.4.0 National Institutes of Health, USA) by calculating the black area in the scanned image.

For needle-leaved species such as *Pinus nigra,* the length and width of each leaf were measured by software Image J (Version 1.4.0 National Institutes of Health, USA) and its average leaf area was calculated by the following formula (Perez-Harguindeguy *et al.* 2016, Zhang *et al.* 2017a):

$$S = \frac{\pi DL}{2}$$

Where S = area of each needle-leaved leaf, D = breadth of each needle-leaved leaf, L = length of each needle-leaved leaf.

2.2.3.5 Group classification by different average leaf area

To discuss the PM capturing efficiency of plant species with different leaf surface area, twelve tested species were classified into four groups based on their average leaf area. Species with an average leaf surface area between 0-10 cm^2 per blade were classified into group I: very small leaf area; species with an average leaf surface area between 10-50 cm^2 per blade were classified into group II: small leaf area; species with an average leaf area between 50-100 cm^2 per blade were classified into group III: middle leaf area; and species with an average leaf area greater than 100 cm^2 per blade were classified into group IV: large leaf area.

2.2.4 Measurement of leaf surface contact angle

For each tested plant species, four leaves were randomly harvest and were used as samples for leaf surface contact angle measurement. Both sides of each leaf were washed by 100 mL distilled water for three times, then the washed leaves were dried in the shade at the room temperature until both sides of the leaves were totally dried. The upper flat leaf surface which is close to the midrib was cut to 1cm x 1cm square, and was then pasted onto a glass slide with double-faced adhesive tapes as the sample for measuring. Drop contact angle system (OCA 15EC, Dataphysics, Germany) was used to measure the leaf surface contact angle. Three water droplets were measured on the surface of each leaf sample, and each water droplet was measured at three time points (initial, 1s later and 4s later) ever science it dropped on the leaf surface. The volume of each tested water drop was 1 μL, and the contact angle of each water-drop at each time point was measured by calculating the average value of the contact angle on the right and the left side of the water-drop (SCA 20 software, Dataphysics Instruments, Germany). The average value of the contact angle measured on the three time points is the contact angle of each tested water drop; the average value of the contact angle of the three water-drops is the contact angle of each leaf sample; the average value of the contact angle of the four leaf samples is the contact angle of each tested plant species.

2.2.5 Optical microscope observation for leaf surface characteristics and the distribution of captured particulate matters

To discuss the characteristics of PM distributed on the leaf surface, leaf surface near the midrid of the leaves was cut to 1cm×1cm square and then was pasted onto a glass slide by double-sided tape as samples for observation. The midrib of leaves, surface area close to midrib and surface area away from the midrib was observed by optical microscope (Olympus BX41 Microscope, Olympus, Japan) at different magnification (10, 20, 40×).

2.2.6 SEM observation for leaf surface characteristics and the distribution of captured particulate matters

To discuss the relationship between the micro-morphological characteristics of the upper leaf surface and its effects on the PM capturing capacity of roadside plant species, leaf samples of the tested plants were observed by a field emission scanning electron microscope (SEM) (JSM 6700F, JEOL, Japan) operated in the vacuum mode. The observation was operated on the same day to avoid desiccation of tested leaves and alteration of the leaf surface micro-morphology. Upper leaf surface was randomly selected and the surface area near the center of midrib was cut to 1 cm x 1 cm square and was then pasted onto a glass slide by double-sided tapes as the sample for observation. Each preliminary-made sample was coated by a layer of carbon by High vacuum sputter coater (EM SCD 500, Leica, Germany) to increase electrical conductivity and to improve optical transmission. For each tested plant species, scanning images with three different magnification (300 times, 1000 times and 3000 times) were taken for the observation.

2.2.7 Statistical analysis

Statistical analysis was performed with SPSS Statistics version 22.0 (IBM, New York, USA). One-way ANOVA analysis and Independent-Sample T-tests were performed to determine if significant statistical differences exist for the amount of accumulated PM_{10} and $PM_{2.5}$ on leaf surface of different roadside plant species. The results are significant at $P < 0.05$. The correlation between leaf surface contact angle and the capacity for PM capture was analyzed by Pearson correlation analysis.

2.3 Results

2.3.1 Change of PM_{10} capturing efficiency between different urban roadside plant species

The efficiency to capture PM_{10} varied significantly ($P < 0.05$) between different roadside plant species (Fig.2.2). *B. thunbergii* and *T. baccata* showed the highest efficiency for PM_{10} capture, while *C. betulus* and *P. laurocerasus* were the tested plant species with the lowest efficiency. The efficiency value of *B. thunbergii* (0.340 ± 0.047 mg cm^{-2}) was around 14 times higher than it of *P. laurocerasus* (0.025 ± 0.001 mg cm^{-2}). In general, needle-leaved species (*T. baccata* and *P. nigra*) were far more effective than broad-leaved species for PM_{10} capturing (Fig. 2.2) and the broad-leaved species with relatively high capturing efficiency were *B. thunbergii* (0.340 ± 0.007 mg cm^{-2}) and *H. helix* (0.153 ± 0.036 mg cm^{-2}). The efficiency value of the other eight broad-leaved species was around 0.05 mg cm^{-2}, which was significantly lower than it of the two tested needle-leaved species (0.303 ± 0.045 mg cm^{-2} and 0.185 ± 0.099 mg cm^{-2}). *B. thunbergii* had not only a relatively high efficiency for PM_{10} capturing, but also it was the tested species which had the smallest leaf surface area. Between the two needle-leaved species, *T. baccata* and *P. nigra*, no significant efficiency difference ($P > 0.05$) was found for PM_{10} capture.

Four tested plant species showed a higher PM_{10} capturing efficiency than the other eight species (Fig. 2.2). Among the four efficient species, two of them were shrub species and the other two were trees species. Taking all shrub species as a whole, the average amount of the captured PM_{10} on unit leaf area (0.106 ± 0.112 mg cm^{-2}) was almost equal to it captured by leaves of tree

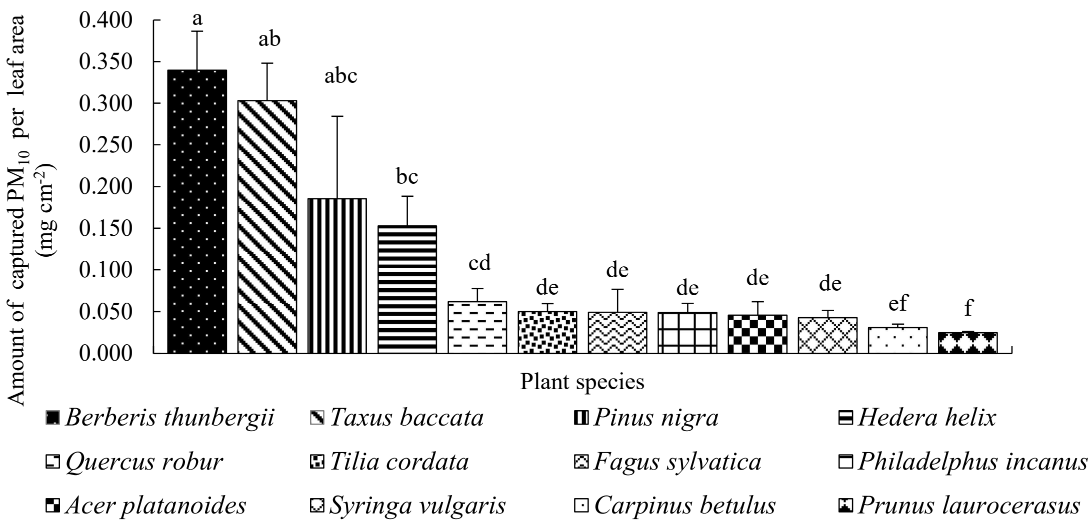


Fig. 2.2 PM_{10} capturing efficiency of different tested roadside plant species. Vertical bars represent the standard deviation (SD); Statistic analysis by one-way ANOVA showed that there are significant differences between different tested plant species (P < 0.05); Data are shown as mean + SD. The same letter means that there is no significant statistical difference (P > 0.05). (Based on the original data from Table C-1, Appendix C)

species (0.094 ± 0.096 mg cm^{-2}). According to Independent Samples T-test, no significant difference (P = 0.747 > 0.05) was found between shrub species and tree species for PM_{10} capture. Taking all evergreen species as a whole, its average capturing efficiency for PM_{10} (0.137 ± 0.109 mg cm^{-2}) also had no significant difference (P = 0.188 > 0.05) with it of the tested deciduous species (0.084 ± 0.097 mg cm-2). Both evergreen species and deciduous species showed similar efficiency for PM_{10} capturing in September.

2.3.2 Change of $PM_{2.5}$ capturing efficiency between different urban roadside plant species

The efficiency to capture $PM_{2.5}$ also varied significantly (P < 0.05) between different tested plant species (Fig. 2.3). *T. baccata* and *B. thunbergii* still showed the highest $PM_{2.5}$ capturing efficiency, while *P. laurocerasus* and *C. betulus* were the two most inefficient species. The efficiency value of the needle-leaved species, *T. baccata* (0.267 ± 0.046 mg cm^{-2}) was around 21 times as much as it of *C. betulus* (0.013 ± 0.004 mg cm^{-2}). Similar with the PM_{10} capturing efficiency, two needle-leaved species (*T. baccata* and *P. nigra*) were still much more effective than broad-leaved species for $PM_{2.5}$ capture (Fig. 2.3). *B. thunbergii* (0.236 ± 0.061 mg cm^{-2}) and *H. helix* (0.144 ± 0.035 mg cm^{-2}) were the two most effective broad-leaved plant species for $PM_{2.5}$ capture in this study. The efficiency value of the other broad-leaved species for $PM_{2.5}$ capturing was around 0.06 mg cm^{-2},

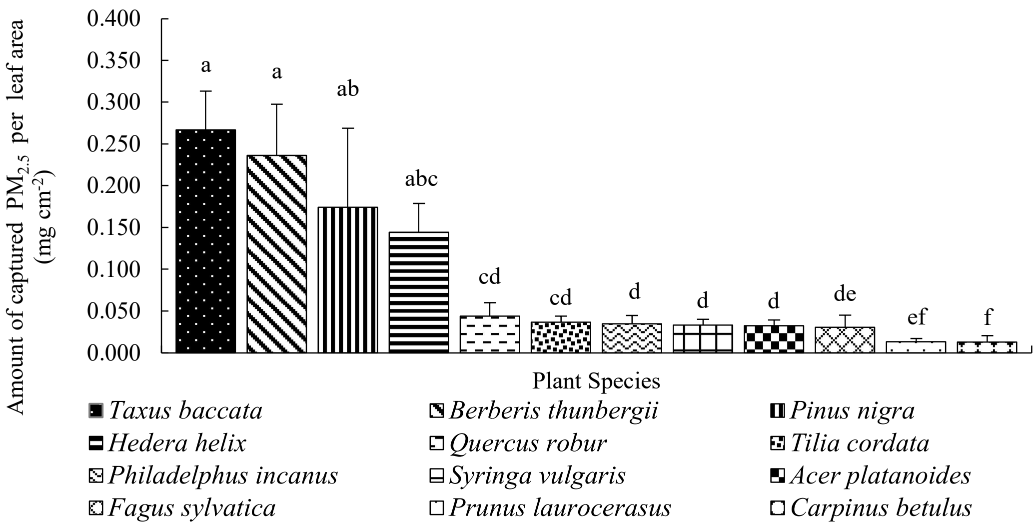


Fig. 2.3 $PM_{2.5}$ capturing efficiency of different roadside plant species. Vertical bars represent the standard deviation (SD); Statistic analysis by one-way ANOVA showed that there are significant differences between different tested plant species for $PM_{2.5}$ capture ($P < 0.05$); Data are shown as mean + SD. The same letter means that there is no significant statistical difference ($P > 0.05$). (Based on the original data from Table C-1, Appendix C)

which was significantly lower than it of the two needle-leaved species (0.267 ± 0.046 mg cm^{-2} and 0.174 ± 0.095 mg cm^{-2}). *B. thunbergii* which had the smallest leaf surface area among all tested broad-leaved species was still the most efficient broad-leaved species for $PM_{2.5}$ capture. Between the two needle-leaved species, no significant efficiency difference ($P > 0.05$) for $PM_{2.5}$ was found.

Four tested species showed notably higher efficiency to capture $PM_{2.5}$ than the other eight tested species (Fig. 2.3). Among these four efficient species, two of them were shrub species and the rest were tree species. Taking all shrub species as a whole, the average amount of captured $PM_{2.5}$ by unit leaf area (0.082 ± 0.085 mg cm^{-2}) was almost equal to it captured by tree species (0.076 ± 0.091 mg cm^{-2}). According to Independent samples T-test, neither significant difference ($P = 0.747 > 0.05$) was found between shrub species and tree species in $PM_{2.5}$ capturing efficiency. When Taking all evergreen species as a whole, the average amount of captured $PM_{2.5}$ by unit leaf area (0.124 ± 0.103 mg cm^{-2}) also had no significant statistical difference ($P = 0.059 > 0.05$) with it captured by tested deciduous species (0.060 ± 0.074 mg cm^{-2}). No evidence was found that that tested evergreen species in this chapter had higher efficiency than deciduous species for $PM_{2.5}$ capture.

2.3.3 Efficiency of roadside plant species with different leaf shapes for PM_{10} and $PM_{2.5}$ capture

The efficiency to capture PM_{10} and $PM_{2.5}$ varied notably ($P < 0.05$) between plants species with different leaf shapes (Fig. 2.4). For PM_{10} capturing, the efficiency value of needle-leaved species (0.244 ± 0.093 mg cm^{-2}) was approximately 3 times higher than it of broad-leaved species (0.078 ± 0.085 mg cm^{-2}). The $PM_{2.5}$ efficiency capacity of needle-leaved plants (0.221 ± 0.081 mg cm^{-2}) was approximately 4 times higher than it of broad-leaved species (0.058 ± 0.066 mg cm^{-2}). Based on the independent samples T-test, there was significant difference ($P < 0.05$) between the capacity of needle-leaved species and broad-leaved species for both PM_{10}, and $PM_{2.5}$ capture.

Taking all needle-leaved species as a whole, no significant difference ($P < 0.05$) was found between its ability to capture PM_{10} and $PM_{2.5}$. there was neither significant capacity difference ($P < 0.05$) for broad-leaved species to capture PM_{10} nor to capture $PM_{2.5}$. For both leaf-shaped species, more PM_{10} was captured on their leaf surface than $PM_{2.5}$

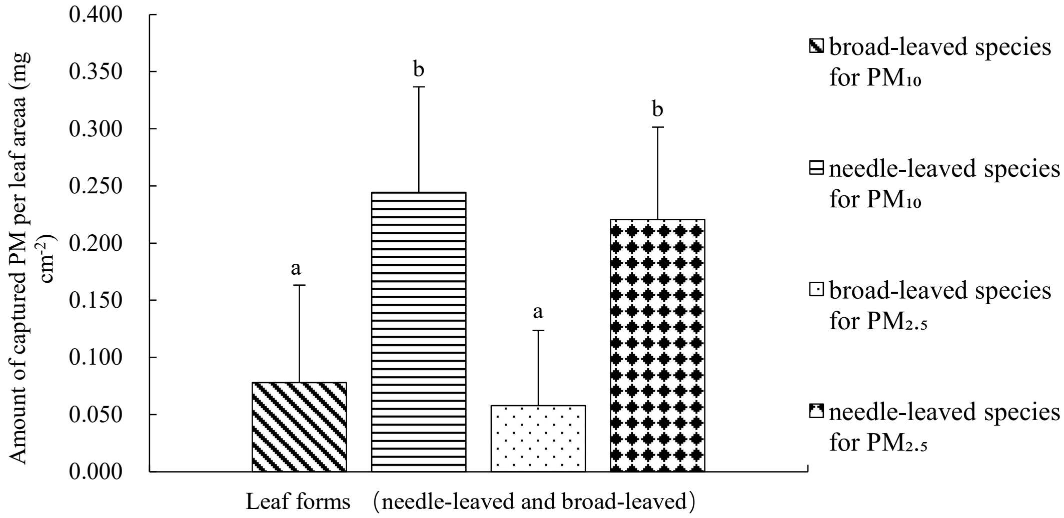


Fig. 2.4 PM capturing capacity between needle-leaved and broad-leaved species. Vertical bars represent the standard deviation (SD.); Statistic analysis by one-way ANOVA showed that there are significant efficiency differences between plants with different leaf shapes ($P < 0.05$); Data are shown as mean + SD. The same letter means that there is no significant statistical difference ($P > 0.05$). (Based on the original data from Table C-1, Appendix C)

2.3.4 Difference of PM_{10} and $PM_{2.5}$ capturing efficiency between species with different leaf area

The efficiency to capture PM_{10} varied significantly between plant species with different leaf surface area (Fig. 2.5). Species with very small leaf area (Group I) showed the highest efficiency value for PM_{10} capture (0.276 ± 0.089 mg cm^{-2}), while species with middle leaf area (Group III) was the most inefficient group (0.045 ± 0.016 mg cm^{-2}). The PM_{10} capturing efficiency of species group with very small leaf surface area (Group I) was about 6 times higher than it of species group with middle leaf area (Group III), and its efficiency value was also much higher than the other two species groups. Based on the one-way ANOVA analysis, there was significant efficiency difference between species group with very small leaf area (Group I) and the other three species groups (Group II, III and IV) for PM_{10} capture ($P < 0.05$). However, no significant difference was found between Group II, III and IV ($P > 0.05$).

The change of leaf surface area also notably affected the efficiency value for $PM_{2.5}$ capture between different roadside plant species (Fig. 2.6). Species with very small leaf surface area (Group I) was still the group with the highest efficiency value for $PM_{2.5}$ capture (0.226 ± 0.069 mg cm^{-2}), while species with middle leaf surface area (Group III) showed the lowest efficiency

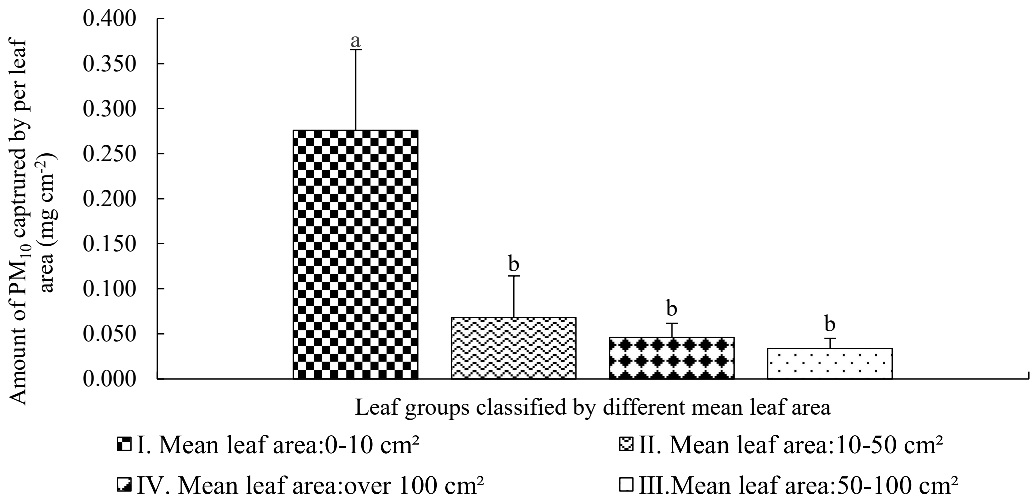


Fig. 2.5 PM_{10} capturing efficiency between different species groups with different average leaf surface area. Vertical bars represent the standard deviation; Statistic analysis by one-way ANOVA showed that there are significant efficiency differences between species groups with different leaf area for PM_{10} capture ($P < 0.05$); Data are shown as mean + SD. The same letter means that there is no significant statistical difference ($P > 0.05$) (Based on the original data from Table C-1, Appendix C).

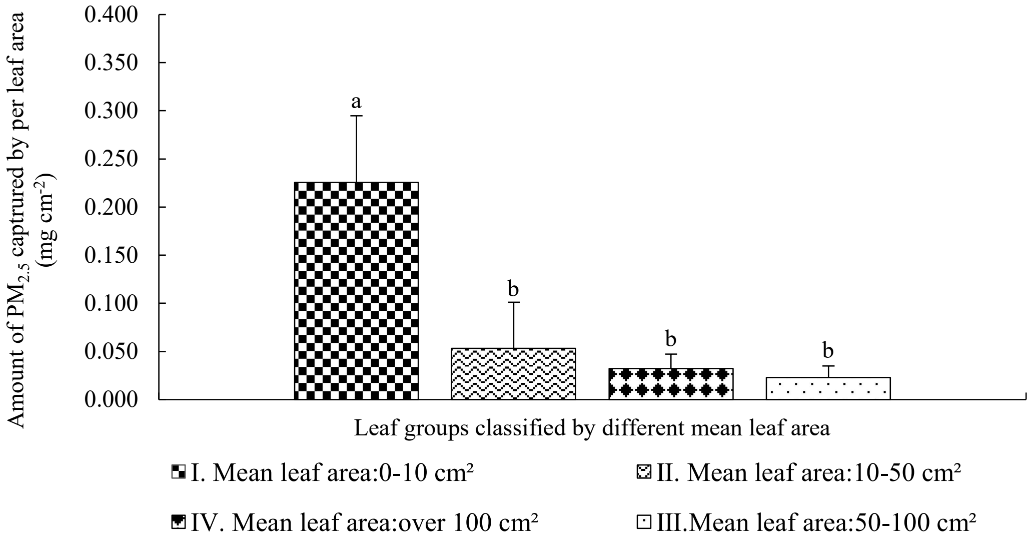


Fig. 2.6 $PM_{2.5}$ capturing efficiency between different species groups with different average leaf surface area. Vertical bars represent the standard deviation; Statistic analysis by one-way ANOVA showed that there are significant efficiency differences between species groups with different leaf area for $PM_{2.5}$ capture ($P < 0.05$); Data are shown as mean + SD. The same letter means that there is no significant statistical difference ($P > 0.05$) (Based on the original data from Table C-1, Appendix C).

(0.023 ± 0.012 mg cm^{-2}). The $PM_{2.5}$ capturing efficiency value of species group with very small leaf area (Group I) was about 10 times higher than it of species group with middle leaf surface area (Group III), and its value was also significantly higher than it of the other two groups. Based on one-way ANOVA analysis, Significant efficiency difference was found between the species group with very small leaf area (Group I) and the other three species groups (Group II, III and IV) for $PM_{2.5}$ capture ($P < 0.05$). But no significant difference was found between the species group II, III and IV ($P > 0.05$).

2.3.5 Relationship between leaf surface contact angle and PM capturing capacity of roadside plants

2.3.5.1 Leaf surface contact angle of different tested roadside plants

The leaf surface contact angle of each tested plants species varied in this study (Table 2.2). Among all tested 12 species, leaf surface contact angle of *Berberis thunbergii* was the highest (116.72° ± 5.59°) which was defined as “non-wettable” and indicate its leaf surface was highly hydrophobic. Leaf surface contact value of *P. laurocerasus*, *Q. robur*, and *H. helix* were all over 100° which means their leaves could but hard to get wet, leaves of *A. platanoides*, *S. vulgaris*, *P.*

nigra, *F. sylvatica* and *P. imcanus* were wettable as their surface contact angle were all between 90° and 100°. Leaves of *T. cordata*, *C. betulus* and *T. baccata* were the three tested species which has "highly-wettable" leaf surface in this study.

2.3.5.2 Relationship between leaf surface contact angle and PM capturing capacity of different plant species

The relationship between leaf surface contact angle and the PM capturing capacity of different plant species was insignificant in this study. *B. thubbergii* has the highest PM_{10} capturing capacity and the highest leaf surface contact angle. *P. laurocerasus* was the tested species which had the lowest PM_{10} capturing capacity while its leaf surface contact angle was the second biggest. Likewise, *A. platanoides* had a relatively low capacity for both PM_{10} and $PM_{2.5}$ capturing and its leaf surface contact angle was high, while *C. betulus* is also the tested species with relatively low capacity for both PM_{10} and $PM_{2.5}$ capturing, but the value of its leaf surface contact angle was quite low.

According to Pearson correlation analysis, the correlation index of PM_{10} capturing capacity and the leaf surface contact angle of the tested roadside plant species was 0.28 which meant there was no correlation between leaf surface contact angle and PM_{10} capturing capacity for the tested roadside plant species from a statistical viewpoint (Fig. 2.7a). The correlation index of $PM_{2.5}$ capturing capacity and leaf surface contact angle was 0.19 which also confirmed that there was no correlation (Fig. 2.7b).

Table 2.2 Leaf surface contact angle of the tested roadside plant species

Samples	Contact angle (°)					
	Initial	1s later	4s later	Mean	SE	Significant difference
Berberis thunbergii	117.43	117.43	115.29	116.72	5.59	ac
Prunus laurocerasus	105.49	104.67	105.39	105.18	3.13	abc
Quercus robur	104.88	103.76	99.70	102.78	7.38	ac
Hedera helix	102.35	101.60	100.35	101.43	5.08	bd
Acer platanoides	101.66	99.51	97.31	99.49	9.12	c
Syranga vulgaris	100.61	67.68	98.10	98.80	7.53	c
Pinus nigra	94.55	93.52	93.79	93.95	5.81	c
Fagus sylvatica	93.23	90.46	89.95	91.21	7.86	c
Philadelphus incanus	96.79	89.66	84.51	90.32	10.01	c
Tilia cordata	93.70	88.59	83.89	88.73	9.64	c
Carpinus betulus	89.34	86.38	85.62	87.11	4.8	c
Taxus baccata	85.95	86.00	85.81	85.92	9.34	d

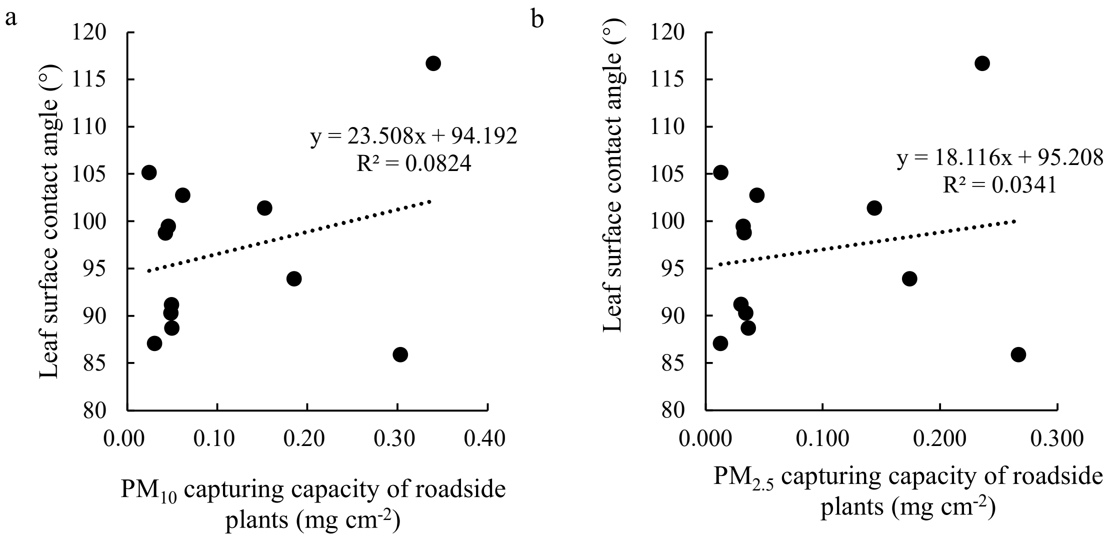


Fig. 2.7 the correlation between PM capturing capacity of roadside plants and its leaf surface contact angle. a: for PM_{10} capture, b: for $PM_{2.5}$ capture.

2.3.6 Relationship between leaf surface characteristics and its efficiency for PM capture

By observing the microscopic images of leaf surface under different magnification, close relationship between the efficiency of leaf surface for PM capture, the PM distribution characteristics and leaf surface structural traits were found (Fig. 2.8).

2.3.6.1 Relationship between PM capturing efficiency and leaf surface structural traits

Cells of *B. thunbergii* on its leaf surface were found quite small and densely arranged (Fig. 2.8 A1, A2), this tight arrangement provided a large number of grooves and wrinkles on its upper leaf surface. PM with various size fractions was found to be embedded in these grooves and wrinkles. Besides, trichomes where PM was adhered onto were also been observed on leaf surface of *B. thunbergii* (Fig. 2.8 A1). Therefore, a rough leaf surface constituted by densely arranged surface cells and a large amount of leaf surface structures, like trichomes, provided sufficient room for PM in the air to be adhered to leaf surface and could be regarded as an important factor which facilitated *B. thunbergii* to be the most efficient broad-leaved species in our measurement.

On leaf surface of *Q. robur*, much PM was found on the midrib or on the area close to the midrib, while with the distance from the midrib widens on the leaf surface, the amount of captured PM on the leaf surface was found significantly decreased (Fig. 2.8 C2, D2 and E2). A considerable amount of PM was also found locate around the stomata on leaf surface of *Q. robur* (Fig. 2.8 B2).

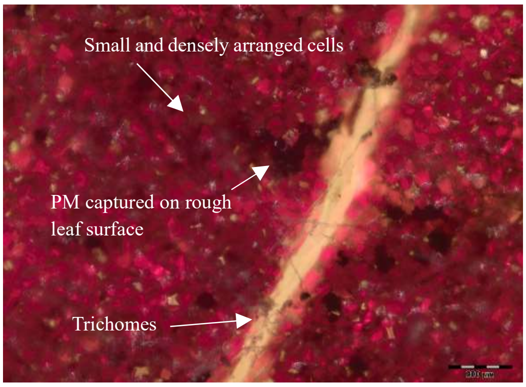
On leaf surface of *F. sylvatica*, a large amount of trichome were found near its midrib and PM with different size fractions was concentrated on surface area close to these trichomes (Fig. 2.8 C1). In contrast, on leaf surface far away from the midrib almost no trichomes were observed, the amount of captured PM on it leaf surface was quite low. (Fig. 2.8 C2). This indicated that trichomes might to be an important surface structure which would facilitate the capture of PM onto leaf surface.

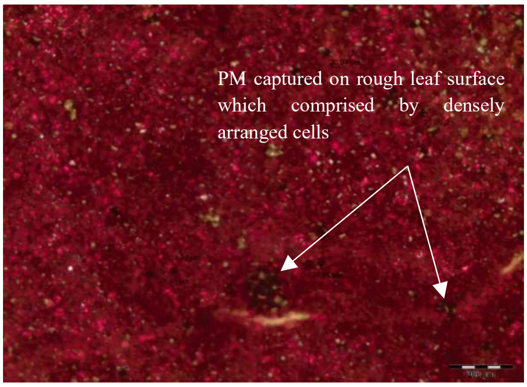
By visual inspection, leaves of *P. laurocerasus* are leathery and smooth, and only a little amount of captured PM was observed on its leaf surface by microscope observation (Fig. 2.8 E2). Because its leathered and smooth leaf surfaces make captured PM hard to be hold on the surface and it would be easily blown away by the subsequent wind, it was the most inefficiency tested species in our measurement. The smooth leaf surface of *P. laurocerasus* indicated that leaf surface with a high level of roughness is a key factor for roadside plants to have a good performance for PM capture.

2.3.6.2 Relationship between leaf surface structural traits and PM distribution characteristics

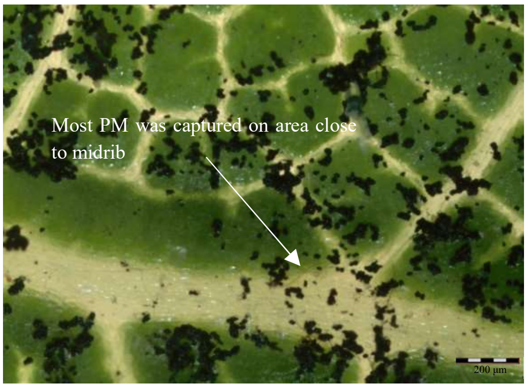
By observing the microscopic images of different leaf surface, most PM was found to be distributed on leaf`s midrib or on leaf surface area close to the midrib. For species which had a medium PM capturing efficiency like *Q. robur* and *T. cordata*, captured PM was found usually concentrate on their leaf midrib (Fig. 2.8 A1, B1, D1). However, with the distance from midrib increases, the amount of captured PM on leaf surface usually significantly decreased (Fig. 2.8 C2, D2). PM with various size fractions tended to be concentrated in grooves and wrinkles, and plant species with a high level of leaf surface roughness, like *B. thunbergii*, usually tended to be the highly efficient, while on leaf surface of species with smooth leaves like *P. laurocerasus,* only little amount of PM could be observed (Fig. 2.8 E2). Besides trichomes and stomata on leaf surface could presumably accelerate the deposition of PM because normally large amount of PM was observed concentrate around these leaf surface structures.

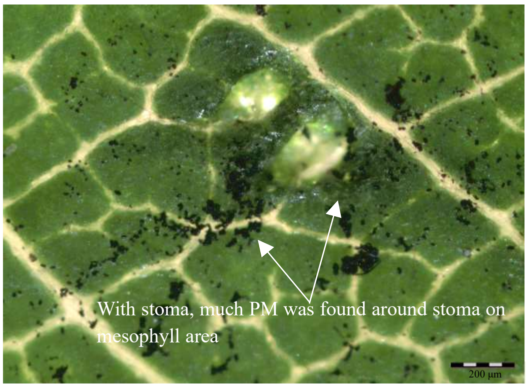
A


Small and densely arranged cells
PM captured on rough
leaf surface
Trichomes

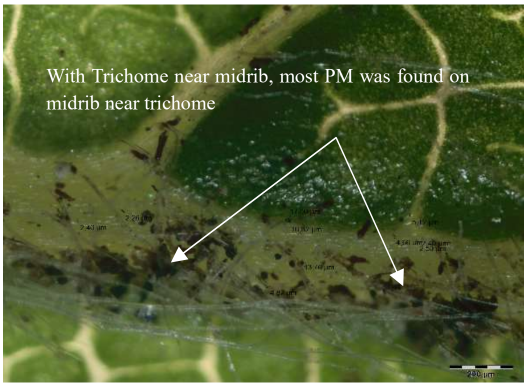

PM captured on rough leaf surface which comprised by densely arranged cells

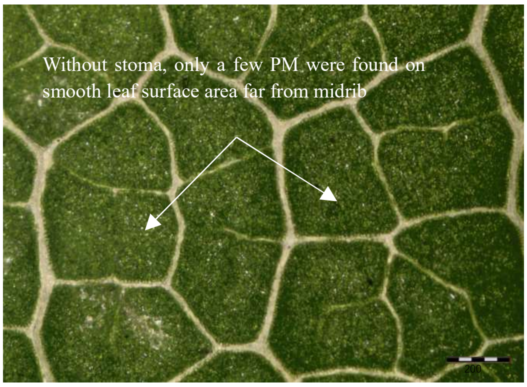
B


Most PM was captured on area close to midrib
200 µm

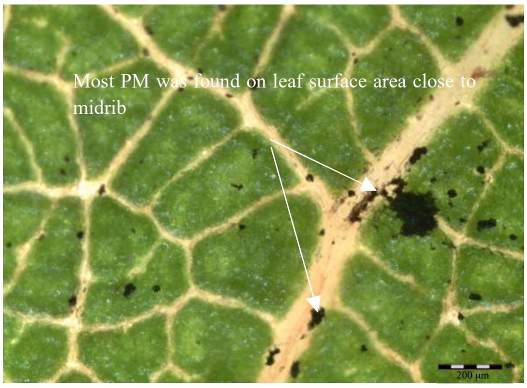

With stoma, much PM was found around stoma on mesophyll area
200 µm

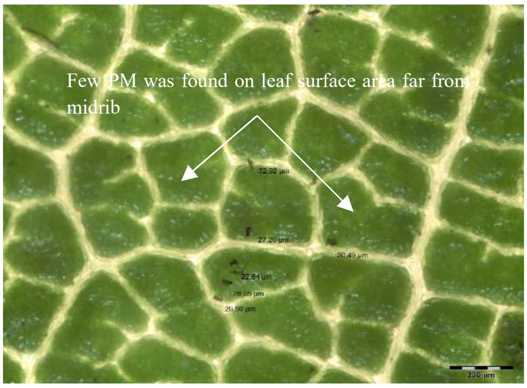
C


With Trichome near midrib, most PM was found on midrib near trichome


Without stoma, only a few PM were found on smooth leaf surface area far from midrib

D


Most PM was found on leaf surface area close to midrib
200 µm


Few PM was found on leaf surface area far from midrib

1 | 2

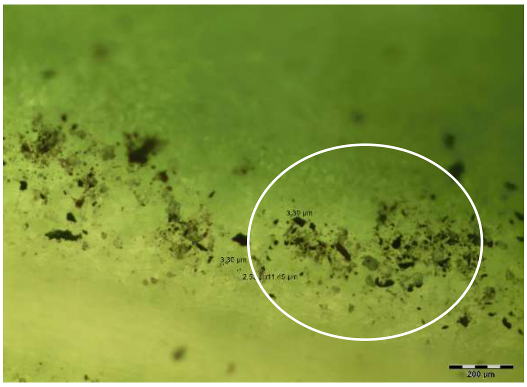
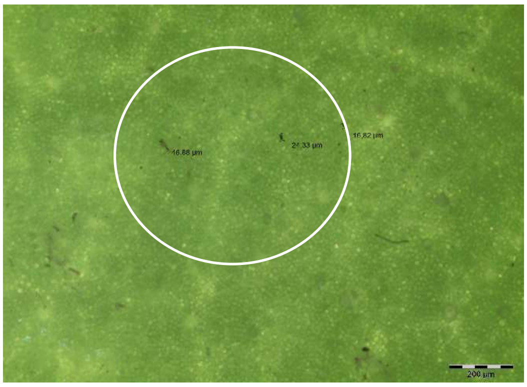
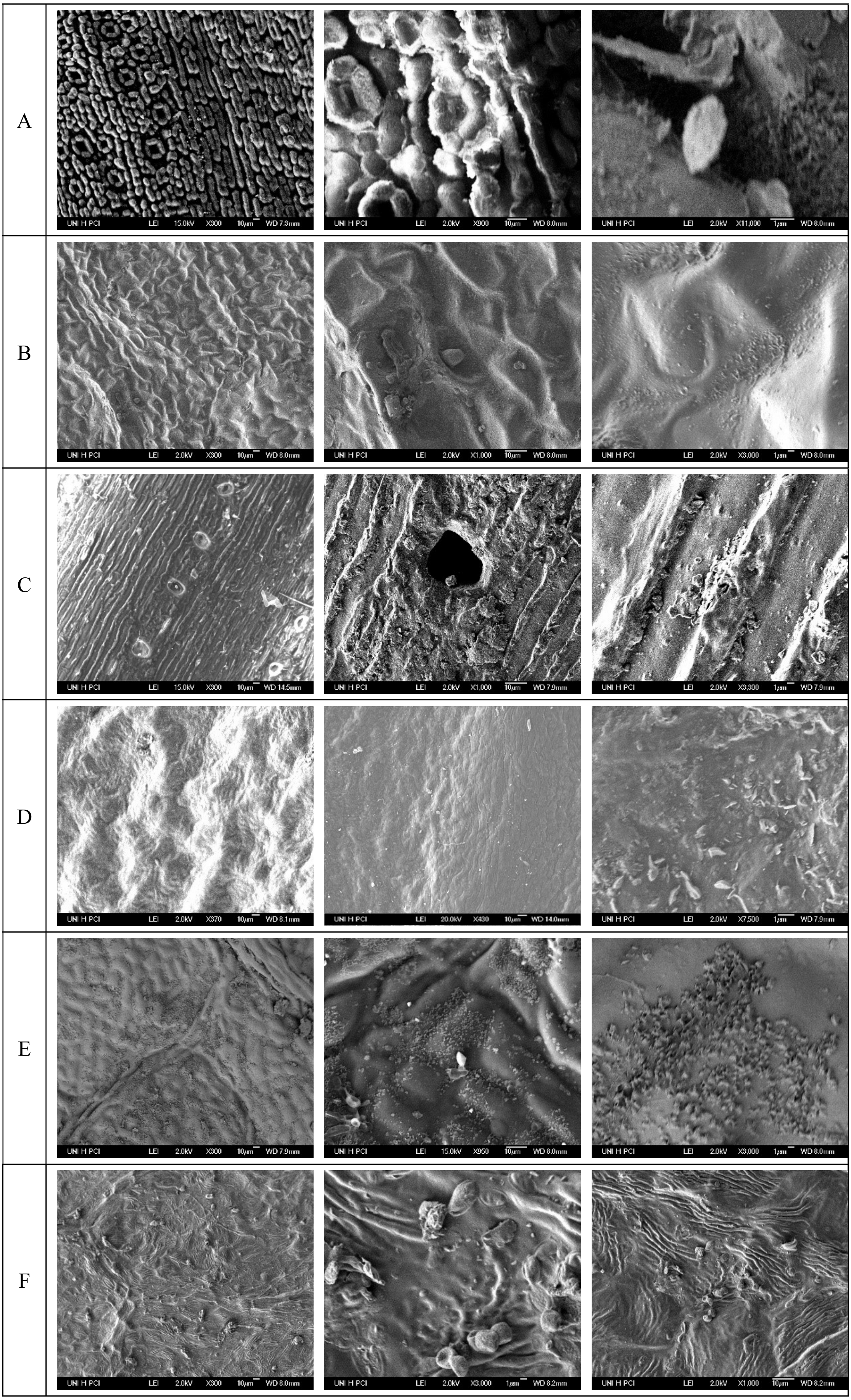
E		
	1	2

Fig. 2.8 Optical microscopic images of PM distribution characteristics on the leaf surface of different species. 1: images of leaf surface areas close to the midrib, 2: images of leaf surface areas far from the midrib. A: *B. thunbergii*; B: *Q. robur*; C: *F. sylvatica*; D: *T. cordata*; E-1: *P. laurocerasus*; (Optical microscopic images are photographed by the author)

2.3.7 Leaf surface characteristics of highly efficient roadside plants by SEM observation

The images taken by SEM confirm that leaf surface roughness is quite important for a certain plant species to have a high PM capturing capacity. Among all tested plants, *T. baccata* had a relatively high capacity for both PM_{10} and $PM_{2.5}$ capture. Its upper leaf surface roughness is also the roughest (Fig. 2.9 A). Plenty of ridges and grooves were densely distributed on its leaf surface, and most of these grooves were quite narrow and deep. PM with different size fractions was found embedded and accumulated in these grooves. A big amount of PM was also observed around stomata. These specific leaf surface traits increased the roughness of upper leaf surface and made *T. baccata* highly effective for PM reduction; as the second most effective plant, leaf surface of *B. thunbergii* was also found quite rough, much wrinkles were observed, and PM with different size fraction was found distribute in the lattice-like structure formed by these wrinkles (Fig. 2.9 B). *P. nigra* has also a relative high PM capturing capacity, its upper leaf surface was covered by a layer of wax except its stomata, this layer of wax was not flat but lumpy. Between every two ridges, there was a sunken area. Unlike the groove area on the upper leaf surface of *T. baccata*, sunken area on the leaf surface of *P. nigra* was relatively shallow, but most particles were still found accumulate on this area (Fig. 2.9 C). With the decrease of PM capturing capacity, the level of upper leaf surface roughness of the tested plants was also found decreased (Fig. 2.9 D-H), for the species with a lower PM capturing capacity (*Fagus sylvatica* and *Carpinus betulus*), their upper leaf surface was found relatively smooth compared to the other 8 tested plant species, a few wrinkles and grooves were observed. like the leaf upper surface observed by optical microscope, leaf upper surface of *P. laurocerasus* was quite smooth, the images taken by SEM also confirmed its smooth leaf surface where only a few tiny wrinkles were observed (Fig. 2.9 K). A relatively rough upper leaf surface contributes to a high PM capturing capacity for roadside plant species.


A
B
C
D
E
F

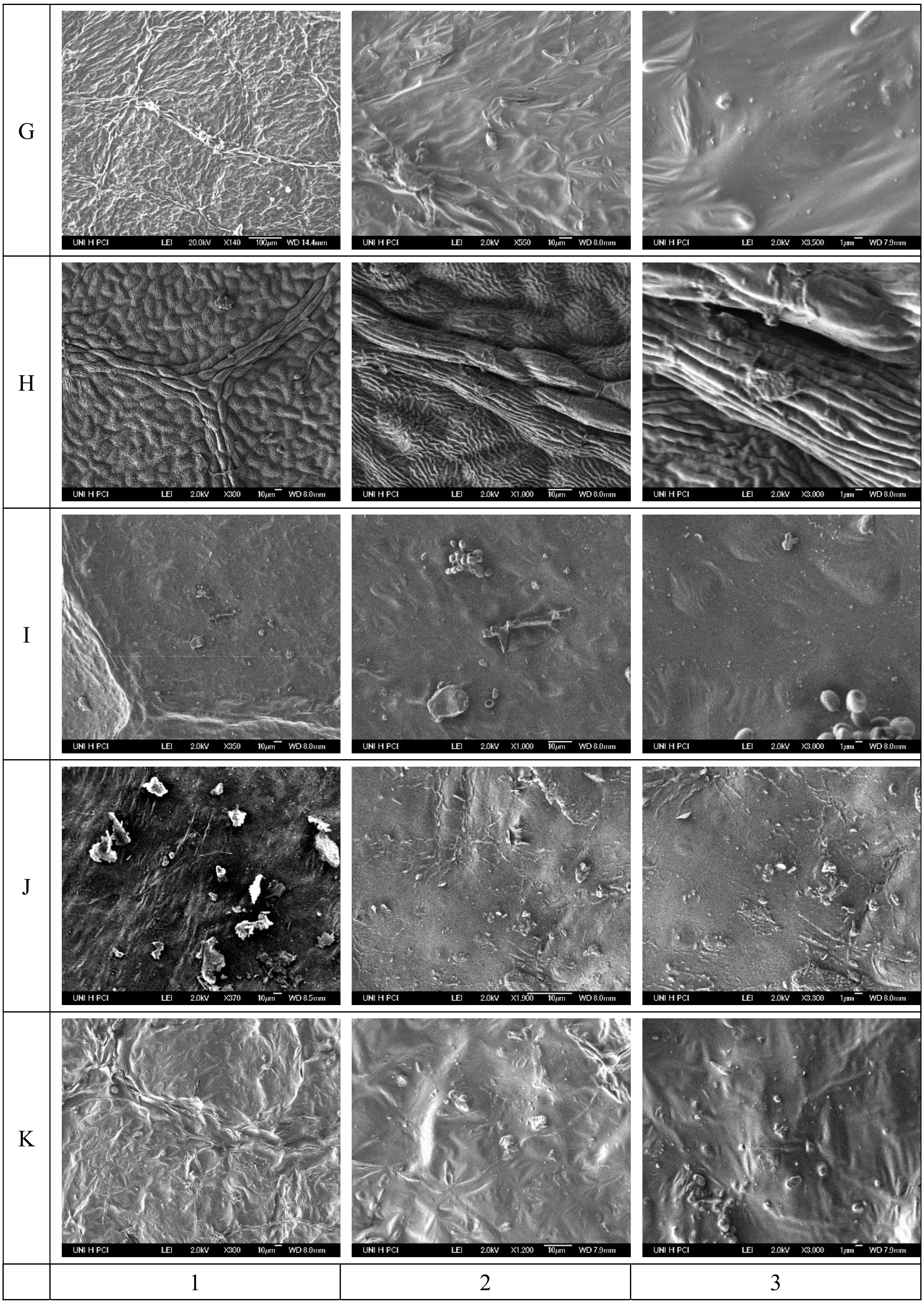


Fig. 2.9 SEM images of the leaf surface of different tested plant species. Different small letter means different magnification, 1: with the magnification by around 300 times; 2: with the magnification by around 1000 times; 3: with the magnification by around 3000 times. Different big letter means different tested plant species, A: *Taxus. baccata;* B: *Berberis. thunbergii*; C: *Pinus. nigra*; D: *Hedera helix;* E: *Quercus robur*; F: *Tilia cordata*; G: *Philadelphus incanus*; H: *Acer platanoides*; I: *Fagus sylvatica;* J: *Prunus laurocerasus*; K: *Carpinus betulus*.

2.4 Discussion

In this chapter, twelve common urban roadside plant species in northern Germany were tested to investigate their PM capturing efficiency. In particular, leaf surface traits were considered. Road traffic is an important source of the airborne PM in this study. Our results support the hypotheses that different plant species present various efficiency levels for PM capture, which depend largely on its vary specific leaf surface characteristics. (Dzierzanowski *et al.* 2011). In particular, our results confirmed the significant otherness among different urban plants for PM capture with various size fractions. We found *B. thunbergii* and *T. baccata* were the two most efficient species for both PM_{10} and $PM_{2.5}$ capture, whereas *C. betulus* and *P. laurocerasus* showed the lowest efficiency. Previous studies have claimed that species with high PM_{10} capturing efficiency also tend to a have high capacity for $PM_{2.5}$ absorption (Zhang *et al.* 2015a). However, one species in our test did not follow this trend. *F. sylvatica* had a relatively high efficiency at capturing PM_{10} which ranked in the middle position among all tested species. However, its efficiency at capturing $PM_{2.5}$ was quite low and ranked in the antepenultimate position among all tested twelve species. This phenomenon may be due to its leaf surface structure. As reported in the literature, plant species with numerous trichomes tend to show larger PM capturing capacity (Song *et al.* 2015). Many trichomes were found on the leaf surface area close to the midrib of *F. sylvatica* and turn out to be quite effective at capturing and retaining relatively large particles such as PM_{10}. However, away from the midrib the leaf surface of *F. sylvatica* was found to be quite smooth. Grooves and wrinkles do not provide enough room to absorb small sized particles such as $PM_{2.5}$, In particular, some captured $PM_{2.5}$ on leaf surface can also be easily removed by the subsequent wind due to the smoothness of the leaf surface.

The leaf surface traits leading the efficiency variation among different urban roadside plant species in this chapter can be divided into three parts. The first part includes leaf shape, leaf area and leaf arrangement on the branches. The second part consist of the leaf surface structural characteristics contributing to change the leaf surface roughness. And the last part is the hydrophilicity which could be quantified by leaf surface contact angle.

Although the leaves of needle-leaved species such as *P. nigra* look quite smooth to the naked eye, its leaf surface is covered with a layer of wax (Tomasz *et al.* 1994, Shao and Zhang 2005).

This surface wax might be an important factor making needle-leaved species the most efficient filter for both PM_{10} and $PM_{2.5}$ capture in our test. Moreover, the needle-leaved species typically show larger PM capturing efficiency also because of its leaf shape and area. Despite the relatively small area per leaf, needle-shaped leaves and other species presenting limited leaf surface areas offer relatively larger surface areas in total for particles in the air to adhere to within the same dimensional range (Chen *et al.* 2017). In addition, in the lower atmosphere, particulate matter, especially fine PM, is mainly transported by the aerodynamic processes such as turbulent eddies, while particle with relatively large size fractions are mainly transported through turbulence processes (Grantz *et al.* 2003). Needle-shaped leaves are densely arranged on branches and thus can decrease the wind speed and make the ambient atmosphere relatively stable, leading to more favorable conditions for PMs to settle in the leaves. Furthermore, mucus oils is secreted on the leaf surface of needle-leaved some species (Zhang *et al.* 2015a), to which particles stick and are prevented from being blown away by the subsequent wind. All these leaf traits make needle-leaved species have higher efficiency for PM capture.

The PM capturing efficiency of broad-leaved species is strongly influenced by leaf structural characteristics such as trichomes, stomata, grooves and wrinkles and the arrangement way of cells on upper epidermis, which contribute to change the roughness of leaf surface. (Freer-Smith *et al.* 2005, Zhao *et al.* 2013, Yang *et al.* 2015a). Our results found that the most effective broad-leaved plant species for PM capture is *B. thunbergii*. By optical microscope observation, Its cells on the upper epidermis are quite small and densely arranged. This kind of cell arrangement leads to many wrinkles and grooves on its leaf surface, making its leaf surface quite wavier and rough (Boize *et al.* 1976). A large number of trichomes with accumulated PM have also been observed close to the midrib of *B. thunbergii*. In addition, through the observation by SEM, a great many wrinkles and grooves were also be found, and a large amount of PM was found concentrated in the lattice-like structure which is formed by these wrinkles. These special characteristics of its leaf surface make its epidermis rough and hairy. For the most effective in this study, the upper leaf surface of *T. baccata* was also found quite rough, plenty deep grooves were found on its upper leaf surface, with rough leaf surface, PM in the air has more chance to be settled on and concentrated onto its leaf surface, and make the species obtain a high PM capturing capacity. Although by the observation of both optical microscope and SEM, the leaf surface of *F. sylvatica* is relatively smooth, we found a big amount of PM tended to be concentrated around the stomata on its upper leaf surface, this discover was consistent with Rai *et al.* (2010). Although the leaf surface of *F. sylvatica* is smooth, a large number of stomata help to increase the roughness of its leaf surface and thus provide *F. sylvatica* with a species with relatively high efficiency for PM capture. Besides, the process of transpiration on leaf surface has also been reported to be accelerated by the existing of a great number of stomata (Räsänen et al. 2013), and with the cooling of leaf surface by transpiration, more PM could be deposited onto leaf surface because of the enhancement of thermophoresis (Burkhardt et al. 2001). Our results confirmed the statement that leaf stoma may facilitate the PM capturing capacity of a certain plant species, and in addition, PM has been reported to get into plants by passing through stomata (Yang *et al.* 2015a). Most captured PMs on the leaves of *T. cordata* and *P. laurocerasus* were also found on the leaf surface with grooves and ridges were found. As the leaf midrib itself is the largest groove and wrinkle on the upper leaf surface, more PM was found close the midrib compared to the leaf surface away from the midrib (Hwang *et al.* 2011). By the SEM observation, with the reduction of the PM capturing capacity of the tested plant species, the level of their leaf surface traits also declined. Compared to the species with a high capturing capacity, the leaf surface of the tested specie with a low capturing capacity was normally much smooth and flat, only a little amount of wrinkle or almost no wrinkles were found on leaf surface of these kinds. Leaf surface roughness is thus a quite important factor for a certain roadside plant to obtain a high capturing capacity for PM reduction. To summarize, plant species with a small leaf area, tensely arranged phyllotaxis and a rough leaf surface which is contributed by specific leaf surface structures such as a densely cell arrangement tended to have a higher PM capturing efficiency, and our third hypothesis in this chapter is rejected.

Besides the leaf surface traits which will affect the capturing capacity, leaf surface hydrophilicity which could be quantified by leaf surface contact angle has also been reported as an important factor for plants to have a high capacity for PM reduction (Wichink Kruit et al. 2008). Negative correlation was reported between the leaf surface contact angle and the PM capturing capacity of plant species. low wettable plant like *Ginkgo biloba* has been reported inefficient to reduce the PM concentration because of its low wettable leaves (Neinhuis and Barthlott 1998). However, the correlation between PM capturing capacity and leaf surface contact angle was insignificant in this study. The correlation index of leaf surface contact angle and capturing capacity for PM10 reduction was 0.28, and the index for PM2.5 was 0.19. The reason caused the discrepancy may be as follows. Firstly, the concentration of PM for roadside plants to reduce was relatively low. As the test was made in September when both deciduous and evergreen plants are in the middle of their growth cycle and their leaves are all fully extended. Former research claimed plants tend to have relatively high PM capturing capacity in winter because the ambient PM concentration in winter is high (Zha et al. 2019). Unlike the condition in winter, as the leaves of plants in September is fully extended, with a big amount of leaves and a relatively large leaf surface area, the average amount of particles for each leaf to capture is relatively low, and thus the correlation between leaf surface contact angle and the capacity for PM reduction is not as significant as it in winter. Secondly, leaf surface epicuticular wax has been reported be eroded by the accumulated particulate matters (Wang et al. 2013). The erosion of leaf wax increases the value of surface contact angle, changes the interfacial area of leaf surface and the particle surface, and makes the adhesion force which keeps PM particles on the leaf surface much weak. As a result, the PM capturing capacity of leaves decreases with the accumulation of particulate matters (Wang et al. 2013). As this study was made in September before a great erosion of leaf surface, the correlation between leaf surface contact angle and PM capturing capacity may be not as significant as it in winter.

The efficiency of plant species to capture PM is affected not only by internal factors like plant height, crown broad and other leaf surface features (Mo *et al.* 2015), but also by other external factors such as wind. Wind may greatly affect the amount of captured PM on the leaf surface, as its speed and direction can change randomly. These peculiarities make wind quite hard to control and to measure in natural condition. Many researchers have tried to perform the measurements in a relatively ideal conditions (Rai *et al.* 2010). As air pollution could be derived from the exhaust of road traffic to a great extent, in cities, traffic intensity may also affect the PM capturing capacity of plants. Leaves of *H. helix* under a high traffic density has been found to show a higher capacity to capture airborne particles than those under non-urban areas (Sternberg *et al.* 2010). Ottelé *et al.* (2010) also has confirmed the positive correlation between the high PM capturing capacity between leaves of *H. helix* and the traffic intensity in Netherlands. Further studies should pay more attention to meteorological and traffic factors in the future. In addition, both deciduous and evergreen roadside plants presented a certain PM capturing efficiency in summer, when their leaves were in the middle of their growth cycle and their leaves are fully extended, whether evergreen species keep to be effective at absorbing urban PM in winter, when deciduous plants lost their capturing ability and the ambient PM concentration is relatively high needs further study.

2.5 Conclusions

The urban roadside plant species tested in this chapter showed notable efficiency differences at capturing particulate matters with different size fractions, including PM_{10} and $PM_{2.5}$. Species with high PM_{10} and $PM_{2.5}$ capturing efficiency were *B. thunbergii*, *P. nigra* and *T. baccata*, while the most inefficient species were *C. betulus* and *P. laurocerasus*. PM tended to be concentrated on leaf surface area close to the midrib, whereas, little amount of captured PM was observed away from the midrib. The leaf shape significantly affects the amount of captured PM on the surface. Needle-leaved species generally showed higher capturing efficiency than broad-leaved species. In addition, leaves with small leaf area and densely arrangement on branches showed higher PM capturing efficiency than those with large leaf area but loosely arranged on branches. For needle-leaved species, the arrangement of leaves on branches, the leaf density, the wax and mucus oil secreted on leaf surface were key traits for PM capture. For broad-leaved species, leaf surface traits including cell arrangements on the upper epidermis, trichomes density, the amount of stomata and midrib characteristics which could increase leaf surface roughness can significantly promote the efficiency of leaf surface for PM capture. The correlation between leaf surface contact angle and the PM capturing capacity was insignificant for all the tested plant species in this study, the hydrophilicity of leaf surface had limited effects on roadside plants for their PM reduction capacity in September, when leaves are in the middle of their growth cycles.

The roadside plant species analyzed in this chapter are species commonly grown in Hanover. Some species showed significant efficiency at capturing PM which was mainly caused by urban road traffic. Selecting effective roadside plant species for future urban planning is thus a feasible and eco-friendly policy option to decrease urban air pollution. Leaf traits found in this study provide a scientific basis for roadside plant species selection.

Chapter 3 Particulate matter diminishing efficiency of roadside evergreen plants during winter

3.1 Background and hypotheses

As a global consensus, air pollution is regarded as one of the greatest threats to all human beings (Kennish 2002, Gupta *et al.* 2016). It has been confirmed that air pollution poses a serious threat to human quality of life and decreases the life expectancy of residents who live in the urban areas (WHO 2003). In Italy, the death number attributed to the exposure to traffic-related air pollution was even over three thousand (GBD 2013). As the main contaminant of urban air pollution, particulate matter (PM) is a mixture of solids and liquids, comprising black carbon, chemical elements, heavy metals, polycyclic aromatic hydrocarbons and other substances in the air (Bell *et al.* 2011). Besides exhausted by vehicles, urban PM caused by transporting system is also from non-exhaust emissions such as brake disks and mechanical wear. Non-exhaust emission contributes mainly to coarse and fine PM, while exhaust emissions generate a mass of fine particles (Thorpe *et al.* 2007, Abu-Allaban *et al.* 2010, Kam *et al.* 2012). Ultrafine PM is reported mostly from transport and photochemical reactions in atmosphere (Chow 2006). Because of its small particle sizes and toxic components, exposure to air PM, especially to PM_{10} and $PM_{2.5}$ results in serious damage to human health, especially during winter months when the ambient urban PM concentration is relatively high (Knaapen *et al.* 2004, Coronas *et al.* 2009, Sturm 2010).

Former studies have confirmed the distinctive effect of city vegetation as a cost-effective method which has significant scavenging functions for urban PM (Escobedo *et al.* 2008). Yang *et al.* (2005) found 772 tons of PM_{10} in Beijing are removed in one year by city vegetation, 0.22 million tons of PM_{10} are removed by shrubs and tresses in the USA every year (Nowak *et al.* 2006) and 5.3% concentration of SO_2, 2.6% concentration of NO_2 are decreased internal a city woodland at a distance of 50 to 100 m in China (Yin *et al.* 2011). Among all city plants, Tree species is considered to be highly efficient because of its crowns (McDonald *et al.* 2007). Big tree crown would cause turbulent air movements which accelerate PM deposition onto leaves (Fowler *et al.*

1989). In addition, 2% to 10% concentration of PM could be reduced if one-quarter urban area is covered by trees (McDonald *et al.* 2007). Plants with specific structural leaf surface characteristics are also reported quite efficient for PM capturing (Nowak *et al.* 2006). Even some unique surface traits like trichomes are reported to be developed to increase the PM capturing efficiency of leaves (Burkhardt 2010). For broad-leaved species, leaf surface roughness is the key factor, and for needle-leaved species, small and needle-shaped leaves and a thicker epicuticular wax on leaf surface greatly accelerate their efficiency for PM retaining (Kaupp *et al.* 2000, Jouraeva *et al.* 2002). In addition, needle-leaved species are claimed normally to possess higher efficiency value than it of broad-leaved species (Beckett *et al.* 1998).

Vegetation in urban area has significant effects on PM diminishing and city air quality improving, but most studies focused on the mechanisms of PM deposition of deciduous species during growing seasons like in summer. Although former studies have confirmed the high PM capturing efficiency of evergreen plant species (Freer-Smith *et al.* 2005), less is known about their PM removal performance during winter months, especially when ambient air pollution concentration is relatively high (Pikridas *et al.* 2013) and most deciduous plants lose their leaves for PM capturing. In addition, as captured PM on leaf surface can be later washed off by dew or by rain, the correlation between leaf surface hydrophilicity of evergreen species and their PM capturing efficiency has been rarely reported.

Based on the results and the analysis from chapter 2, in this chapter, we compared four common roadside evergreen species (*P. laurocerasus*, *H. helix*, *T. baccata and P. nigra*) which are widely cultivated in urban area, to further discuss the foliage efficiency of evergreen roadside plants for PM capturing during winter (from November to March). The main objectives of this chapter is to evaluate PM capturing efficiency of evergreen roadside plant species and its variation during different winter months; to gain a further understanding about the leaf surface structural differences which led to the efficiency variation between different species by SEM observation; and to discuss the correlation between leaf surface hydrophilicity and its PM capturing efficiency. In order to have a better evaluation, the preliminary hypotheses of this chapter are as follows: (1) the foliage PM capturing efficiency varies between different evergreen species and the efficiency value of each species increases along with time during winter. (2) Taking all winter months as a whole, needle-leaved species still shows higher PM capturing efficiency than broad-leaved species. (3) Positive correlation exists between leaf surface hydrophilicity and its PM capturing efficiency. As the choice of species would have great effects on the performance of PM filtering for urban vegetation, this study provides a scientific basis.

3.2 Materials and methods

3.2.1 Description of sampling fields

The test in this chapter was carried out in Hanover, the capital city of the state Lower Saxony, Germany. The average temperature between November and March ranges from 2.9 ℃ to 5.6 ℃, the average total rainfall ranges from 40-59 mm and the wind direction during winter is southwest. Like most large cities, Hanover also suffers from various kinds of pollution, especially air pollution which is caused by daily urban transportation. In winter, as the leaves of deciduous roadside plants fall and die, air pollution near city streets becomes far worse.

Leaf samples were harvested alongside one main street in northwestern Hanover, which is located in the "environmental zone" which is designated by the city government (Hannover 2011). In this zone, there are no industrial facilities and the main pollution sources are city road traffic and the residental area. The sampling area chosen was along Nienburger Street, between the Schneiderberg-Wilhelm-Busch-Museum and the Herrenhaeusen Gaerten metro stations (52°23'29.1" - 52°23'05.5"N, 9°42'04.6" - 9°42'45.7"E). The street is a two-way street which is that is approximately 8 metres wide and has two metro tracks running down one side. The sampling points were randomly set alongside both sides of the sampling-used street (marked by the red line in Fig. 3.1), and all sampling points are away from the main intersection and traffic lights to avoid the relatively higher pollutant concentration caused by idling cars. For each tested species, three sampling points were selected, and the sampling points were approximately 50 m - 200 m away from each other. The location of the sampling points is listed in Table 3.1 and all sampling points are marked with different symbols in Fig. 3.1.

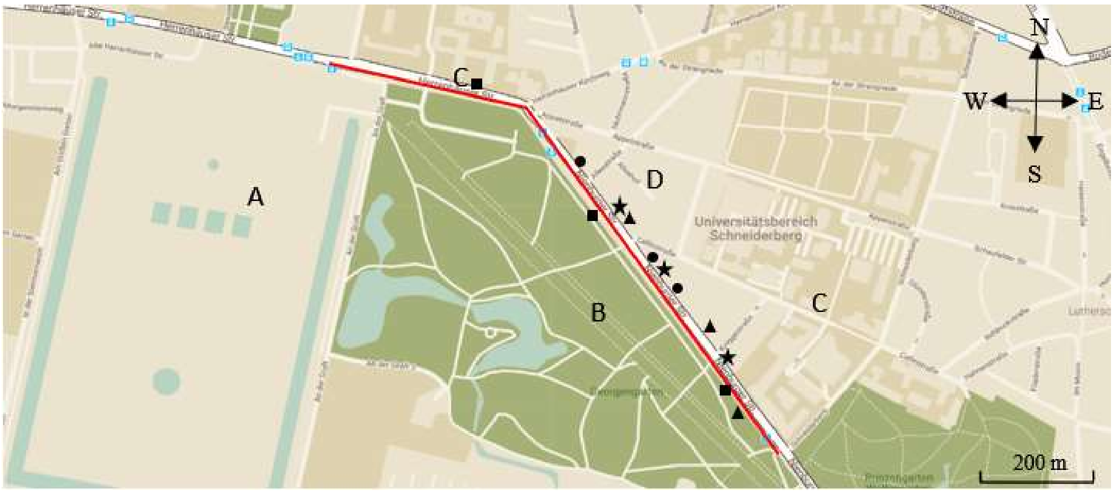


Fig. 3.1 Map of sampling used street and the location of the sampling points in Hanover, Germany. Red line: sampling used area along the street; A: Herrenhaeuser Garden; B: National park "Georgengarten"; C: University campuses; D: Residential area. Black triangle: sampling points for *Taxus baccata*; black dot: sampling points for *Hedera helix*; black square: sampling points for *Pinus nigra*; black star: sampling points for *Prunus laurocerasus*. (Map remodified by the author based on the map: www.google.com/intl/de/earth, changed)

3.2.2 Tested plant species and sampling methods

In order to explore the capacity of different evergreen species to capture PM during winter, *Prunus laurocerasus*, *Hedera helix*, *Taxus baccata* and *Pinus nigra* were chosen as tested the plant species. These four evergreen species are commonly cultivated along streets in Hanover. All plants had already been growing in the selected location for several years and were in good condition. Characteristics of the tested species are shown in table 3.1.

Tab. 3.1: Types and characteristics of tested plant species. SN: Scientific name of plant species; F: Family; H: Habit; PT: Plant type; LS: Leaf shapes; MA: the mean leaf area (cm2 leaf -1); AH: Average plant height (m); CD: Average crown diameter (m); S: Shrub; T: Tree; Evg.: Evergreen.

SN	F	H	PT	LS	MA	AH	CD
Prunus laurocerasus	*Rosaceae*	S	Evg.	Leathery shiny broad	54.90	3.4 ± 0.2	3.3 ± 0.1
Hedera helix	*Araliaceae*	S	Evg.	Five-lobed juvenile broad	27.87	2.6 ± 0.1	6.8 ± 1.1
Taxus baccata	*Taxaceae*	T	Evg.	Needle	0.79	6.6 ± 0.6	5.0 ± 0.4
Pinus nigra	*Pinaceae*	T	Evg.	Needle	5.05	5.6 ± 0.2	5.2 ± 0.3

For each species, three sampling points were randomly set along the sampling-street, and each sampling point was five to seven meters away from the street curb. Leaves from the outermost layers of the canopy that directly faced to the street were collected from each sampling point as tested material. The sampling height at each sampling point was between 1.5 m to 2 m above from the ground. Samples were taken once a month from November 2017 to March 2018, five days after a continuous rainfall with an accumulated precipitation of 15 mm. This process was selected because most particles (70%) on the leaf surface from the outermost canopy could be considered to have been completely washed off (Wang *et al.* 2015a, Xu *et al.* 2017). For each broad-leaved species, twelve individual leaves were gathered; and for each needle-leaved species, fifty leaves were harvested randomly from each sampling point within a sampling area 1.5 to 2 meters above from the ground. In total, 372 blades were collected in each month (72 blades from broad-leaved species and 300 blades from needle-leaved species). All sampled plants were in similar growing conditions, and all sampled leaves were healthy without disease or pests. In order to prevent further contamination, disposable gloves were used when harvesting the leaves by pinching the petioles. All samples were then packed in a valve bag and kept in a clean lab refrigerator at a temperature of 8 °C for further laboratory analysis.

3.2.3 Testing methods and statistic

3.2.3.1 Measurements of the amount of captured PM on leaf surface

Based on the original protocol by Dzierzanowski *et al.* (2011) and by Sæbø *et al.* (2012) which collected 3 fraction of PM (large: $PM_{>10}$, coarse: $PM_{10\text{-}2.5}$ and fine: $PM_{<2.5}$), improved weight difference protocol patented by Liu *et al.* (2014) was applied to quantify the amount of captured PM_{10} and $PM_{2.5}$ on each unit leaf surface area. All samples were dipped in 200 mL of distilled water for 5 min and then both sides of the leaves were scrubbed with a non-depilatory brush to ensure that all PM from the leaf surface was transferred into the water. Two hundred millilitres of distilled water was used flush the leaf surface for three times. The total of 400 mL of turbid solution was weighed, and the weight of the solution was recorded as M_{ST}. An amount of 50 mL turbid solution was placed in a plastic test tube after 5 min of stirring, and its weight was recorded as M_{S50}. The 50 mL turbid solution was dried in the test tube using a vacuum freeze-drier (Alpha 1-2 LD plus Entry Freeze Dryer Package, Martin Christ, Australia) for 72 h until all solution in the tube was completely dried out. The weight of the particles left in the dried test tube was recorded as M_{SP}.

The remaining 350 mL of the solution was filtered through a filtration apparatus equipped with a 47 mm glass filter funnel connected to a vacuum pump (KNF Neuberger, USA). The first filter was a nylon hydrophilic membrane with a bore diameter of 10 μm (HNWP04700, Millipore, Ireland, 2017). The filtered solution then passed through an extraction filtration apparatus again for a second time using a filter paper with a bore diameter of 2.5 μm (CAT-1442-047, Whatman Labware Products, UK, 2017). All fibre membranes and filter papers were then dried in a drying oven with a temperature of 60 °C for two hours until all filters were completely dried. The filter papers and fibre membranes were then placed in a polytetrafluoroethylene desiccator under a constant temperature conditions for two hours until their temperature reached room temperature to prevent further interference during the next weighing process. The dried filter papers and membranes were weighed to calculate the weight difference before and after filtration. The weight difference of the membranes was recorded as $M_{P>10}$, and the weight difference of the filter papers was recorded as $M_{P2.5\text{-}10.}$ The following formula was used to calculate the amount of captured PM_{10} and $PM_{2.5}$ on leaves of different evergreen species (Liu *et al.* 2014). The PM capturing efficiency was defined as the amount of captured PM on each unit of leaf surface area.

$$MT_P = M_{SP} \times \frac{M_{ST}}{M_{S50}}$$

$$MT_{PM>1} = \frac{M_{PM>10} \times M_{ST}}{M_{ST} - M_{S50}}$$

$$MT_{PM2.5-10} = \frac{M_{PM2.5-10} \times M_{ST}}{M_{ST} - M_{S50}}$$

$$MT_{PM2.5} = MT_P - MT_{PM>1} - MT_{PM2.5-10}$$

$$MT_{PM10} = MT_{PM2.5} + MT_{PM2.5-10}$$

Where MT_P = Weight of total particulate matter (PM_{10} and $PM_{2.5}$); $MT_{PM>10}$ = Weight of total particulate matter with a grain diameter greater than 10 μm; $MT_{PM2.5\text{-}10}$ = Weight of total particles with a grain diameter between 2.5 and 10 μm; $MT_{PM2.5}$ = Weight of total $PM_{2.5}$; MT_{PM10} = Weight of total PM_{10}; M_{SP} = Weight of particulate matters in 50 mL solution; M_{ST} = Weight of the turbid solution; M_{S50} = Weight of 50 mL solution which was taken from 400 mL turbid solution; $M_{PM>10}$ = Weight of PM which grain diameter is greater than 10 μm; $M_{PM2.5\text{-}10}$ = Weight of PM which grain diameter is between 10 μm and 2.5 μm.

3.2.3.2 Measurement of leaf surface area

For broad-leaved species, the leaves were first scanned (MP C3004exS, Ricoh, Tokyo, Japan) and the scanned images were transformed into black and white images, in which the leaf surface area could be seen in black against a white background. The image processing software "ImageJ" (Version 1.40 National Institutes of Health, USA) was used to calculate the black leaf surface area in the image. For needle-leaved species such as *Pinus nigra*, the length and width of the leaves were measured and the leaf surface area was calculated using the following formula (Pérez-Harguindeguy *et al.* 2013, Zhang *et al.* 2017a):

$$S = \frac{\pi DL}{2}$$

Where S = leaf area of needle-leaved species, D = breadth of each needle leaf, L = length of each needle leaf.

3.2.3.3 SEM observation for upper leaf surface morphology

To assess the relationship between the upper leaf surface micro-morphological traits and the PM capturing efficiency of different evergreen species, leaf samples were scanned by a field emission scanning electron microscope (SEM) (JSM 6700F, JEOL, Japan) operated in the vacuum mode. The scanning and the test were performed on the same day to prevent the desiccation of the leaves and the alteration of leaf surface micro-morphology. The upper leaf surface near the center of the lamina was cut to a 1 cm x 1 cm square and then was pasted to glass slide by double-sided tape as the sample to be observed. Then, samples were coated with a slice of carbon using a high vacuum sputter coater (EM SCD 500, Leica, Germany) to increase electrical conductivity and to improve optical transmission. For each species, images were scanned at different magnification levels (90-3000 ×) to allow for better observation.

3.2.3.4 Measurement of the leaf surface contact angle (CA)

Both sides of the leaves from each tested evergreen species were flushed three times with 100 mL distilled water. All leaves were dried in the shade at room temperature until both sides were completely dry. The flat upper leaf surface near midrib was cut to 1cm x 1cm square and pasted it onto a glass slide with double-sided adhesive tape as the samples for the next measurement. A drop contact angle system (OCA 15EC, Dataphysics, Germany) was used for leaf surface CA measurement. Each pure water on the leaf surface was 1 μL Four repetitions were made for each evergreen species, and the average leaf surface CA was calculated by SCA 20 software (Dataphysics Instruments, Germany) by calculating the average value of the CA on the right and the left side of the water drop (Fig. 3.2).

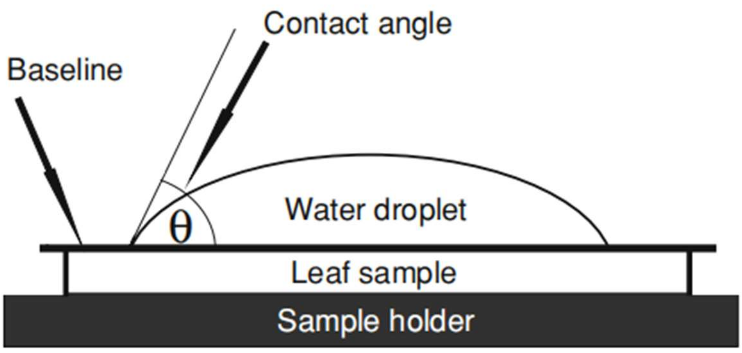


Fig. 3.2 Measurement of contact angle (θ) between the baseline and the point of contact angle of a 1-μL water droplet with the surface of a leaf sample. (by Aryal *et al*. 2010, changed)

3.2.3.5 Statistical analysis

Statistical analysis was performed with SPSS Statistics version 22.0 (IBM, New York, USA).One-way ANOVA was performed to determine whether significant statistical differences exist in the amount of accumulated PM_{10} and $PM_{2.5}$ on the leaf surface of the different evergreen species within the same winter month; this analysis also determined whether there was a significant difference in leaf surface CA among the different evergreen species. The results are deemed significant at $P < 0.05$. Pearson correlation analysis was conducted to evaluate the correlation between the leaf surface contact angle and the PM capturing capacity of tested evergreen plants in winter.

3.3 Results

3.3.1 PM capturing efficiency of common roadside evergreen species during winter

3.3.1.1 Efficiency of different evergreen species during the same winter month

The efficiency for PM_{10} capturing varied among the different evergreen species in the same winter month (Fig. 3.3). In December, all species showed a relatively high PM_{10} capturing efficiency. *P. nigra* was the most efficient species (0.3413 ± 0.0693 mg cm^{-2}) and captured the highest proportion (39.65%) of PM_{10} among all tested evergreen species, while *H. helix* showed the lowest efficiency value (0.1613 ± 0.0138 mg cm^{-2}). There were significant differences between *P. nigra* and the other three tested evergreen species in terms of PM_{10} capturing ($P < 0.05$), but within the other three species, no significant difference was found ($P > 0.05$). In January, *T. baccata* was the most efficient species (0.2259 ± 0.2701 mg cm^{-2}), contributing 48.23% of the total PM_{10} capture, while *P. nigra* was the species with lowest efficiency value (0.0696 ± 0.0483 mg cm^{-2}). In November and February, the PM_{10} capture efficiency of each tested species was relatively low. And in March, all tested species reached their lowest PM_{10} capturing efficiency respectively. The most efficient species in March was still *P. nigra*, but its efficiency value declined significantly to 0.0770 ± 0.0370 mg cm^{-2} (with 38.23% of the captured PM_{10}). *H. helix* was still the most inefficient tested species (0.0383 ± 0.0130 mg cm^{-2}), capturing only 19.02%. There was no statistical efficiency difference between each tested evergreen species for PM_{10} capture in March ($P > 0.05$).

The efficiency of four tested evergreen species for $PM_{2.5}$ capturing also varied in each winter month (Fig. 3.4). Similar to the efficiency for PM_{10} capture, all tested species showed relatively high $PM_{2.5}$ capturing efficiency in December. *P. nigra* captured the highest amount of $PM_{2.5}$ onto its leaf surface (0.3189 ± 0.0382 mg cm^{-2}) which were the highest proportion (38.99%) of total captured $PM_{2.5}$, while *H. helix* was the most inefficient species (0.1557 ± 0.0078 mg cm^{-2}) in the month. Significant differences were found for $PM_{2.5}$ capture between *P. nigra* and the other three evergreen species ($P < 0.05$), but within the three other species, no statistical difference was found ($P > 0.05$). In January, *T. baccata* showed the highest $PM_{2.5}$ capturing efficiency (0.2109 ± 0.1544 mg cm^{-2}, 51.10%), but *P. nigra* was the weakest (0.0554 ± 0.0258 mg cm^{-2}, 13.43%). There were significant statistical differences between *T. baccata* and the other three tested species ($P > 0.05$) for $PM_{2.5}$ absorbing efficiency, but no significant difference existed within the other three species. In February and November, the amount of captured $PM_{2.5}$ by each tested species declined. And in March, each tested evergreen species reached their lowest $PM_{2.5}$ capturing efficiency value. Although *P. nigra* was the most efficient species in March, its value declined to 0.0719 ± 0.0224 mg cm^{-2}. *H. helix* was still the most inefficient species in March for $PM_{2.5}$ absorbing (0.0362 ± 0.0078 mg cm^{-2}, 19.55%).

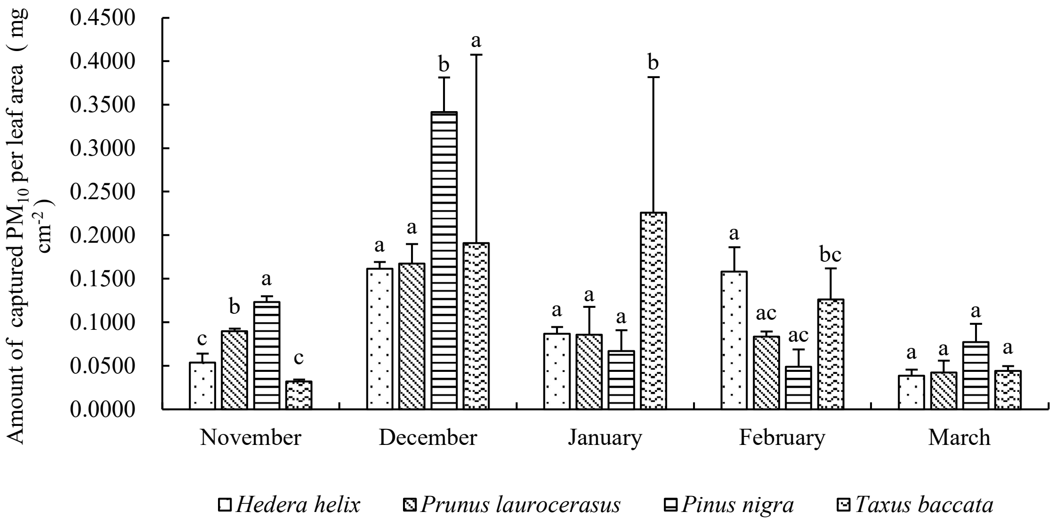


Fig. 3.3 PM_{10} capturing efficiency of different evergreen species in the same winter months. Vertical bars represent the standard error; Statistic analysis by one-way ANOVA showed that there are significant differences between different tested species ($P < 0.05$); Data are mean ± SE. Within the same winter month, the same letter means there is no significant statistical difference at the 0.05 level. (Based on the original data from Table C-2, Appendix C)

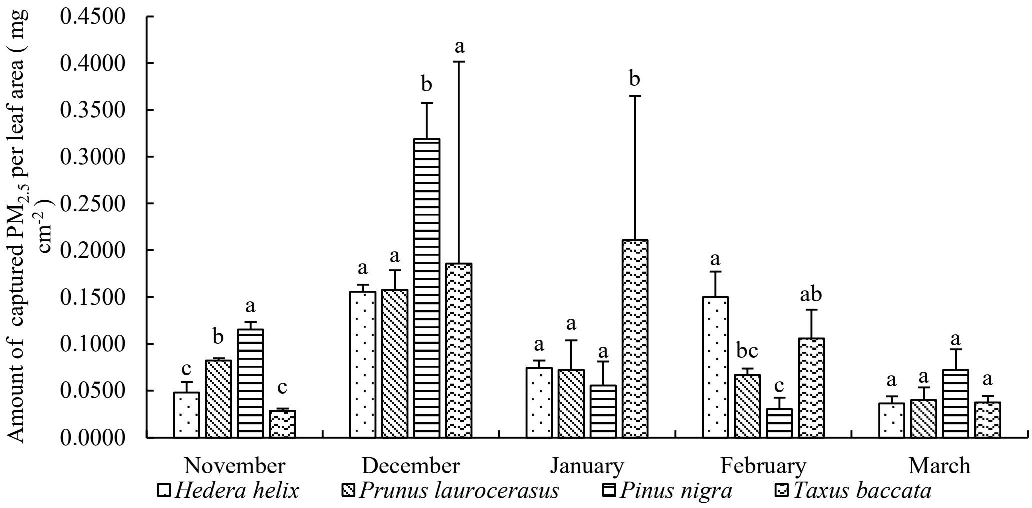


Fig. 3.4 $PM_{2.5}$ retention efficiency of different evergreen species in the same winter months. Vertical bars represent the standard error; Statistic analysis by one-way ANOVA showed that there are significant differences between different tested species ($P < 0.05$); Data are mean ± SE. Within the same winter month, the same letter means there is no significant statistical difference at the 0.05 level. (Based on the original data from Table C-2, Appendix C)

3.3.1.2 Efficiency of the same evergreen species during different winter months

The PM_{10} capturing efficiency of each tested evergreen plant species varied in the different winter months (Fig. 3.5). Among all tested species, *P. nigra* showed a relatively high efficiency for PM_{10} capturing in early of winter, and its PM_{10} capturing efficiency value increased

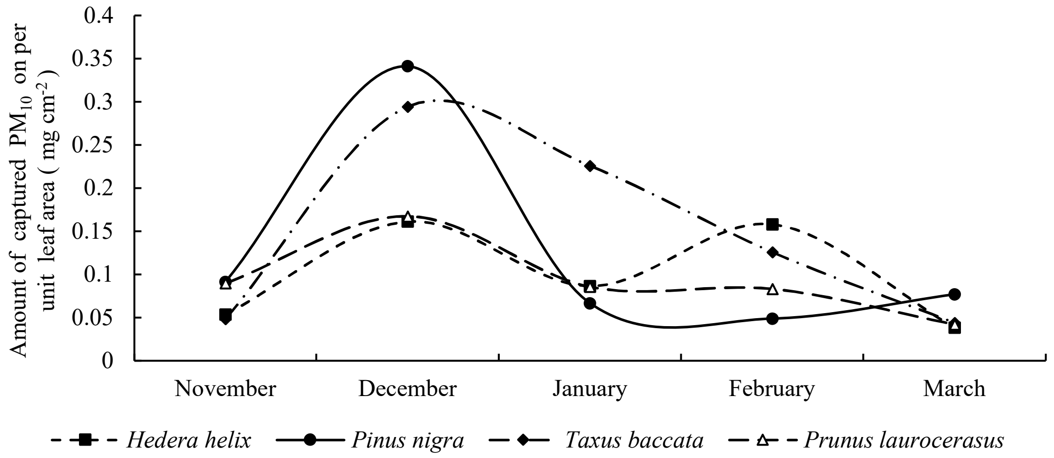


Fig.3.5 Change of PM_{10} capturing efficiency for the same evergreen species during different winter months. (Based on the original data from Table C-2, Appendix C)

sharply from November and reached its peak in December (0.3413 ± 0.0400 mg cm^{-2}). However, the value declined fast to its minimum in February (0.0489 ± 0.0201 mg cm^{-2}) and only increased slightly in March. *T. baccata* also showed a sharp increasing trend at the start of the winter for PM_{10} capturing. From November, its PM_{10} capturing efficiency increased sharply and reached its peak value in December (0.2944 ± 0.1478 mg cm^{-2}), then the value declined gradually to its minimum in March (0.0440 ± 0.0056 mg cm^{-2}). *H. helix* and *P. laurocerasus* demonstrated a similar changing trend for PM_{10} capturing during the winter, but *H. helix* recorded two peak value in December and in February (0.1612 ± 0.0080 mg cm^{-2} and 0.1581 ± 0.0281 mg cm^{-2}), while *P. laurocerasus* reached its peak value only once in December (0.1674 ± 0.0224 mg cm^{-2}). The efficiency of the two broad-leaved species changed much slightly during winter.

The $PM_{2.5}$ capturing efficiency for the same evergreen species was also different in different winter months (Fig. 3.6). Similar to its efficiency for PM_{10}, *P. nigra* recorded its highest efficiency for its $PM_{2.5}$ at the beginning of the winter months. From November, its efficiency increased sharply and reached its peak value in December (0.3189 ± 0.0382 mg cm^{-2}), while it decreased fast to its minimum (0.0489 ± 0.0201 mg cm^{-2}) in February and only slightly increased in March. *T. baccata* was also an efficient species for $PM_{2.5}$ capturing. From November, its efficiency value increased sharply to its peak in December (0.2920 ± 0.1459 mg cm^{-2}) and then gradually declined to its minimum in March (0.0375 ± 0.0068 mg cm^{-2}). *H. helix* and *P. laurocerasus* demonstrated a similar changing trend for $PM_{2.5}$ capturing efficiency during winter.

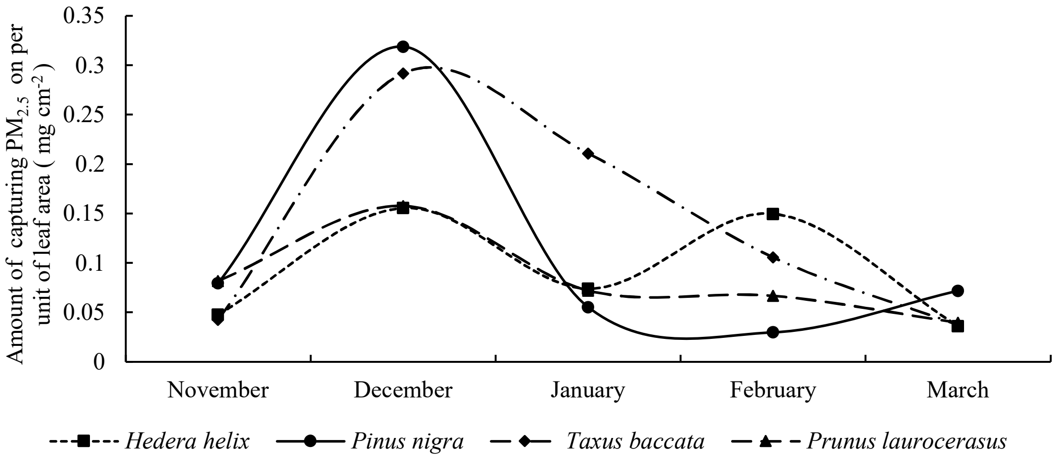


Fig. 3.6 Change of $PM_{2.5}$ capturing efficiency for the same evergreen species during different winter months. (Based on the original data from Table C-2, Appendix C)

H. helix reached its peak value twice in December and in February (0.1557 ± 0.0078 mg cm^{-2} and 0.1498 ± 0.0277 mg cm^{-2} respectively), while *P. laurocerasus* showed its highest efficiency only in December (0.1578 ± 0.0210 mg cm^{-2}). The rate of changing for the capturing capacity of these two broad-leaved species was quite low.

3.3.1.3 Efficiency of different evergreen species during the whole winter

Taking all the winter months as a whole, the PM_{10} capturing efficiency of the different evergreen species varied (Fig. 3.7). *T. baccata*, in general, showed the highest efficiency than any other tested species (0.1477 ± 0.0454 mg cm^{-2}), *P. nigra* was the second most efficient species (0.1251 ± 0.0311 mg cm^{-2}), while *H. helix* and *P. laurocerasus* showed relatively low efficiency during the entire winter (0.0996 ± 0.0148 mg cm^{-2} and 0.0937 ± 0.0130 mg cm^{-2} respectively). No significant efficiency differences were found among different evergreen species for PM_{10} capture.

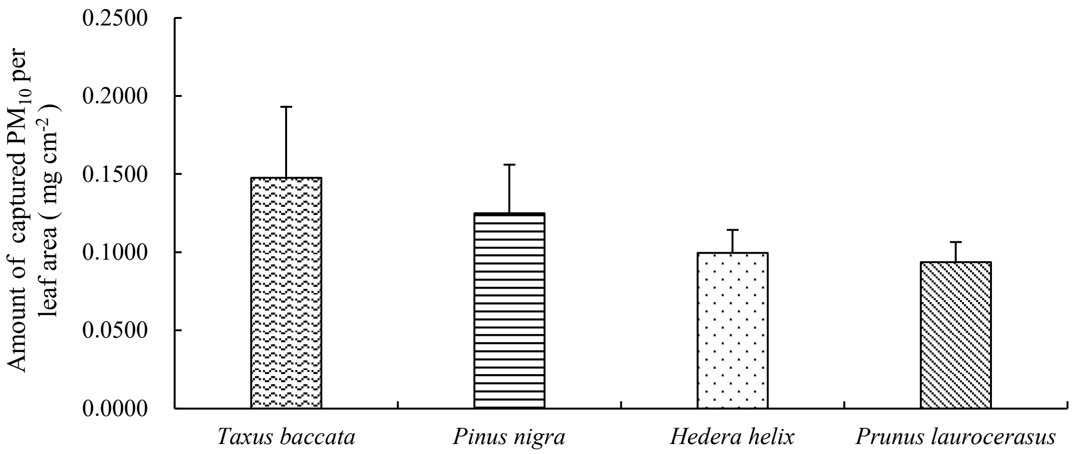


Fig. 3.7 PM_{10} capturing efficiency of different evergreen species during the whole winter. Vertical bars represent

the standard error; Data are mean ± SE. (Based on the original data from Table C-2, Appendix C)

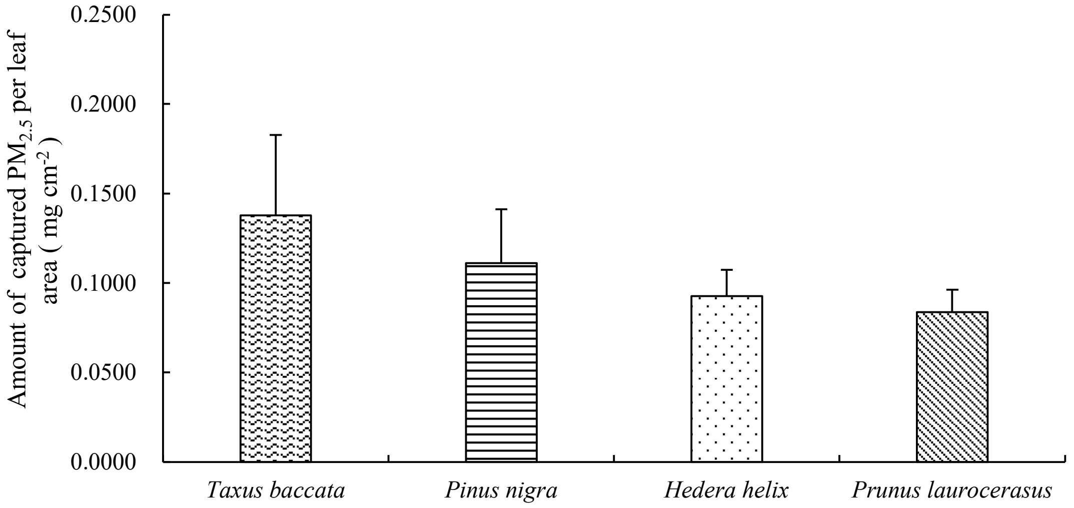


Fig. 3.8 $PM_{2.5}$ capturing efficiency of different evergreen species during the whole winter. Vertical bars represent the standard error; Data are mean ± SE. (Based on the original data from Table C-2, Appendix C)

As was true for PM_{10} capture, the different tested species showed varying capacities for $PM_{2.5}$ capture during the whole winter (Fig. 3.8). In general, *T. baccata* was still the evergreen species that demonstrated the highest capturing efficiency for $PM_{2.5}$ (0.1379 ± 0.0450 mg cm^{-2}), and *P.nigra* ranked the second place (0.1112 ± 0.0301 mg cm^{-2}), *H. helix* exhibited a moderate $PM_{2.5}$ capturing efficiency (0.0928 ± 0.0146 mg cm^{-2}), but *P.laurocerasus* maintained the lowest efficiency for $PM_{2.5}$ capture throughout the entire winter (0.0837 ± 0.0127 mg cm^{-2}). Neither significant statistical differences were found among the different evergreen species for $PM_{2.5}$ capturing during the whole winter.

3.3.2 Relationship between the PM capturing efficiency of the different evergreen species and their upper leaf surface micro-morphological traits

3.3.2.1 Relationship between the PM capturing efficiency and upper leaf surface micro-morphological traits of *Taxus baccata*

By observing the micro-morphological characteristics of the upper leaf surface, a significant link was found between the upper leaf surface roughness of *T. baccata* and its PM capturing efficiency (Fig. 3.9). As the most efficient species for PM capturing, the upper leaf surface of *T.*

baccata was the roughest among all the tested evergreen species. An abundance of ridges and grooves were densely distributed across the leaf surface, with the majority of these grooves being quite narrow and deep. PM of diverse sizes was found embedded and accumulated in these grooves. A large amount of PM was also observed around the stomata. These specific leaf surface traits increased the roughness of upper leaf surface and provided sufficient room on the leaf surface of *T. baccata* for airborne PM to settle. The densely distributed ridges and grooves also effectively prevented the accumulated PM on the leaf surface from being blown away again by the subsequent wind.

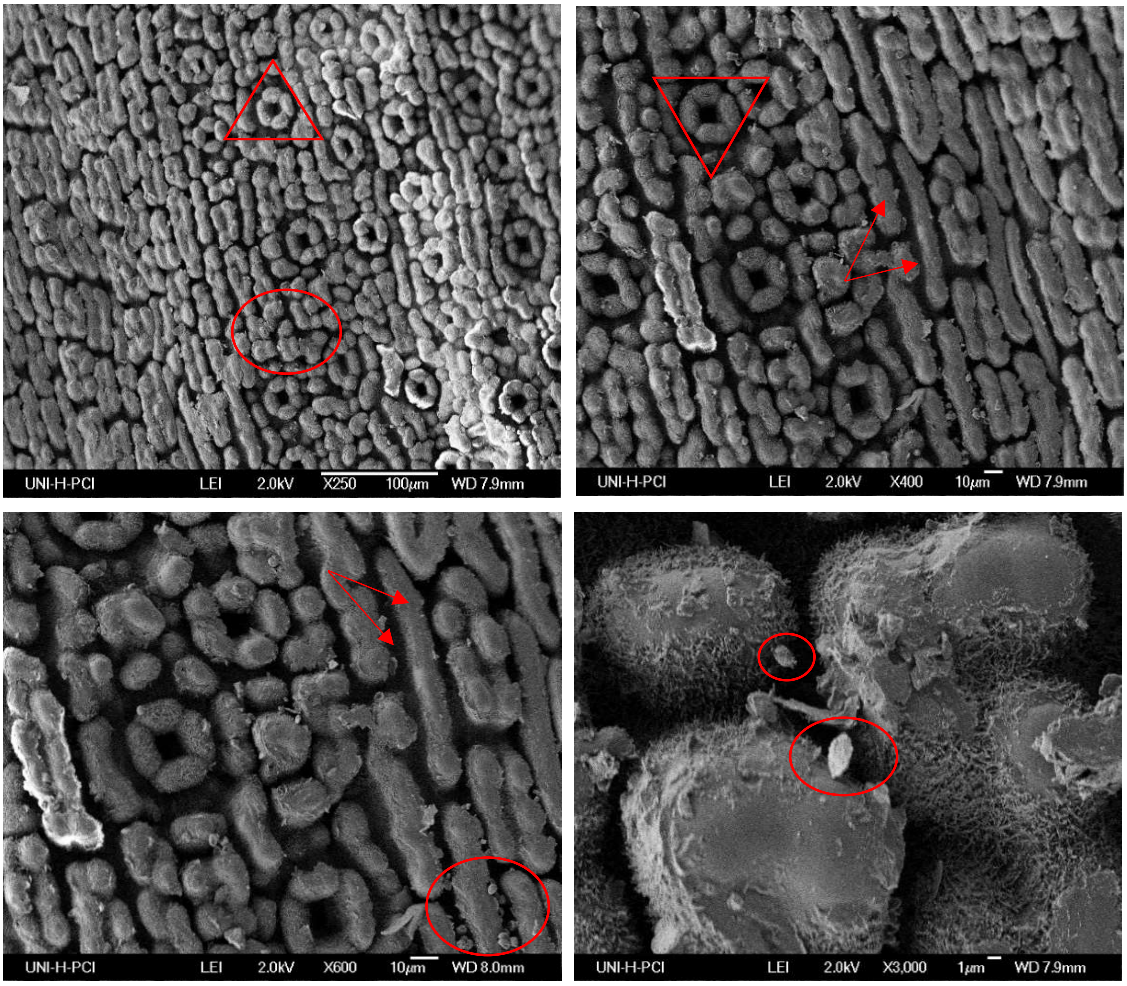


Fig. 3.9 Scanning electron microscope images of upper leaf surface for *Taxus baccata* with diverse magnification, symbols indicate examples of stoma (in the triangle), ridges and grooves on leaf surface (solid arrow) and PM with different sizes (bright spots in the red circles). (Images are photographed by the author)

3.3.2.2 Relationship between the PM capturing efficiency and leaf surface micro-morphological traits of *Pinus nigra*

A significant correlation was found between the upper leaf surface morphological traits and its PM capturing efficiency for *P. nigra* (Fig. 3.10). The entire leaf surface area except stoma was covered with an uneven layer of wax. A sunken area could be observed between each ridge on the leaf's surface. Unlike the grooved area on the upper leaf surface of *T. baccata*, the sunken area on the leaf surface of *P. nigra* was relatively shallow; however, the majority of the particles accumulated in this area. In addition, particles were also found around the stomata. As the leaves of *P. nigra* are needle-shaped, the plant provided a relatively large total leaf area, and the leaf surface therefore provided more sunken areas for airborne PM to be deposited. Rows of densely arranged stomata on the leaf surface were also observed to improve the PM capturing efficiency of *P. nigra.* Although *P. nigra* had a relatively high PM capturing efficiency, its PM capturing value was lower than *T. baccata* as the grooves on its leaf surface were not as deep. However, it was still ranked the second most efficient among all tested evergreen species in this study.

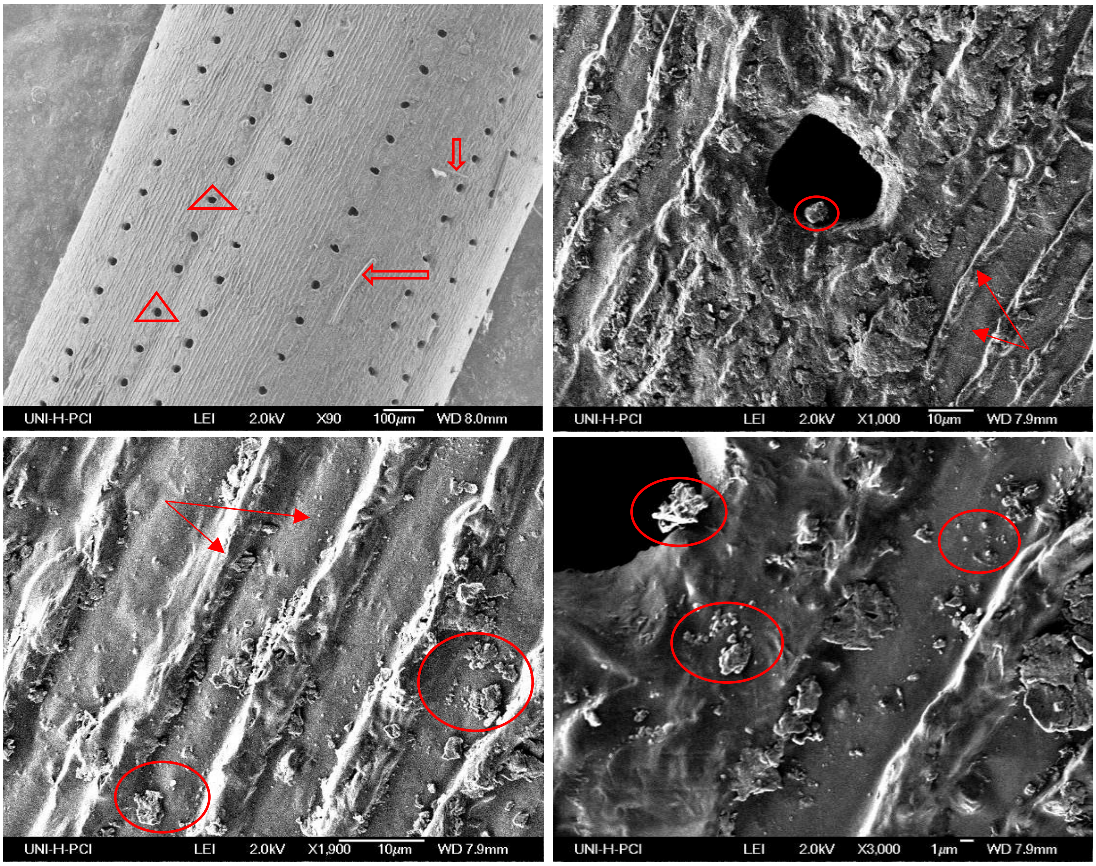


Fig. 3.10 Scanning electron microscope images of *Pinus nigra* with various magnification, symbols indicate examples of stoma (in the triangle), ridges and grooves on leaf surface (solid arrow), trichome (open arrow) and PM with different sizes (bright spots in the red circle) (Images are photographed by the author).

3.3.2.3 Relationship between the PM capturing efficiency and upper leaf surface micro-morphological traits of *Hedera helix*

Compared to the leaf surfaces of *Taxus baccata* and of *Pinus nigra*, the upper leaf surface of *Hedera helix* was relatively smooth (Fig. 3.11). Densely arranged grooves and ridges were also observed on its surface, but unlike *T. baccata,* the ridges were small and narrow, and the grooves were slight and shallow. Using scanning electron microscopy, it was found that most PM was also distributed in these grooves; however, the total amount of PM was relatively low. The shallow grooves resulted in a relatively low level of leaf surface roughness; thus, only a small amount of PM was observed on the leaf surface within the same field of view. Compared to the two tested needle-leaved evergreen species, the low level of upper leaf surface roughness and the unique leaf surface traits of *H. helix* led to a relatively low PM capturing efficiency value.

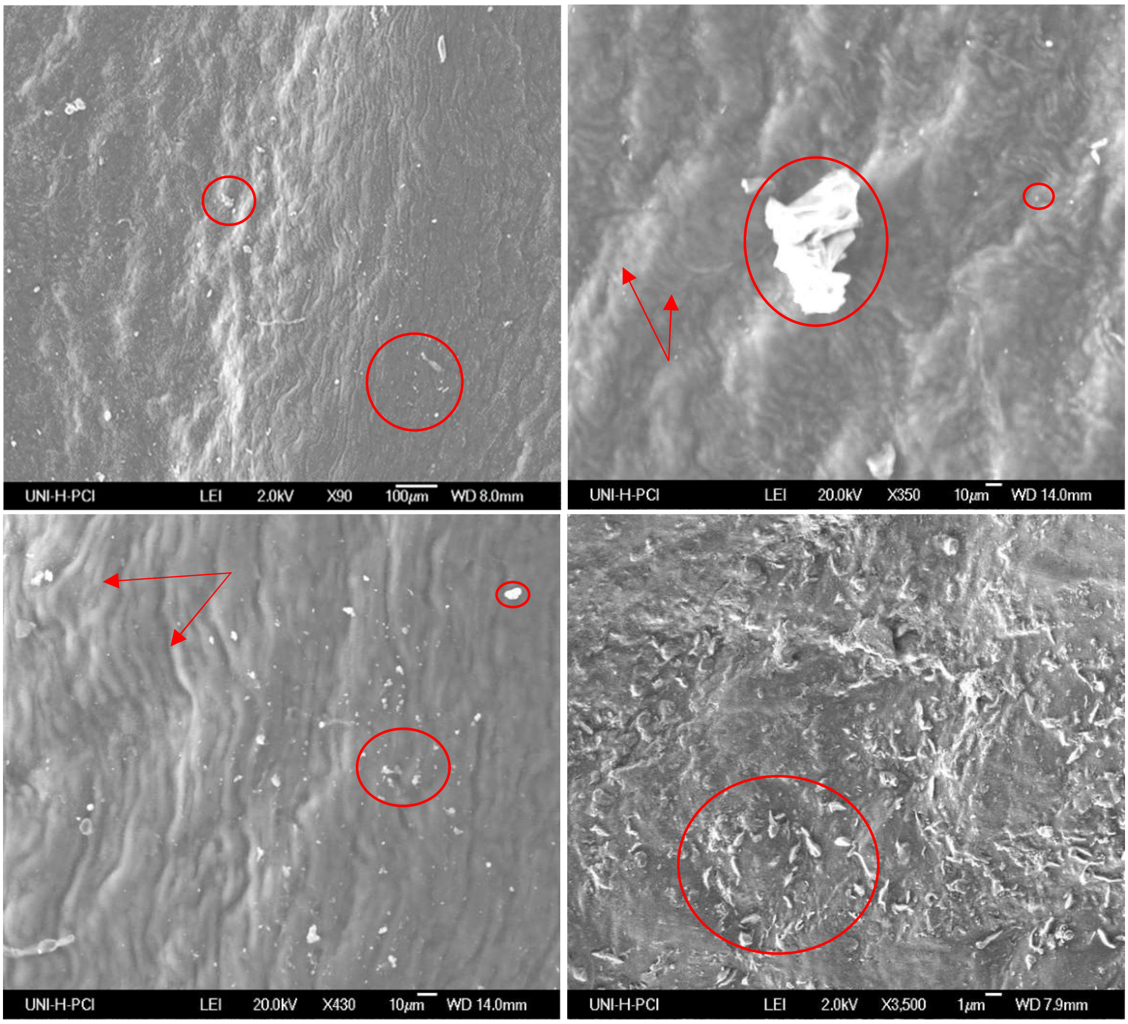


Fig. 3.11 Scanning electron microscope images of *Hedera helix* with diverse magnification, symbols indicate examples of ridges and grooves on the leaf surface (solid arrow) and PM with different sizes (bright spots in the red circle) (Images are photographed by the author).

3.3.2.4 Relationship between the PM capturing efficiency and leaf surface micro-morphological traits of *Prunus laurocerasus*

SEM observation of *P. laurocerasus* (Fig. 3.12) showed that its upper leaf surface was the smoothest among those of all the tested evergreen species. The leathery leaf surface was flat, and only a small number of wrinkles and grooves were observed. Most particles were scattered across the blade surface, and the particles itself had a relatively large diameter. The wrinkles and ridges on its leaf surface were quite narrow and shallow and were unable to prevent captured PM from being blown away by the subsequent wind. Due to its relatively smooth, leathery leaf surface, leaves of *P. laurocerasus* had the lowest surface roughness of all the tested plant species and therefore was most inefficient evergreen species in capturing PM in the winter.

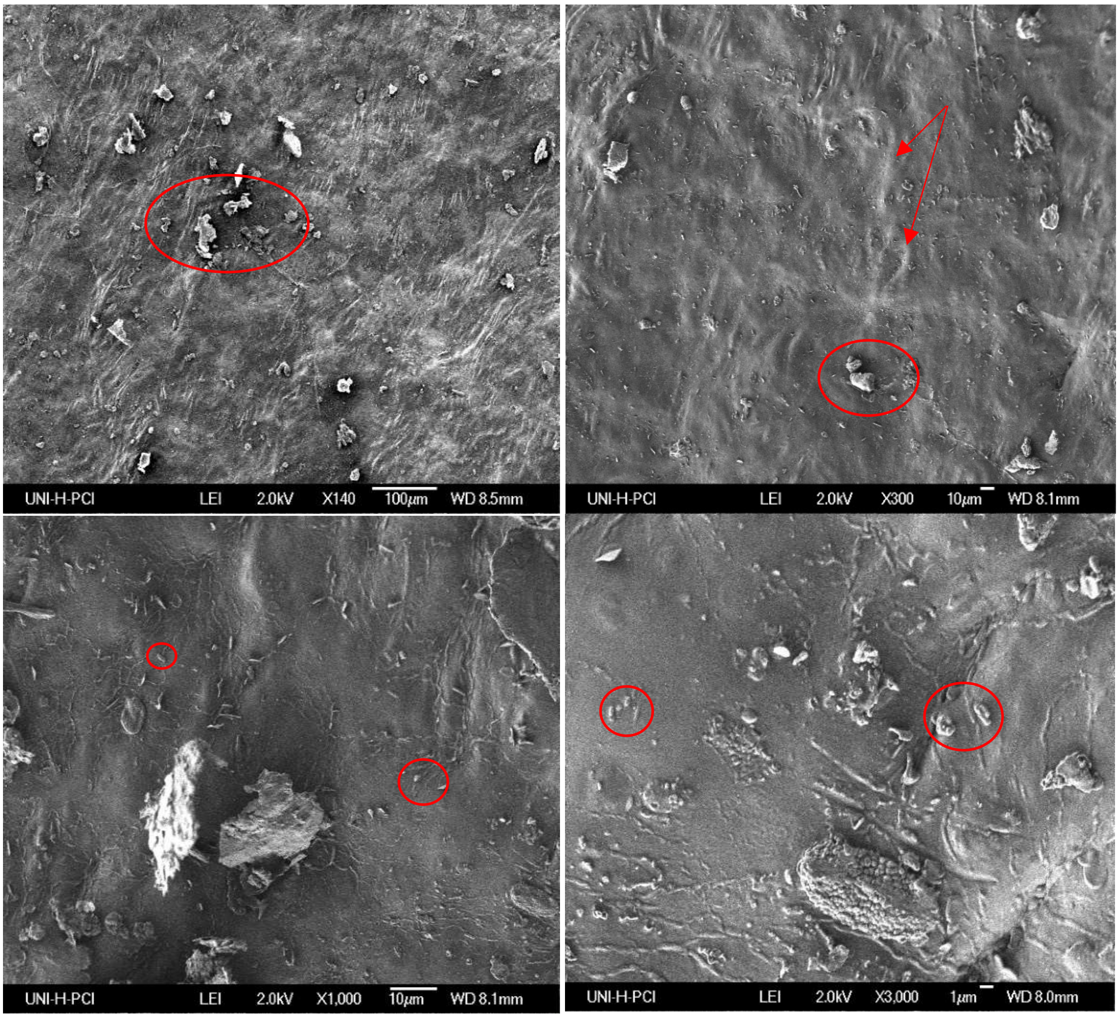


Fig. 3.12 Scanning electron microscope pictures of *Prunus laurocerasus* with various magnification, symbols indicate examples of ridges and grooves on the leaf surface (solid arrow) and particles with different sizes (bright spots in the red circle) (Images are photographed by the author).

3.3.3 Correlation between the leaf surface contact angle and the PM capturing efficiency of different evergreen species during winter

3.3.3.1 Leaf surface contact angle of different evergreen species in winter

Leaves with different surface contact angles showed varying surface hydrophilicity (Fig. 3.13). Throughout our study, the CA varied among species (Fig. 3.14). Among all tested evergreen species, leaf surface CA of *P. laurocerasus* was the highest indicating that its leaf surface was highly hydrophobic. The leaf surfaces of *H. helix* and *P. nigra* were hydrophobic because their leaf surface CA were both over 90°. Leaf surface of *T. baccata* was found to be highly hydrophilic because its CA was less than 90°, and it was the smallest among all tested species. By one-way ANOVA, significant statistical differences in leaf surface CA were found between *T. baccata* and the other three tested species ($P < 0.05$).

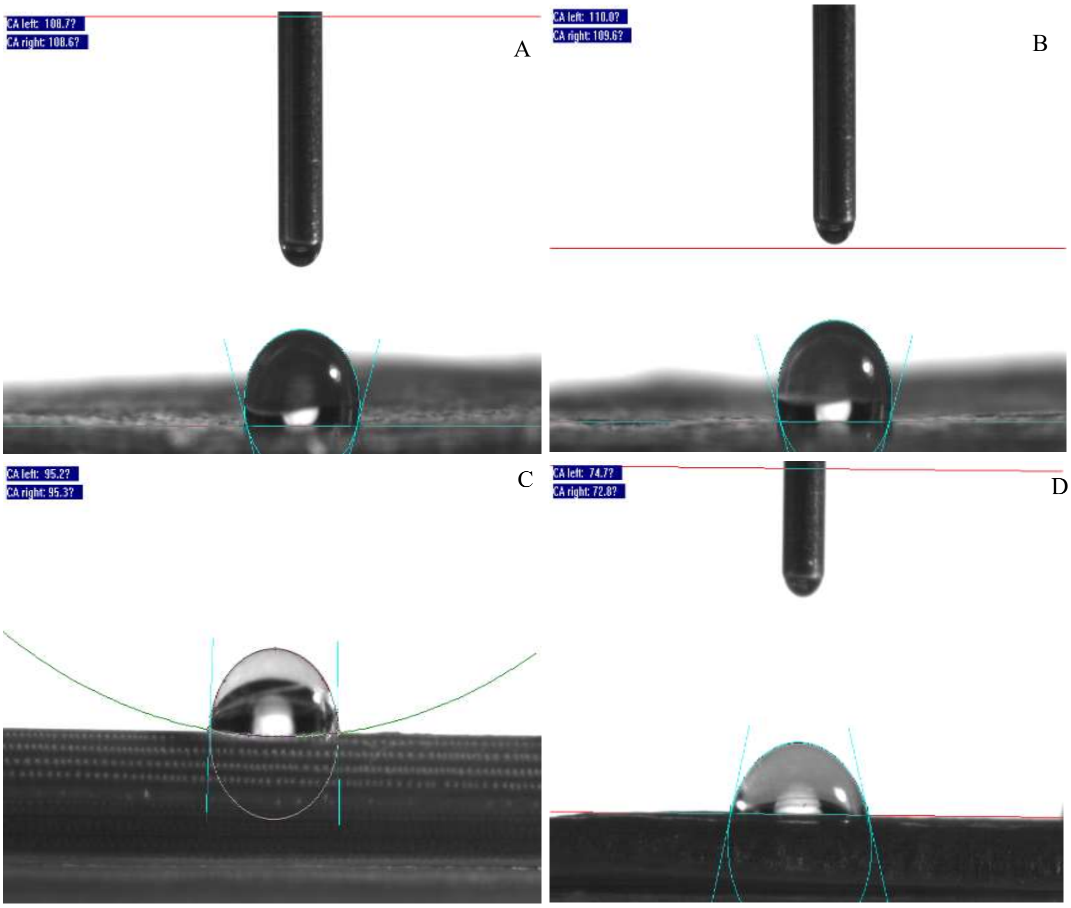


Fig. 3.13 Water shape on leaf surface of each tested evergreen species and the CA measurement process. Green lines are tangent line between liquid surface and solid leaf surface. A: water drop on leaf surface of *Prunus laurocerasus* B: water drop on leaf surface of *Hedera helix* C: water drop on leaf surface of *Pinus nigra* D: water drop on leaf surface of *Taxus baccata* (Images are photographed by the author).

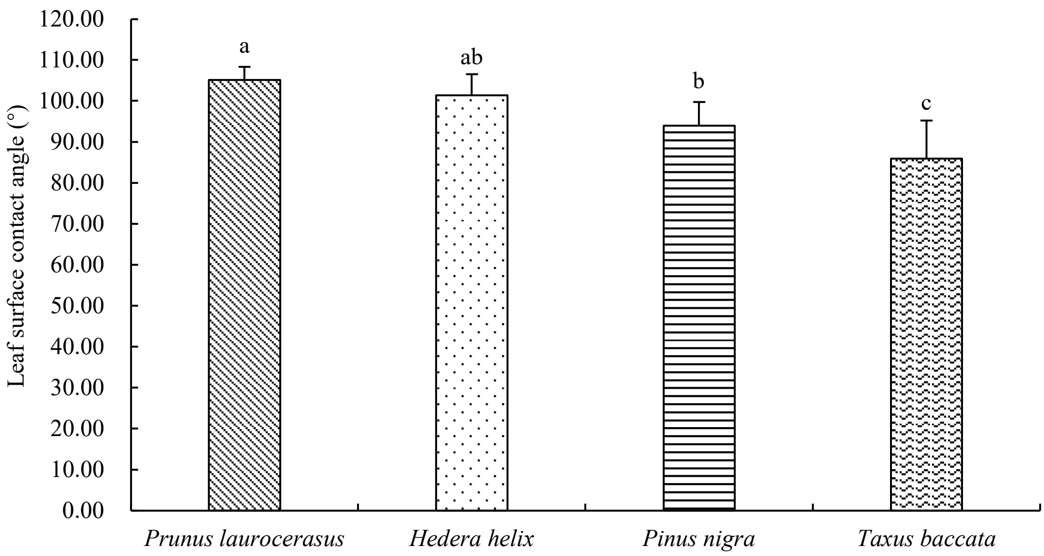


Fig. 3.14 Leaf surface CA of different tested evergreen species. Vertical bars represent the standard deviation; Statistic analysis by one-way ANOVA showed that there are significant differences between different species ($P < 0.05$); Data are mean ± SD. The same letter means there is no significant statistical difference at 0.05 level. (Based on the original data from Table C-3, Appendix C)

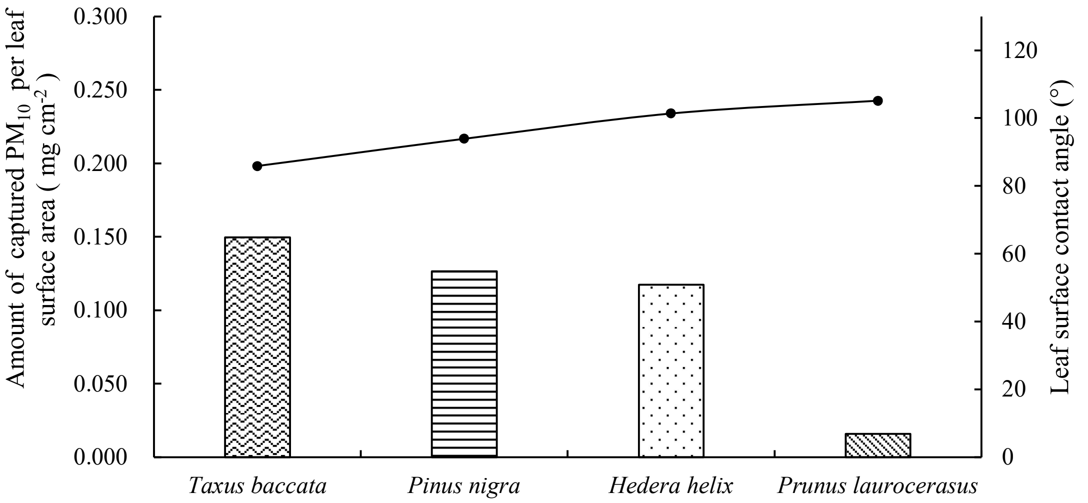
3.3.3.2 Extension speed of drops of water on leaf surface of tested evergreen species

To evaluate the extension speed of drops of water on leaf surfaces, CA at different time points were measured, and the relationship between CA and time was calculated. The extension speed of water drops varied between different tested species (Tab. 3.2). Water drops on leaf surface of the *H. helix* extended faster than those on any other tested species. From the initial time to 4 seconds later, the CA decreased from 102.35° ± 4.96° to 100.35° ± 4.99°, while the changing slope between the CA and time was -0.50, which was the smallest among all tested species. Water drops on leaf surface of *Pinus nigra* extended relatively quickly, as its slope value as -0.190.

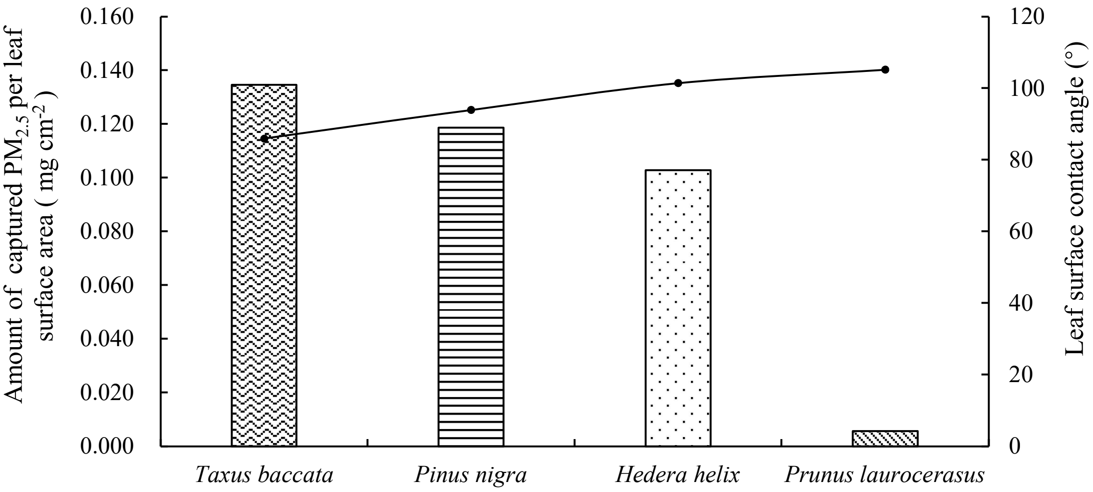
Table 3.2. leaf surface CA of tested roadside evergreen species at different time points, Data are mean ± SD.

Samples	Leaf surface CA (°)			Slope
	Initial	1s later	4s later	
Hedera helix	102.35 ± 4.96	101.6 ± 5.21	100.35 ± 4.99	-0.500
Pinus nigra	94.55 ± 5.98	93.52 ± 5.55	93.79 ± 6.09	-0.190
Taxus baccata	85.95 ± 10.56	86 ± 8.33	85.81 ± 9.36	-0.035
Prunus laurocerasus	105.49 ± 2.92	104.67 ± 3.96	105.39 ± 2.33	-0.025

Although leaf surface of *T. baccata* was highly hydrophilic due to aleaf surface CA of less than 90° (the smallest leaf surface contact angle), its slope value was relatively high (-0.035), which indicated that the water drop extended quite slowly on its leaf surface. Its CA declined only from 85.95° ± 10.56° to 85.81° ± 9.36° in four seconds. The leaf surface of *P. laurocerasus* was highly hydrophobic, and a water drop on its leaf surface could hardly extend due to a changing slope value of -0.025, the highest among all tested evergreen species.



A

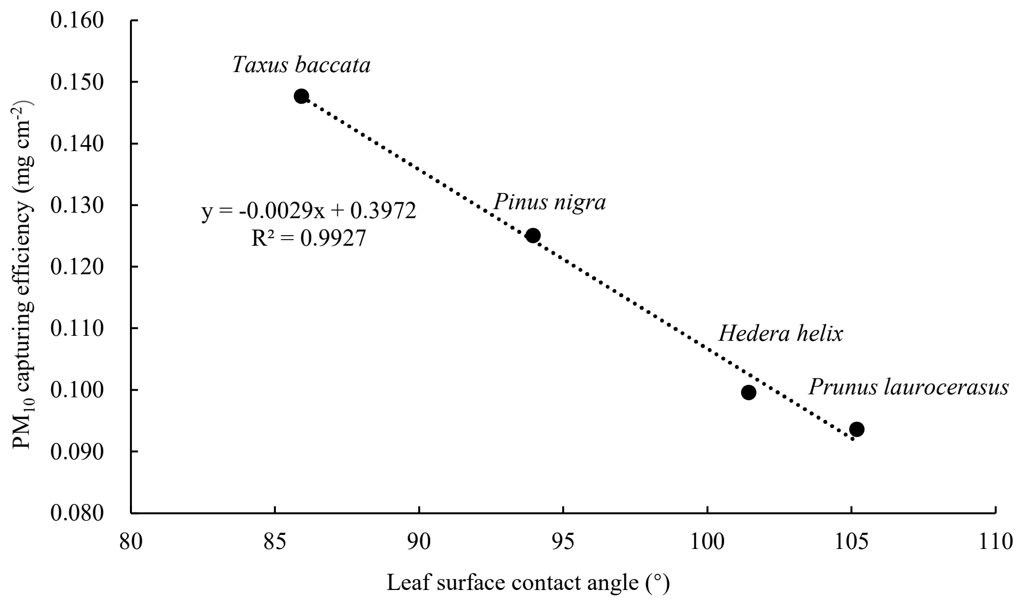


B

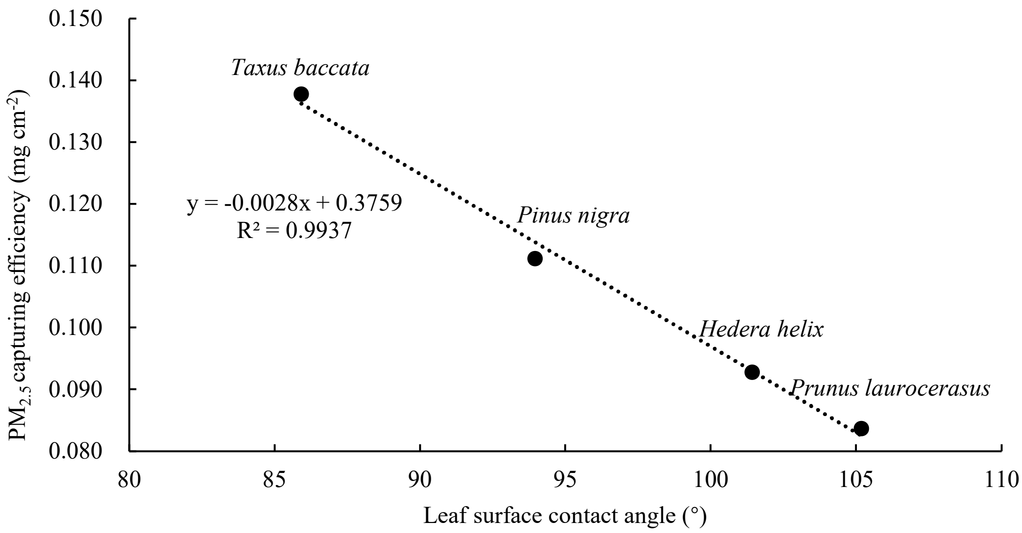
Fig. 3.15 Correlation between PM capturing efficiency and leaf surface CA of tested evergreen species. Figure A: Correlation between CA and PM_{10} capturing efficiency, Figure B: Correlation between CA and $PM_{2.5}$ capturing efficiency. Bars represent the amount of captured PM on unit leaf surface area and lines represent the leaf surface CA. (Based on the original data from Table C-2 and Table C-3, Appendix C)

3.3.3.3 Correlation between the leaf surface contact angle and the PM capturing efficiency of different evergreen species during winter

Leaf surface CA had notable effects on the efficiency of evergreen plant species for PM capturing during winter. Taking all winter months as a whole, a negative correlation was found between CA and PM_{10} capturing efficiency (Fig. 3.15A, Fig. 3.16a). *T. baccata* was the species with the highest PM_{10} capturing efficiency among all tested evergreen plants, and its leaf surface CA was only 85.92°, which was the smallest of all the tested species. As the second most efficient species, the amount of PM_{10} captured by *P. nigra* was 0.119 mg cm^{-2}, but its leaf surface CA was the second smallest. *Prunus laurocerasus* was the species with the biggest leaf surface CA (105.18°), and its efficiency for PM_{10} capture was the lowest (only 0.006 mg cm^{-2}). The correlation between leaf surface CA and their $PM_{2.5}$ capturing efficiency was also negative (Fig. 3.15B, Fig. 3.16b). The $PM_{2.5}$ capturing efficiency declined notably with increasing leaf surface CA for all tested evergreen species in our study. By means of Pearson correlation analysis, the correlation index of PM_{10} capturing efficiency and the leaf surface contact angle of the tested evergreen species was -0.997 ($P < 0.05$), confirming a significant negative linear correlation (Fig.3.16a). The correlation between the leaf surface contact angle and $PM_{2.5}$ capturing efficiency was also significantly negatively linear ($R= -0.996$, $P < 0.05$) (Fig. 3.15B and Fig. 3.16b).



a



b

Fig. 3.16 Correlation between leaf surface contact angle and the PM capturing efficiency of the tested evergreen vegetation during winter. (a: for PM_{10} capturing; b: for $PM_{2.5}$ capturing)

3.4 Discussion

In this chapter, four roadside evergreen roadside plant species were tested to investigate the variation in their PM capturing efficiency in different winter months (from November to March). The results documented in our study confirmed our first hypothesis. The PM capturing efficiency of the tested species varied between different winter months, which was in line with the results of a previous study conducted in Poland and in Norway (*Sæbø et al.* 2012). Taking all winter months as a whole, the PM diminishing efficiency of four tested evergreen species ranked as *Taxus baccata* > *Pinus nigra* > *Hedera helix* > *Prunus laurocerasus*. Compared to broad-leaved species like *H. helix* and *P. laurocerasus*, two needle-leaved species showed relatively higher efficiency. Compared to the PM absorbing efficiency of the vegetation in other seasons, the efficiency value in winter was relatively high. Xu *et al.* (2018) tested the PM capturing efficiency of 17 roadside plants in Beijing from summer to autumn. They found that the most efficient needle-leaved species for PM_{10} capture were *Platycladus orientalis* (0.053 mg cm^{-2}) and *Pinus armandii* (0.055 mg cm^{-2}), although their efficiency value was lower than that in our results (*Pinus nigra*: 0.125 mg cm^{-2} and *Taxus baccata*: 0.147 mg cm^{-2}). Sæbø *et al.* (2012) compared the efficiency of different plants for PM absorption during late September and early October in Norway and Poland. In Norway, the PM_{10} average capturing efficiency value of the two highly efficient conifer species are approximately 0.080 mg cm^{-2} (*Pinus mugo*) and 0.054 mg cm^{-2} (*Pinus sylvestris*), while the highest efficiency value recorded in this study is 0.125 mg cm^{-2} (*Pinus nigra*). For the same tested broad-leaved species, *Prunus laurocerasus,* their efficiency value obtained by Sæbø *et al.* (2012) in early autumn is also much lower than the result in this study in winter. (0.014 mg cm^{-2} by Sæbø and 0.083 mg cm^{-2} by us). In Poland, Sæbø found the efficiency value of *Hedera helix* and *Taxus baccata* for PM_{10} to be 0.020 mg cm^{-2} and 0.017 mg cm^{-2}, respectively, which is still lower than the values recorded in this study for the same species (*Hedera helix*: 0.093 mg cm^{-2} and *Taxus baccata*: 0.138 mg cm^{-2} respectively). The efficiency of the tested vegetation for $PM_{2.5}$ capturing had the same change trend as shown for PM_{10} absorption. Although the differences between the previous studies and this study could be attributed to interspecies differences, soil and meteorological conditions, urban vegetations is generally found to be more efficient for PM capture in winter than in summer and autumn (Li *et al.* 2019, Przybysz *et al.* 2019, Zha *et al.* 2019). Compared to broad-leaved species such as *H. helix* and *P. laurocerasus*, the two needle-leaved species showed relatively higher PM capture efficiency. This result is consistent with previous conclusions that needle-leaved species is more effective as PM sinks (Sæbø *et al.* 2012, Gourdji 2018, Xu *et al.* 2018) and PM tends to be deposited on needle-leaved species rather than on broad-leaved plants (Freer-Smith *et al.* 2005). Although pines such as *P. nigra* have high PM accumulation efficiency, a point noted by several previous studies, and is recommended as a phytoremediation treatment to pure air quality in urban area (Beckett *et al.* 1998, Tiwary *et al.* 2009, Tallis *et al.* 2011), researchers also reported its sensitivity to air pollution and salt density. Pines are thus neither proper to be planted alongside urban streets where salt is needed for de-icing, nor along the streets where the pollution and salt concentration are relatively high (Sæbø *et al.* 2012). Our study found that as needle-leaved species, *T. baccata* was generally more efficient for PM diminishing than *P. nigra*. Taking *T. baccata* as the substitutes for pine species and plant more *T. baccata* directly alongside the verges of heavily-trafficked streets as the main PM filter in winter would be a proper choice for city managers (Sæbø *et al.* 2012).

The reason *T. baccata* and *P. nigra* had higher PM capturing efficiency than that of *H.helix* and *P. laurocerasus* in winter can be explained in two main parts. First, as found in previous studies, the results of this study confirmed that tree species are more efficient than small vegetation at PM capturing (Fowler *et al.* 2004). As tree species, *T. baccata* and *P. nigra* have a relatively large canopy that provides sufficient leaf surface area for PM to settle within the same dimensional range (Chen *et al.* 2017). Furthermore, more turbulent air mixing of the air is caused by the large leaf surface area of tree species than by small vegetation, and PM has thus enough time and opportunities to be deposited onto leaf surfaces (Beckett *et al.* 2000a). In addition, tree species are proved to cause an increase in PM concentration by reducing air circulation, when it is planted along streets (Salmond *et al.* 2013). The second reason can be interpreted by different leaf surface morphology. The images of leaf surface by using scanning electron microscopy showed that the leaf surface of *T. baccata* was the roughest of all the tested evergreen species. This result confirmed our second hypothesis that PM capturing efficiency increases with the level of leaf surface roughness. An abundance of wrinkles and grooves were found on the leaf surface of *T. baccata*, and PM of different grain sizes was found embedded in those grooves. Even fine PM with a diameter of approximately 1 µm was found to stuck in the grooves on its leaf surface. Possessing the roughest leaf surface made *T. baccata* the evergreen species with highest PM capturing efficiency in this study. As the second most efficient species, the long needle leaves of *P. nigra* provided abundant total leaf surface area in total, and due to its thin boundary layers, it was more likely to capture PM when compared to species with large, flat leaves (Sæbø *et al.* 2012). Consistent with a previous study (Kupcinskiene and Huttunen 2005), we found by SEM observation that the leaf surface of *P. nigra* was covered with wax by SEM observation. The wax layer on the leaf surface of *P. nigra* was not flat but lumpy, with ridges and grooves arranged in a staggered pattern. Between each ridge, a sunken area was found where the majority of the PM was concentrated. Rows of stomata were densely arranged on its leaf surface, and PM was observed close to the stomata, which indicated that rows of stoma may enhance the PM capturing efficiency of plants (Xie *et al.* 2014). However, the grooves of *P. nigra* were found to be shallower than those of *T. baccata*. Therefore, *P. nigra* had a lower PM capturing efficiency than *T. baccata* and was only the second most efficient among the tested evergreen species. For the two broad-leaved species, shallow grooves and tiny wrinkles were observed on the leaf surface of *H. helix*. The amount of PM observed on its leaf surface was much lower than that on the leaf surface of the needle-leaved species. Initial observation by the naked eye revealed the leaf surface of *P. laurocerasus* to be leathery and it was deemed the smoothest among the tested species. SEM observation of *P. laurocerasus* confirmed the initial impression that it possessed the smoothest leaf surface; almost no grooves or ridges were observed. Only PM with a relatively large grain diameter was found distributed on its leaf surface. In short, needle-leaved species demonstrated higher PM capturing efficiency than broad-leaved species, mainly because of their large total leaf surface area as well as their special leaf surface traits that increased the level of leaf surface roughness.

The PM capturing efficiency of all tested evergreen species showed variation throughout each of the winter months. From early winter (November and December), the efficiency of all tested species increased and reached peak values in December; from December onwards, the efficiency of each tested species started to decrease. *P. nigra* recorded its lowest efficiency in February, and the other three evergreen species recorded their lowest efficiency for PM removal in March. The cause of the increasing trend for each of the tested species in early winter related to several aspects. The first aspect was the increase in the ambient concentration of PM. According to previous study, plants tend to be relatively more efficient at capturing PM during winter compared to other seasons (Zha *et al.* 2019) The falling leaves of most deciduous species from November onwards means that the ambient PM concentration in the air continues to be relatively high (Wang *et al.* 2015b, Zha *et al.* 2019). As the leaves of evergreen species remain on the plant, these species therefore become the main pollutant sink for PM removal. Prusty *et al.* (2005) reported that the amount of PM captured by leaves increases with the increasing vehicle pressure near a national highway in India, and Przybysz *et al.* (2014) found that *T. baccata*, *H. helix* and *Pinus sylvestris* accumulate more PM on their leaves at a heavily polluted site rather than at a lightly contaminated area. Our results agreed with his study that the increasing of pollution density for evergreen species in November and December increase their leaf`s PM capturing efficiency. Previous studies claimed a large amount of PM tends to be obtained on the leaf surface in months with less precipitation (Prusty *et al.* 2005, Przybysz *et al.* 2014, Rodriguez-Germade *et al.* 2014). In our study, there was only a small amount of rainfall (49.6 mm on average) (WetterKontor 2018) since November at the sampling site chosen for this study, the relatively dry weather enhanced the deposition process of PM onto the leaf surface. And a low amount of precipitation prevents captured PM on the leaf surface from being flushed off. From late December, the amount of rainfall started to grow (62.2 mm on average) (WetterKontor 2018) and the PM capturing capacity of each tested species therefore demonstrated a clear decline from

January onwards. For needle-leaved species, the epicuticular wax on leaf surface has notable effects on their PM capturing efficiency. By SEM observation of *P. nigra*, this study found that most PM was concentrated in the wax grooves on the leaf surface. However, Godzik *et al.* (1979) noted that a great number of pollutants captured on leaf surface of pines can cause serious physiological damage to their leaves. In some cases, the captured particulate pollutants could even degrade leaf surface epicuticular wax of some pine species (Burkhardt and Pariyar 2014). This could also partly explain the sharp decreasing trend in PM capturing capacity of *P. nigra* from late December in this study and why pine species might be more sensitive to PM capture during winter. Compared with those of the needle-leaved species, the monthly changes in the PM capturing abilities of broad-leaved species were much less dramatic. It was determined that for broad-leaved species, the leaf surface roughness has a greater impact than the leaf surface wax (Liang *et al.* 2014). Some leaf surface traits would accelerate the deposition of PM. A large number of stomata was found to be surrounded by PM on the leaf surface of *P. nigra* by SEM observation in this study. Burkhardt *et al.* (2001) noted that a large density of stomata will cause the increase of leaf transpiration and PM is thus more easily to be deposited because of its deliquescent character. Besides, with the increasing of transpiration, leaf surface is cooled and more PM is deposited by thermophoresis (Räsänen *et al.* 2013). As dry deposition velocity is greatly affected by surface humidity which can be changed by stoma, foliar PM capturing efficiency can thus be impacted (Mariraj Mohan 2016). Kardel *et al.* (2010) found leaves in the industrial area have the highest stoma density, in urban polluted area, the density of stoma is higher than it in the urban green area and in the suburban green area, stoma density is the lowest. This may indicate the increasing trend of evergreen species for PM capturing in early winter when deciduous species lose their function and the ambient PM concentration was high. In conclusion, the PM capturing efficiency of evergreen species increased during early winter until December and then decreased to their individual minimum values for each species in February and March. This finding rejected our first hypotheses, that the PM capturing efficiency of evergreen plants increases with time during winter. Needle-leaved evergreen species are found to be a better choice for urban PM removal, because of their high efficiency during the whole year, including during winter when the PM concentration is normally the highest (Freer-Smith *et al.* 2005).

In addition to the impacts of leaf surface traits and meteorological factors on PM accumulation, leaf surface wettability is also important (Neinhuis and Barthlott 1998, Wichink Kruit *et al.* 2008). The CA of standardized water droplets on leaf surface can be regarded as an indicator of leaf surface wettability (Brewer *et al.* 1991). This parameter indicates the hydrophilicity of leaf surface, which is determined by the physical and chemical composition of the leaf cuticle (Holloway 1969). A negative correlation is found between the PM capturing efficiency and leaf surface CA in a previous study (Koch *et al.* 2009). Neinhuis and Barthlott (1998) found leaves of less wettable species such as *G. biloba* is inefficient in PM capturing. Kardel *et al.* (2011) noted species with a higher leaf surface contact angle are hydrophobic and are unable to accumulate the same amount of particles on the leaf surface as hydrophilic species. Our results confirmed such a negative linear correlation. The leaf of *Prunus laurocerasus* was "wettable", as it recorded the highest surface contact angle among the studied species; its PM capturing efficiency was also the lowest among all tested species. The leaf of *Taxus baccata* was "highly-wettable", its contact angle was lower than that of *P. laurocerasus,* and it was the species with the highest PM capturing efficiency in this study. The reason that a high CA leads to a non-wettability property is due to the presence of air between the contact area of the water and the leaf surface, which makes it difficult for the leaf to become wet. An insufficient contact area between a particle and the underlying leaf surface reduces the physical adhesion force (Wang *et al.* 2013). It is then difficult for particles to adhere to the leaf surface and water drops are more easily able to pick up the contaminating particles when rolling off the leaves. Thus, plant species with hydrophobic leaf leads to low PM capturing efficiency. Haines *et al.* (1985) also noted that epicuticular wax layer on the leaf surface is more vulnerable to air pollution and the erosion of wax crystals increases surface CA and decreases the amount of captured PM on the leaf surface (Koch *et al.* 2009, Kardel *et al.* 2012). This may partly explain the declining trend shown by the evergreen species in PM capturing after the increasing trend from November to December in this study. In conclusion, our third hypothesis, that a significant negative correlation exists between leaf surface CA and the PM capturing efficiency of evergreen species during winter, is confirmed.

3.5 Conclusions

Evergreen species evaluated in this chapter exhibited differentPM capturing efficiency during each winter month. Although the most efficient species diverse in each month, it was found that, in general, *T. baccata* displayed the highest efficiency during the whole winter, while *P. laurocerasus* was the least efficient tested species. *T. baccata* demonstrated a stable efficiency throughout the winter, its PM capturing efficiency increased to its peak value in December, and then gradually declined to its minimum value in March. *P. nigra* was the second most efficient species among all tested species, but its efficiency declined sharply from January onwards after reaching its peak value. Although *H. helix* had two peak values, one in December and one in February, its PM capturing efficiency was still relatively low, and it ranked in the third place. *P. laurocerasus* was consistently the least-efficient species during the whole winter period. All tested evergreen species reached their own peak efficiency in December and declined to their minimum value in February and in March. Leaf surface roughness is a key factor impacting the efficiency of broad-leaved species for PM capture. High levels of leaf surface roughness normally resulted in a high PM capturing efficiency. On the leaf surface of *T. baccata*, PM with a diverse range of diameter was observed to be stuck to the abundant ridges and grooves, which could be seen by SEM scanning. However, on the leathery, smooth leaves of *P. laurocerasus*, only a small amount of PM was found. Finally, a negative correlation was found between leaf surface hydrophilicity and its PM capturing efficiency. Leaves that were highly hydrophobic, such as those of *P. laurocerasus*, had the highest leaf surface CA but the lowest PM capturing efficiency. Conversely hydrophilic leaves from species such as *T. baccata*, exhibited the highest PM capturing capacity.

As most deciduous plant species lost their PM capturing ability during winter, understanding the role of roadside evergreen species in reducing PM emitted from road traffic and resident areas along urban streets can provide a scientific basis for future city planning. The functions and traits of the evergreen species identified in our test provide effective and feasible options for city managers in addressing urban air pollution in the future, particularly during winter, when the urban ambient PM concentration is relatively high and the leaves of most deciduous species lose their ability for PM reduction.

Chapter 4 Reduction of traffic-related particulate matter by roadside plants: Effect of traffic pressure and growth height

4.1 Background and hypotheses

Many attempts have been made by the public to reduce the harm brought by air pollutions, however, particulate matters in the air is still a great threat to modern society. In 2012, 3.7 million premature deaths were estimated to be related to outdoor air pollution (WHO 2016). More than 2 million deaths were believed to be caused by urban PM (WHO 2005), and 470,000 premature deaths were considered to be related to $PM_{2.5}$ exposure (EEA 2016). In recent year, the traffic-related PM obtains more attention from the researchers. Traffic-related PM is regarded to be responsible for a great portion of anthropogenic PM in the urban area (Pant and Harrison 2013), 25% of $PM_{2.5}$ and PM_{10} is reported caused by the traffic emission all over the world (Karagulian *et al.* 2015), and more than 50% PM_{10} in Europe is from the road traffic (Kunzli *et al.* 2000). As most traffic-related PM contains toxic compounds like heavy metals, dibenzo-*p*-dioxins, dibenzofurans and polychlorinated biphenyls which make them quite hazardous (Dzierzanowski *et al.* 2011), long-term exposure to them results in various diseases to the cardio-pulmonary system and causes other serious illness such as allergies, lung cancer and brain damage (Seaton *et al.* 1995, Pascal *et al.* 2014, Maher *et al.* 2016). Besides, the rate of cardiac and ischemic mortality is also be found when followed short-term PM exposure (Ranft *et al.* 2009). Traffic-related PM could also be generated by the brake disk, the mechanical wear and the wheel friction. The PM from these process even falls within ultrafine range (Thornes *et al.* 2017). Compared to other size fractions, $PM_{0.1}$ in the ultrafine range has drawn more concern because of its small particle size and considerable number which make it more toxic and dangerous (Lin *et al.* 2005). Although traffic-related PM put serious threats to residents` health, the traditional mitigation approaches such as enhancing atmospheric dispersion, emission reduction, have been reported to have limited impacts on urban PM reduction (Weerakkody *et al.* 2017). The surface deposition has been confirmed as an effective short-term way for the traffic-related PM absorption (Pugh *et* *al.* 2012). As introduced by former chapters, roadside vegetation has significant efficiency for the PM absorption in both summer and winter, bioremediation is also widely conducted by former studies to reduce the concentration of traffic-related pollutants (Gromke 2011, Vos *et al.* 2013, Blanusa *et al.* 2015, Janhäll 2015, Mori *et al.* 2018).

Trees are reported to be highly effective for PM capture because of its large crown (McDonald *et al.* 2007, Sæbø *et al.* 2012) and are regarded as a PM sink in urban area (Weerakkody *et al.* 2017). However, practical factors in city area, such as the utilization of urban space, the consideration of driving safety, different soil conditions of different city roads and the height of adjacent constructions behind, set great barriers and limitations to the use of trees as the only roadside filter for PM absorbing (Johnston and Newton 2004). Therefore, the green wall system alongside city streets is recommended as a supplement for city PM reducing (Abhijith *et al.* 2017, Perini *et al.* 2017). Transforming building walls and other urban constructers to green wall by coving them with climbing plants or other suitable vegetations could overcome the limitations mentioned above, and bring additional benefits such as noise reduction, enriching the city biodiversity and rewilding of cityscapes (Johnston and Newton 2004, Chiquet *et al.* 2013, Dover 2015, Jepson 2016).

Previous studies focused mainly on the efficiency of different plant species in different seasons and its changes caused by different leaf traits, like leaf shape, surface area and leaf morphological diversity between species (Beckett *et al.* 1998, Kaupp *et al.* 2000, Jouraeva *et al.* 2002, Nowak *et al.* 2006, McDonald *et al.* 2007, Escobedo *et al.* 2008). However, the responses of roadside plant species to the change of traffic pressures are rarely reported. Green wall could be widely applied in city area as a highly effective facility which overcomes many limits and barriers, however, less is known about the PM capturing performance of its surface leaves at different height ranges.

Based on the results from last chapters, the main objectives of this chapter are to explore the efficiency of two common highly efficient roadside plant species (*H. helix* and *T. baccata*) for PM reduction (PM_{10} and $PM_{2.5}$) under three traffic pressures (high, middle and low); a green wall covered with leaves of *H. helix* alongside a busy city road was investigated to compare the efficiency of leaves at four height ranges (0.5-1m, 1-1.5m, 1.5-2m over 2 m) to capture PM with three size fractions (large, coarse and fine); Capturing efficiency difference of leaf surface and of epicuticular wax at different height ranges was compared to explore the distribution characteristics of the PM with different size fractions on the green wall. The preliminary hypotheses of this chapter are as follows: (1) the efficiency of the two roadside species for both PM_{10} and $PM_{2.5}$ capturing rises with the increase of traffic pressure. (2) leaves from different height ranges on the green wall have specific capturing preference for PM with different size fractions. Large PM will be concentrated at the area with low height while most fine PM will be captured by leaves from the high area on the green wall. (3) the efficiency of leaf surface and epicuticular wax is different to capture PM with different size fractions. Leaf surface is the main capturing area for particulate matters.

4.2 Materials and methods

4.2.1 Description of sampling sites

4.2.1.1 Sampling site to quantify the PM capturing efficiency of roadside plants under different traffic pressures

In order to figure out the variation of PM capturing efficiency of roadside plant species under different traffic pressures, three sampling-used streets with high, middle and low traffic pressure were chosen in the urban district, Hanover. Based on the government report and data measured by the nearest air quality monitor station (about 2-3 km apart) set by the Department of Environment and City Green of Hanover, the average air PM concentration in the city is about 26 $\mu g/m^{-3}$ for PM_{10} and 16.7 $\mu g\ m^{-3}$ for $PM_{2.5}$ (Hannover 2011, 2017). As the sampling used streets are all distributed in the “emission zone” which was designated by the city government (Hannover 2011), in this zone, there is no industrial facilities and the main pollution source is from city transport system. It is a reasonable assumption that all tested species were exposed to the same background PM concentration, and the level of pollution in different streets could be reflected by the number of vehicles. In this chapter, the street with over 2500 car number per hour was defined as under “the high traffic pressure”, the street with car number between 800 to 2500 per hour was defined as under “the middle traffic pressure” and the street with car number lower than 800 per hour was defined as under “the low traffic pressure”. The detailed information of each sampling-used street is shown in table 4.1 and Fig.4.1.

Table 4.1. Information about the sampling-used streets under different traffic pressures.

TP	SN	WS (m)	CN	LL	DS (m)
High	Friedrichswall	28.24 ± 0.62	3712 ± 154.5	52°22`8`` N 9°44`9`` E	8.01 ± 0.32
Middle	Celler straße	13.97 ± 0.19	1108 ± 10.6	52°23`5`` N 9°44`37`` E	4.73 ± 0.51
Low	Culemann straße	7.94 ± 0.46	632 ± 86.6	52°21`57``N 9°44`7`` E	6.24 ± 0.53

TP: Traffic pressure, SN: Street name, WS: Width of the street, CN: Car number per hour, LL: Latitude and longitude of the sampling-used street, DS: Distance from sampling site to the curb. Data are mean ± SE.

The sampling-used street under the high traffic pressure is in the commercial area and is alongside the street “Friedrichswall”. The street is located in front of the city hall, and is a dual three-lane carriageway. The width of the street is about 28 meters, and it connects two main cross-roads. The number of cars was about 4000 per hour. It is one of the arteries of urban connectivity and one of the busiest streets in city Hanover. The sampling point was set on a fence which faces directly to “Friedrichswall” street (Fig. 4.2-A) and the distance from the sampling point to the curb was about 8 meters.

The sampling-used street under the middle traffic pressure was set along the street “Celler straße” which is located near the main railway station in Hanover and connects the north-east part of the city to the city center. The width of the street is about 14 meters and the number of vehicles on the street was about 1000 per hour. It is also one of the main streets in Hanover. The sampling points were set in a flower bed outside a residential building and faces directly to the street (Fig. 4.2-B), the distance from the sampling points to the curb was about 4 meters.

The sampling-used street under the low traffic pressure was set along the street “Culemann straße”. It is a side road alongside the city garden “Maschpark”. The street is about 8 meters wide and only a few vehicles run on the street. The number of cars per hour on the street was only about 500. The sampling points were set on the outer side of the greenbelt which faces to the street. The distance from the sampling points to the curb was about 6 meters.

4.2.1.2 Sampling site to quantify PM capturing efficiency of roadside plants at different heights on the green wall

In order to explore the relationship between the sampling height and the PM capturing efficiency of urban roadside plants, a green wall was chosen as the sampling site in Hanover (Fig. 4.3). The green wall is about 43.5m long and 2.3 m high which locates alongside the street “Dragoner straße”. The distance from the green wall to the curb is about 6 m, and the wall surface which faces to the street is all covered by leaves of *H. helix* from 0.1 m to 2.5 m above from the ground (Fig. 4.4). The street “Dragoner straße” is a two-way street which is about 8 m wide and the number of cars on it was about 980 per hour. On the other side of the street locates a large parking lot which belongs to a busy supermarket. The green wall thus bears heavy PM pollution caused mainly by urban traffic system. The sampling points on the green wall were randomly set in sampling zones which were defined by different height ranges above from the ground. All sampling points faced directly to the street.

Fig. 4.1 Location of the sampling-used streets. Red dots: the location of the streets which had different traffic pressures in urban area, Hannover. Black dots: sampling points for *Hedera helix*, black triangle: sampling points for *Taxus baccata*. A: location of street "Friedrichswall", B: location of street "Celler straße", C: location of street "Culemann straße" D: city garden "Maschpark". Black line: street under the high traffic pressure, red line: street under the middle traffic pressure, blue line: street under the low traffic pressure. Green area: city parks and greenbelts. (Map remodified by the author based on the map: www.google.com/intl/de/earth, changed)

Fig. 4.2. Photos of sampling points alongside the streets. A: sampling points under the high traffic pressure at street "Friedrichswall", B: sampling points under the middle traffic pressure at street "Celler straße", C: sampling points under the low traffic pressure at street "Culemann straße" (Images are photographed by the author).

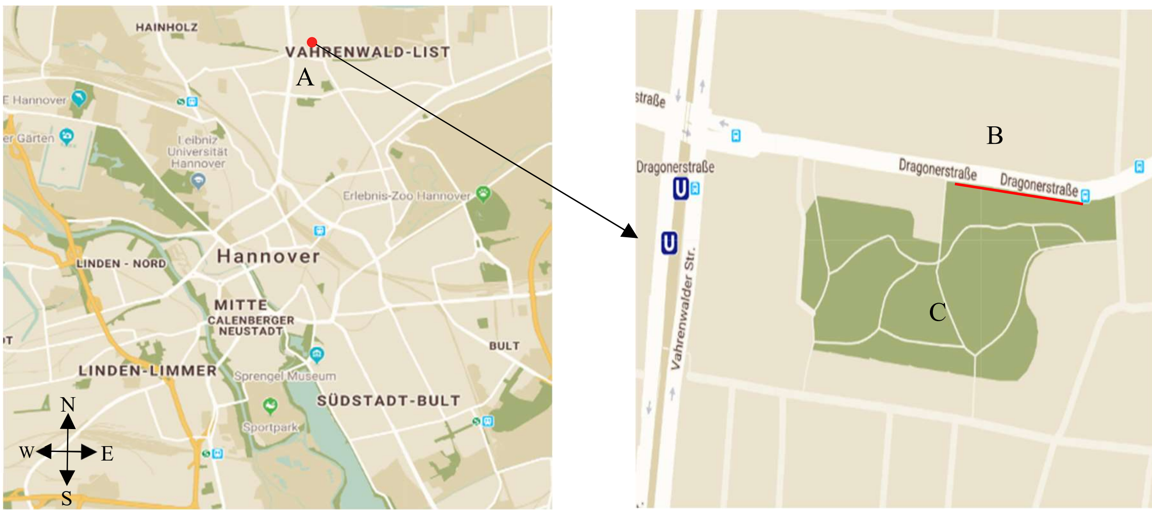


Fig. 4.3 Location of the sampling-used green wall in Hanover. A: location of the green wall in urban district Hanover, B: parking lot which belongs to the supermarket, C: City park: "Vahrenwalder Park", Red line: the sampling-used "green wall" (Map remodified by the author based on the map: www.google.com/intl/de/earth, changed).

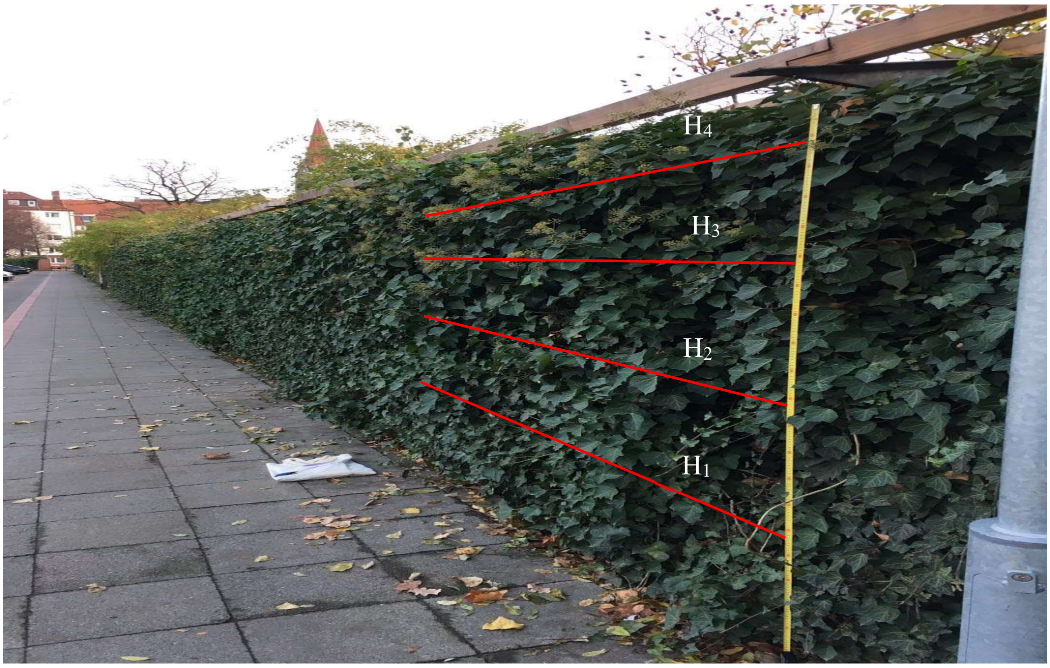


Fig. 4.4 Sampling-used green wall and the sampling zones with different height ranges. H_1: sampling zone 0.5-1 m above from the ground, H_2: sampling zone 1-1.5 m above from the ground, H_3: sampling zone 1.5-2 m above from the ground and H_4: sampling zone over 2 m above from the ground. (Images are photographed by the author)

4.2.2 Tested plant species and sampling methods

4.2.2.1 Tested plant species

In order to explore the PM capturing efficiency of roadside plants under different external conditions, common urban roadside species with relatively high efficiency were chosen as tested plants. *Taxus baccata* and *Hedera helix* were thus used in this chapter to explore the relationship between the traffic pressure and the PM capturing efficiency, and *H. helix* was applied to find the variation of PM capturing efficiency for roadside plants at different height ranges. Characteristics of the tested plant species are shown in table 4.2.

Table 4.2: Types and characteristics of tested plant species. SN: Scientific name of the plant species; F: Family; H: Habit; LS: Leaf shapes; MA: the mean leaf surface area (cm^2 $leaf^{-1}$); AH: Average plant height (m);

SN	F	H	LS	MA	AH
Hedera helix	*Araliaceae*	Climbing plant	Five-lobed broad or unlobed cordate	30.94	20-30
Taxus baccata	*Taxaceae*	Tree	Flat needle	0.42	10-20

4.2.2.2 Sampling methods

All tested leaves in this study were harvest in August when all plants were in the middle of their growth cycle, and all leaves were mature and fully expanded. For the tests which were taken under different traffic pressures, three sampling points were randomly set at each sampling used street, each sampling points was about 5 meters away from the curb. Leaves from the outermost layers of the canopy which faced directly to the street were collected from each sampling point as the tested material in the case of no precipitation for 10 consecutive days. For *H. helix*, the sampling zone is 0.5- 1m above from the ground and for *T. baccata*, the sampling zone is 1-1.5m above from the ground. The collecting process was repeated three times in each sampling point. For broad-leaved species, ten individual leaves were gathered, and for needle-leaved species, 50 leaves were harvest randomly from each sampling point. In total 540 blades were collected (90 blades from broad-leaved species and 450 blades from needle-leaved species). As leaf surface could be considered as totally cleaned by an accumulated precipitation of 15 mm (Wang *et al.* 2015a, Xu *et al.* 2017), Leaves from each sampling point were washed with 200 mL distilled water by using a sprinkling can 10 days before the harvest to ensure all leaf surface was totally cleaned before the PM deposition.

For the tests which were taken at different height ranges, four sampling zones were set on the tested green wall by different heights above from the ground (Fig. 4.4). Zone H_1 was the sampling area 0.5-1 m above from the ground, zone H_2 was the area 1-1.5m above from the ground, zone H_3 was the area 1.5-2m above from the ground and zone H_4 was the area over 2 m above from the ground. In each sampling zone, 12 individual leaves were randomly harvested, and the harvesting process was repeated three times in each sampling area. In total 144 leaves were collected. All sampled leaves were washed with 200 mL distilled water 10 days before the harvest, same as the tests which were taken under different traffic pressures.

Plants for sampling were in the similar growing condition. All sampled leaves were healthy without disease or pests, and were sampled on the same day. In order to prevent contamination, disposable gloves were used to harvest leaves by pinching petioles. All samples were then packed in a valve bag and kept in a clean lab refrigerator with a temperature of 6 ℃ for further analysis in the lab.

4.2.3 Testing methods and statistic

4.2.3.1 Capturing efficiency for PM_{10} and $PM_{2.5}$ under different traffic pressure

To compare the PM capturing efficiency of roadside plant species under different traffic pressures, the mass difference method was used to quantify the captured PM_{10} and PM $_{2.5}$ on the leaf surface (Liu *et al.* 2014). Each sample was dipped in 200 mL distilled water for 5 min and then both sides of leaves were scrub with a non-depilatory brush to ensure all PM on the leaf surface dropped into water. Another 200 mL distilled water was used to flush leaf surface for three times. The entire 400 mL turbid solution from last two steps was then weight, and the value was recorded as M_{ST}. 50 mL turbid water was taken to a plastic test tube after 5 min`s stirring, and its weight was recorded as M_{S50}. 50 mL solution was then dried by a Vacuum Freeze Drier (Alpha 1-2 LD plus Entry Freeze Dryer Package, Martin Christ, Australia) for 72h until all solution in the tube was totally dried out. The weight of particles in the 50 mL solution was then recorded as M_{SP}. The rest 350 mL solution was filtrated through a filtration apparatus which was equipped with a 47 mm glass filter funnel which was connected to a vacuum pump (KNF Neuberger, USA). The first filter paper was a nylon hydrophilic membrane filter with a bore diameter of 10 μm (HNWP04700, Millipore, Ireland, 2017). Then the filtration from last step was filtrated through the extraction filtration apparatus with the second filter paper, of which bore diameter was 2.5 μm (CAT-1442-047, Whatman Labware Products, UK, 2017). All fiber membranes and filter papers were then dried in a drying oven with a temperature of 60 ℃ for 2 hours until the weight of filter paper and fiber membranes were constant. All filter paper and fiber membranes were then put in a polytetrafluoroethylene desiccator under constant temperature for 2h until their temperature reached room temperature to avert further interference during next weighing process. All dried filter paper and membranes were weight and filter`s weight difference before and after filtration was calculated. The weight difference of fiber membranes was recorded as $M_{PM>10}$, and the weight difference of filter paper was recorded as $M_{PM2.5\text{-}10}$. Use the following formulas to calculate the amount of captured PM_{10} and $PM_{2.5}$ on the leaf surface. All filter papers and membranes used in this test were pre-dried in a drying chamber at 60 °C for 30 min. The PM deposition on leaves of each species was expressed as the average amount of deposited PM on unit leaf surface area.

$$MT_P = M_{SP} \times \frac{M_{ST}}{M_{S50}}$$

$$MT_{PM>10} = \frac{M_{PM>10} \times M_{ST}}{M_{ST} - M_{S50}}$$

$$MT_{PM2.5-10} = \frac{M_{PM2.5-10} \times M_{ST}}{M_{ST} - M_{S50}}$$

$$MT_{PM2.5} = MT_P - MT_{PM>10} - MT_{PM2.5-10}$$

$$MT_{PM10} = MT_{PM2.5} + MT_{PM2.5-1}$$

Where MT_P = the weight of all particulate matter; $MT_{PM>10}$ = the weight of total PM which grain diameter was greater than 10 μm; $MT_{PM2.5-10}$ = the weight of total PM which grain diameter was between 2.5 and 10 μm; $MT_{PM2.5}$ = the weight of total $PM_{2.5}$; MT_{PM10} = the weight of total PM_{10}; M_{SP} = the weight of PM in 50 mL solution; M_{ST} = the weight of the entire turbid solution; M_{S50} = the weight of the 50 mL solution which was taken from turbid solution; $M_{PM>10}$ = the weight of PM which grain diameter was greater than 10 μm; $M_{PM2.5-10}$ = the weight of PM whose grain diameter was between 10 μm and 2.5 μm.

4.2.3.2 Capturing efficiency for PM with different size fractions at different heights

To compare the efficiency of roadside plants at different height ranges to capture PM with different size fractions (large PM, coarse PM and fine PM), the testing process of Dzierzanowski *et al.* (2011) was carried out. All filters were pre-dried in a drying chamber at 60 °C for 30 mins, and then the humidity of filter papers was stabilized in the weighing room for 30 mins before weighing. The weight of pre-weighed filter paper was recorded as M_{fb}. Each sample was placed in a glass container with 250 mL distilled water for 60s to wash off PM on the leaf surface. The water was then filtered through a metal sieve with a mesh diameter of 100 μm to eliminate particles larger than 100 μm. The solution was then filtrated by using a 47 mm glass filter funnel which was connected to a vacuum pump, and had a filter with retention of 10 μm to stop large PM with a diameter over 10 μm. The solution from the last step was then filtrated again by the system with a filter paper which retention was 2.5 μm to stop coarse PM with a diameter between 2.5 to 10 μm. Finally, PTFE membrane filters (retention 0.2 μm) (all Whatman, UK) were used to stop fine PM. All filters were dried again and post-weighed with the same procedure as pre-weighted filters. The weight of post-weight filters was recorded as M_f.

After rinsing with distilled water, all samples were rinsed again by 150 mL chloroform for 40s to dissolve the epicuticular wax layer of the leaf, and to wash out the PM trapped in the leaf epicuticular wax. The filtration and calculating procedure were same as it for water-washed PM. The capturing efficiency for different sized PM (M_{PM}) was calculated by the following formula.

$$M_{PM} = (M_f - M_{fb}) \div LA$$

Where LA= the total leaf surface area, M_{fb}= the weight of pre-weighted filter paper, M_f= the weight of post-weighed filter paper.

4.2.3.3 Measurement of leaf surface area

Leaves were first scanned (MP C3004exS, Ricoh, Tokyo, Japan), and the scanned images were transformed into black and white images in which leaf surface area was black against a white background. To calculate leaf surface area, processing software "Image J" (Version 1.40 National Institutes of Health, USA) was used. The leaf area was the scanned area value multiplied by two.

4.2.3.4 Measurement of leaf surface CA

For each plant species, three repetitions were made. For each repetition, four leaves were randomly sampled under each traffic pressures as the testing material for the measurement of leaf surface contact angle. Both leaf sides were flush with 100 mL distilled water thrice, and then were dried in the shade at the room temperature until both leaf sides were completely dried. The flat upper leaf surface near midrib was cut to 1cm x 1cm square, and was pasted onto a glass slide with double-faced adhesive tapes as the sample for measuring. Drop contact angle system (OCA 15EC, Dataphysics, Germany) was used to measure the leaf surface contact angle. On each leaf sample, three water-drops were measured. The volume of each water-drop was 1μL, and each water-drop was measured at three time points (initial, 1s later, and 5s later) ever since it dropped on the leaf surface. The contact angle of each water-drop at each time point was measured by calculating the average value of the contact angle on the right and the left side of each water-drop (SCA 20 software, Dataphysics Instruments, Germany). The contact angle value of each water-drop is the average value of the value taken at three time points, the contact angle value of each leaf sample is the average value of the three tested water-drops, the contact angle value of each repetition is the average value of the four tested leaf samples, and the contact angle value of each plant species is the average value of the three repetitions.

4.2.3.5 Statistical analysis

Statistical analysis was performed by SPSS Statistics version 22.0 (IBM, New York, USA). One-way ANOVA analysis was performed to determine whether significant statistical differences exist between different tested species to capture PM with different size fractions under different traffic pressures and at different sampling heights. The results are significant at the level of $P < 0.05$. Independent sample T test was used to determine if significant differences exist for the amount of deposited PM on leaf surface of the two tested roadside plants under the same traffic pressure.

4.3 Results

4.3.1 PM capturing efficiency of roadside plant species under different traffic pressures

4.3.1.1 PM capturing efficiency of *Hedera helix* under different traffic pressures

The efficiency of *H. helix* to capture PM_{10} and $PM_{2.5}$ varied under different traffic pressures (Table 4.3). For PM_{10} capturing, *H. helix* showed its highest efficiency (0.067 ± 0.008 mg cm^{-2}) under the high traffic pressure. With the traffic pressure getting lower, its efficiency value declined slowly to its minimum (0.043 ± 0.003 mg cm^{-2}) when was under the low traffic pressure. According to one-way ANOVA analysis, no significant efficiency difference was found ($P = 0.268 > 0.05$) between under high, middle and low traffic pressures for *H. helix* to capture PM_{10}.

For $PM_{2.5}$ capture, *H. helix* showed its highest capturing efficiency under the middle traffic pressure (0.042 ± 0.012 mg cm^{-2}). When was under high and low traffic pressures, its efficiency value was almost similar (0.035 ± 0.006 mg cm^{-2} under the high traffic pressure, and 0.031 ± 0.003 mg cm^{-2} under the low traffic pressure). No statistical efficiency difference was found between the three traffic pressures for $PM_{2.5}$ capturing ($P = 0.636 > 0.05$).

Table 4.3: Leaf surface PM capturing efficiency of different roadside plant species under the same traffic pressure

PM	Traffic pressure	The amount of captured PM (mg cm^{-2})		t	p
		H. helix	*T. baccata*		
PM_{10}	High	0.067 ± 0.008	0.135 ± 0.025	-2.612	0.059
	Middle	0.059 ± 0.014	0.067 ± 0.009	-0.474	0.66
	Low	0.043 ± 0.003	0.039 ± 0.001	1.331	0.254
$PM_{2.5}$	High	0.035 ± 0.006	0.103 ± 0.026	-2.591	0.061
	Middle	0.042 ± 0.012	0.036 ± 0.007	0.839	0.449
	Low	0.031 ± 0.003	0.005 ± 0.006	3.882	0.018

n=3, and Data of the amount of captured PM are mean ± SE, the unit is mg cm^{-2}.

In most conditions, the amount of captured PM on leaves of the tested two plants species showed no significant statistical differences when they were under the same traffic pressure. However, under the low traffic pressure, the amount of captured $PM_{2.5}$ on leaves of *T. baccata* was significantly lower than it captured by leaves *H. helix* (Table 4.3). The difference was 0.026 ± 0.007 mg cm^{-2} (95% confidence interval was 0.007-0.044). According to Independent Samples T test, $t = 3.882$ and $P = 0.018 < 0.05$ which indicated that under the low traffic pressure, *T. baccata* had significantly lower PM capturing efficiency than *H. helix* for $PM_{2.5}$ capture.

4.3.1.2 PM capturing efficiency of *Taxus baccata* under different traffic pressures

The efficiency of *T. baccata* to capture PM_{10} and $PM_{2.5}$ were also different under different traffic pressures (Table 4.3). For PM_{10} capturing, *T. baccata* showed its peak efficiency value under the high traffic pressure (0.135 ± 0.025 mg cm^{-2}). With the traffic pressure mitigating, its efficiency value declined sharply and reached its minimum value when was under the low traffic pressure (0.0399 ± 0.001mg cm^{-2}). The efficiency value for PM_{10} capturing under the high traffic pressure was about three times as much as it when was under the low traffic pressure. According to one-way ANOVA analysis, there was a significant efficiency difference for PM_{10} capturing between the high traffic pressure and the other two traffic pressures ($P < 0.5$), but the efficiency value under middle and low traffic pressure was similar. No statistical efficiency difference was found ($P > 0.5$).

For $PM_{2.5}$ capturing, *T. baccata* showed the similar trend as its efficiency for PM_{10} capture. The highest efficiency was found under the high traffic pressure (0.103 ± 0.026 mg cm^{-2}). Under the middle traffic pressure, its $PM_{2.5}$ capturing efficiency decreased significantly to 0.036 ± 0.007 mg cm^{-2}, and under the low traffic pressure, the value reached its minimum value (0.005 ± 0.006 mg cm^{-2}). The efficiency value under the high traffic pressure was about 19 times as much as it when was under the low traffic pressure. Significant statistical difference was found between each traffic pressure.

4.3.1.3 Comparation of PM capturing efficiency of different leaf-shaped species under different traffic pressures

Regarding *H. helix* as broad-leaved species and *T. baccata* as needle-leaved species, positive relationship was found between traffic pressures and their PM_{10} capturing efficiency (Fig. 4.5). Needle-leaved species was more sensitive than broad-leaved species to the change of traffic pressure. From high traffic pressure to low traffic pressure, PM_{10} capturing efficiency of needle-leaved species decreased sharply from 0.135 ± 0.025 mg cm^{-2} to 0.039 ± 0.001 mg cm^{-2}. While the efficiency value of broad-leaved species decreased gently from 0.067 ± 0.008 mg cm^{-2} to 0.043 ± 0.003 mg cm^{-2}.

Needle-leaved species captured more PM_{10} onto their leaves than broad-leaved species under the high traffic pressure, its efficiency value was about 2 times as much as it of broad-leaved species. Under the middle traffic pressure, although the PM_{10} capturing efficiency of needle-leaved species was a little higher, the value was almost similar. But under the low traffic pressure, the efficiency of broad-leaved species turned to be slightly higher than it of needle-leaved species.

For $PM_{2.5}$ capturing (Fig. 4.6), needle-leaved species only showed notably higher efficiency than broad-leaved species under the high traffic pressure (3 times higher). Under middle and low traffic pressures, broad-leaved species was more effective. Its efficiency was even 6 times higher than it of needle-leaved species under the low traffic pressure.

Positive correlation was found between PM_{10} capturing efficiency and the change of traffic pressures for both leaf-shaped species. However, for $PM_{2.5}$ capturing, positive correlation was only found for needle-leaved species. Its efficiency value was the highest when was under the high traffic pressure (0.103 ± 0.026 mg cm^{-2}), but with the changing of traffic pressure from high to low, the efficiency value declined significantly and linearly. The $PM_{2.5}$ capturing efficiency of broad-leaved species, however, changed in nonlinear trend with the decrease of traffic pressure.

4.3.1.4 Correlation between leaf surface contact angle and the PM capturing efficiency under different traffic pressures

Leaf surface CA of roadside tested plants varied under different traffic pressures (Table 4.3). *H. helix* recorded its highest leaf surface CA (100.9° ± 6.1°) under the low traffic pressure and showed the smallest

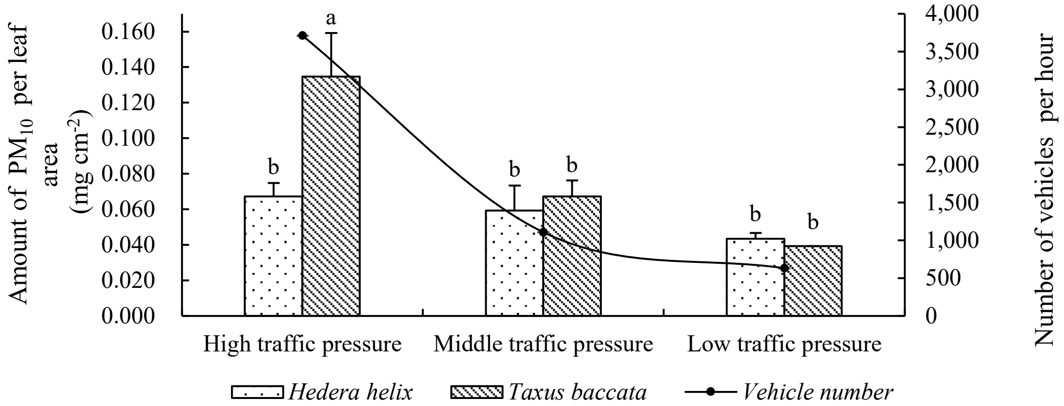


Fig. 4.5 Correlation of traffic pressure and leaf surface PM_{10} capturing efficiency of urban roadside plants. Vertical bars represent the standard error; Data are mean ± SE. Within the same species, the same letter means there is no significant statistical difference at 0.05 level. (Based on the original data from Table C-4, Appendix C)

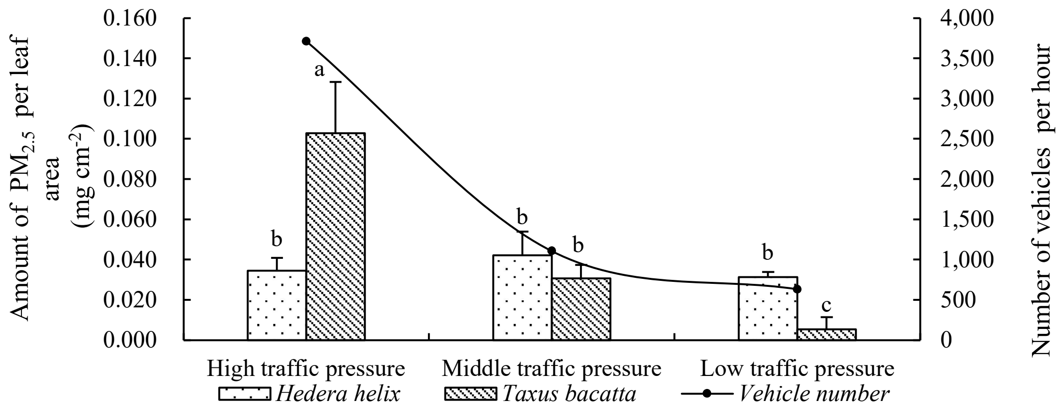


Fig. 4.6 Correlation of traffic pressure and Leaf surface $PM_{2.5}$ capturing efficiency of urban roadside plants. Vertical bars represent the standard error; Data are mean ± S.E. Within the same plant species, the same letter means there is no significant statistical difference at 0.05 level. (Based on the original data from Table C-4, Appendix C)

CA (95.6° ± 6.0°) under the middle traffic pressure. Although the value varied between different traffic pressures, the changing rate was usually quite small, which indicated that water drops on its leaf surface tended to keep stable and hard to be spread. Leaf surface of *H. helix* was always hydrophobic and showed no great changes with traffic pressures. The highest leaf surface CA (110.1° ± 10.7°) of *T. baccata* was found under the middle traffic pressure, and the smallest value (87.3° ± 10.1°) was found under the low traffic pressure. Unlike *H. helix*, leaf surface CA of *T. baccata* changed significantly between traffic pressures. Water drops on its leaf surface spread quite fast when was under the low traffic pressure, but its leaf surface was relatively hydrophobic under middle and high traffic pressures.

No statistical correlation was found between the leaf surface contact angle and the amount of captured PM_{10} on leaves of both tested species (Fig. 4.7 and Fig. 4.8). With the mitigating of traffic pressure, the amount of captured PM_{10} by *H. helix* continuously declined, while its leaf surface CA dropped at first and then slightly rose up to its peak value. According to Pearson correlation analysis, the correlation was insignificant ($P = 0.55 > 0.05$). For *T. baccata*, the phenomenon was similar, with the continuous declining of captured PM_{10}, its leaf surface CA firstly rose up to its peak value and then declined to its minimum. (Fig. 4.7c) Although negative relationship was only found between the amount of captured $PM_{2.5}$ and leaf surface contact angle for *H. helix*. (Fig. 4.7b), from the statistical viewpoint, the correlation was still insignificant at 0.05 level ($P = 0.13 > 0.05$) (Fig. 4.8b). For *T. baccata*, the correlation between its $PM_{2.5}$ capturing efficiency and its leaf CA was still non-linear ($P=0.93 > 0.05$) (Fig. 4.7d).

Table 4.3: Leaf surface contact angle of roadside species at different time points and under different traffic pressures. Data are mean ± SE, Within the same plant species at the same time point, same small letter means no significant difference is found at 0.05 level.

Samples	Contact angle (°)				Gradient
	Initial	1s later	5s later	Mean	
Hedera helix-high	101.4 ± 2.0 a	100.4 ± 1.6 a	98.8 ± 1.8 ac	98.8 ± 1.0 ab	-0.52
Hedera helix-middle	100.3 ± 1.4 a	98.4 ± 1.8 a	95.6 ± 1.7 bc	95.6 ± 1.0 b	-0.94
Hedera helix-low	104.5 ± 1.8 a	101.5 ± 1.9 a	100.9 ± 1.8 a	100.9 ± 1.1 a	-0.73
Taxus baccata-high	97.0 ± 2.0 b	92.8 ± 1.6 b	92.2 ± 1.6 b	92.2 ± 1.1 b	-0.97
Taxus baccata-middle	111.2 ± 2.3 a	110.7 ± 3.3 a	110.1 ± 3.1 a	110.1 ± 1.6 a	-0.21
Taxus baccata-low	94.2 ± 2.4 b	91.0 ± 3.7 b	87.3 ± 2.9 b	87.3 ± 1.8 b	-1.37

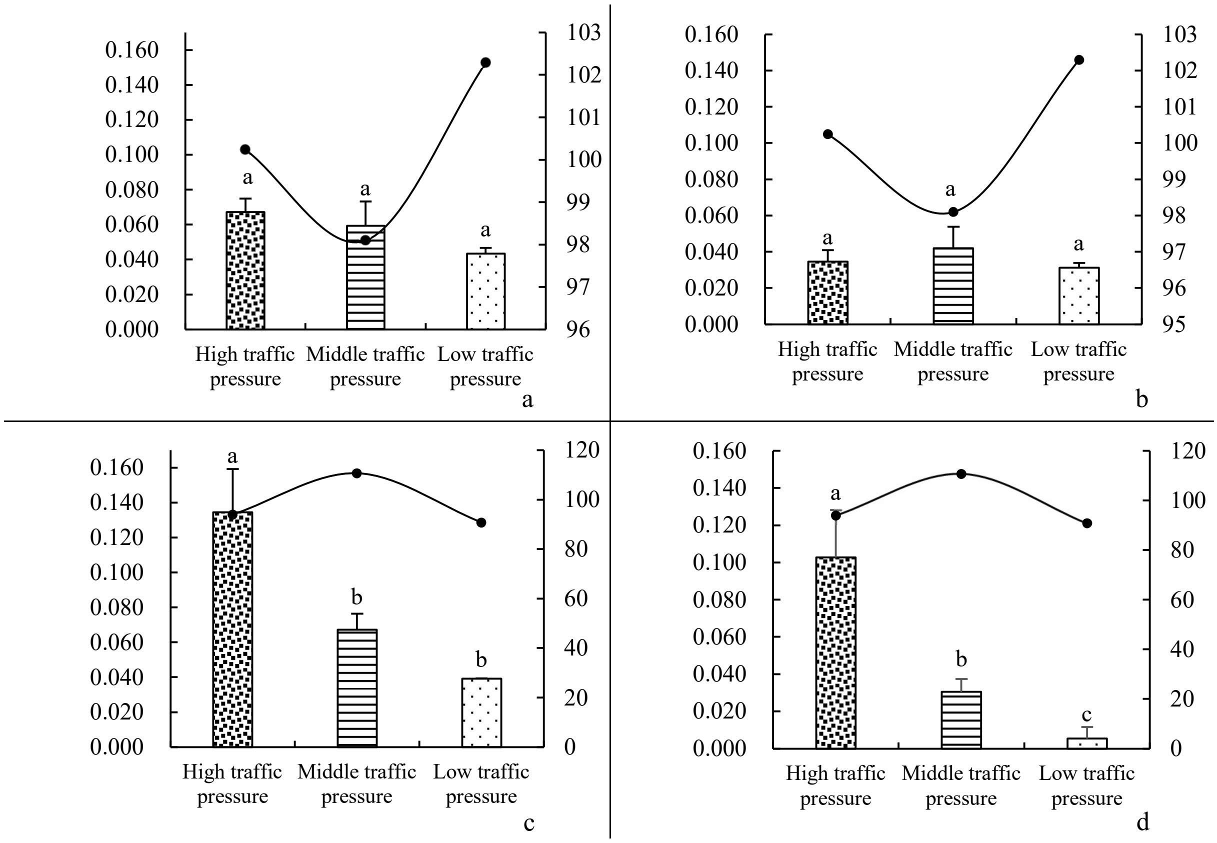


Fig. 4.7 Relationship between leaf surface contact angle and the amount of deposited PM by leaves of urban roadside plants. Bars represent the amount of captured PM per leaf area (mg cm^{-2}), and lines represent the leaf surface contact angle (°). a: PM_{10} capturing by *Hedera helix*, b: $PM_{2.5}$ capturing by *Hedera helix*, c: PM_{10} capturing by *Taxus baccata*, d: $PM_{2.5}$ capturing by *Taxus baccata*. Vertical axis on the left refers to the amount of captured PM per leaf area (mg cm^{-2}), and the vertical axis on the right refers to the leaf surface contact angle (°). The same letter means there is no significant statistical difference at 0.05 level. (Based on the original data from Table C-4 and Table C-5, Appendix C)

4.3.2 PM capturing efficiency of roadside plants at different sampling heights

4.3.2.1 PM capturing efficiency of leaf surface

Within the sampling zones which had same height range, leaf surface of *H. helix* showed notable efficiency differences in capturing PM with different size fractions (Fig. 4.9a). Its efficiency for the large PM was always higher than it for the other two sized PMs. The efficiency for the small sized PM was always the lowest. Between sampling zones which had different height ranges, leaf surface showed its highest large PM capturing efficiency (19.832 ± 0.988 μg cm^{-2}) at the height between 0.5 m to 1 m above from the ground. The value was 4 times as much as it for coarse PM capturing (5.342 ± 0.583 μg cm^{-2}), and 51 times as much as it for fine PM absorbing (0.387 ± 0.029 μg cm^{-2}). In each sampling zone, significant efficiency differences were found to capture PM with different size fractions.

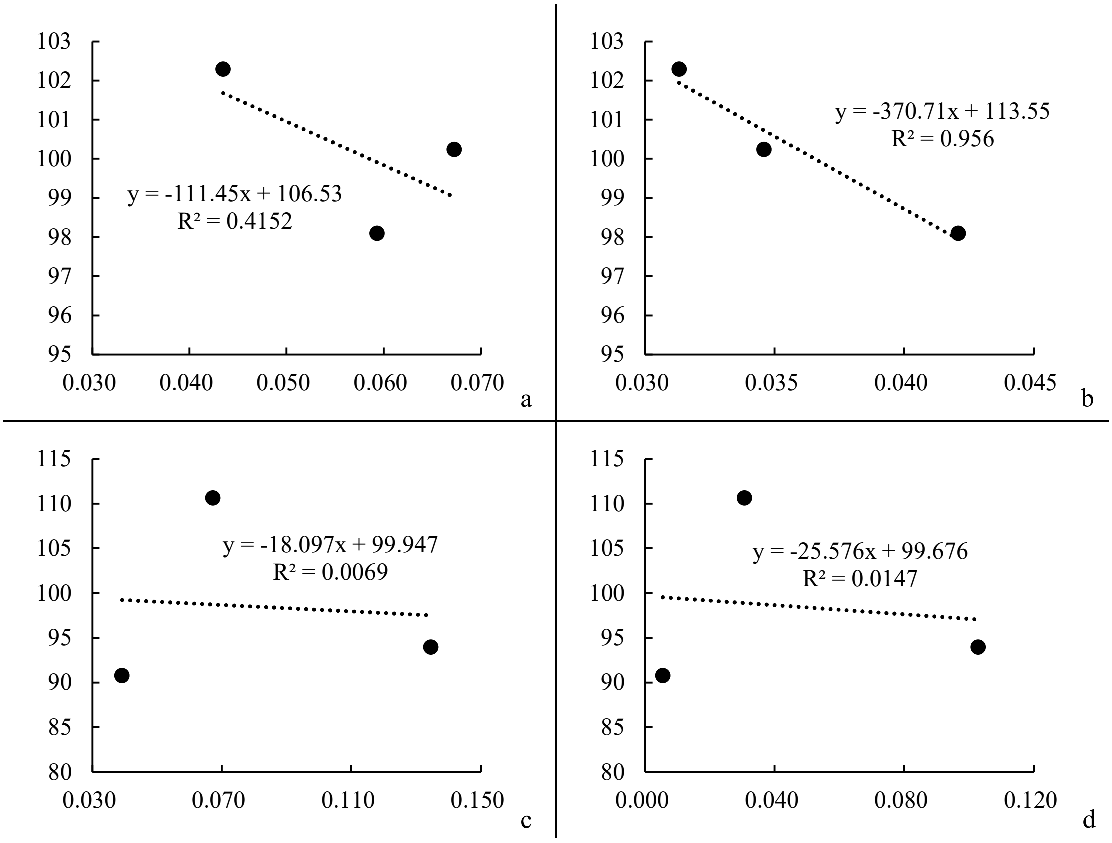
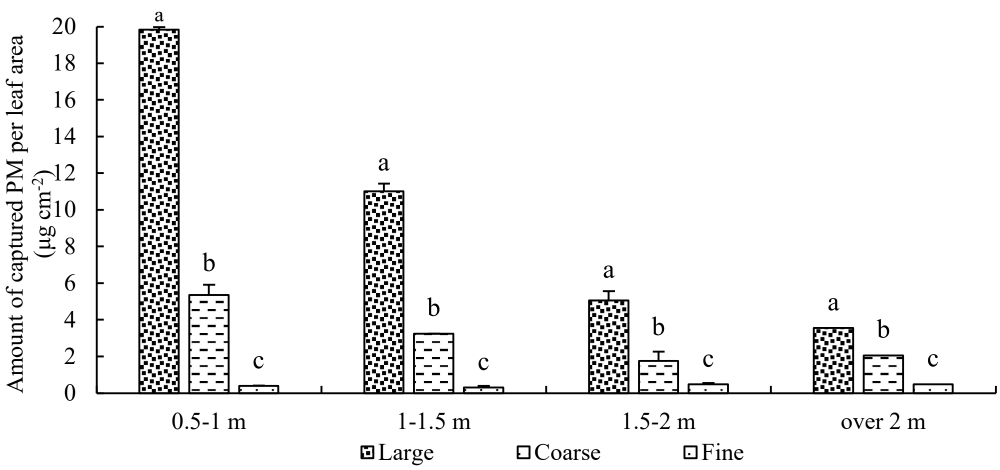


Fig. 4.8 Correlation between leaf surface contact angle and the amount of deposited PM by leaf surface of urban roadside plants. Vertical axis refers to the leaf surface contact angle (°) and abscissa refers to the amount of captured PM per leaf area (mg cm^{-2}). a: PM_{10} capturing by *Hedera helix*, b: $PM_{2.5}$ capturing by *Hedera helix*, c: PM_{10} capturing by *Taxus baccata*, d: $PM_{2.5}$ capturing by *Taxus baccata.* (Based on the original data from Table C-4 and Table C-5, Appendix C)

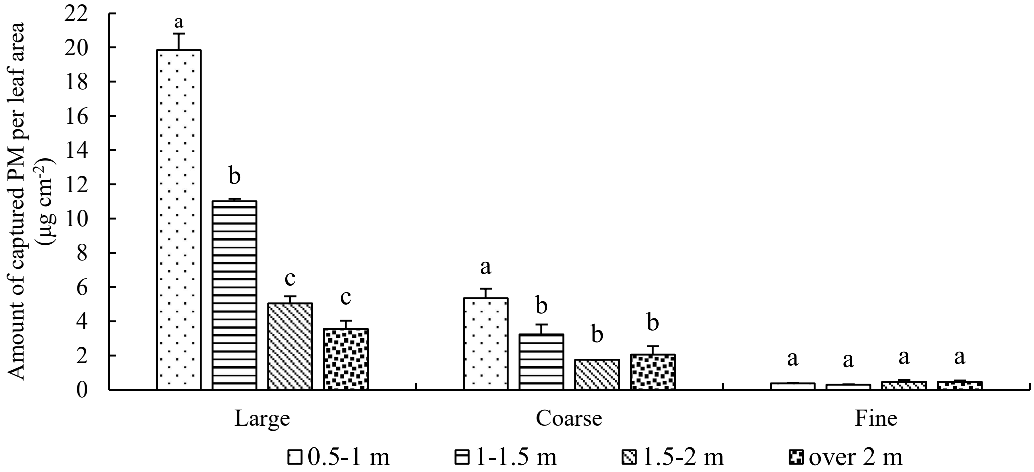
Between sampling zones which had different heights, the efficiency of leaf surface to capture same sized PM also varied (Fig. 4.9b). With the sampling height rising up from 0.5 m to over 2 meters, the large PM capturing efficiency of leaf surface declined significantly from 19.832 ± 0.988 µg cm^{-2} to 3.549 ± 0.504 µg cm^{-2}, the efficiency at 0.5-1m was 6 times as much as it at over 2 m. For coarse PM capturing, the efficiency of leaf surface from all sampling zones was generally low and changed slightly with heights. Leaf surface at 0.5-1 m was only three times effective as it at over 2 m. For fine PM capturing, leaf surface from all sampling zones showed similar low efficiency. Significant statistical difference was found for the large and coarse PM capturing between different sampling zones, while for fine PM, there was no statistical difference.

4.3.2.2 PM capturing efficiency of leaf epicuticular wax

Despite the great amount of PM deposited on the leaf surface, leaf epicuticular wax also showed high efficiency to capture PM with different size fractions. Within sampling zone which had same sampling height, the amount of captured fine PM was normally about 7 to 9 times as much as it of captured large PM (Fig. 4.10a). Within the sampling zone with a height of 1-1.5 m above from the ground, leaf



a



b

Fig. 4.9 Capturing efficiency for PM with different particle sizes on the leaf surface. Vertical bars represent the standard error; Statistic analysis by one-way ANOVA showed that there are significant differences between different species ($P < 0.05$); Data are mean ± SE. Within the same PM size fractions and height groups, the same letter means there is no significant statistical difference at 0.05 level. a: results for PM with different particle sizes at the same sampling height. b: the results for PM with same particle sizes at different sampling heights. (Based on the original data from Table C-6, Appendix C)

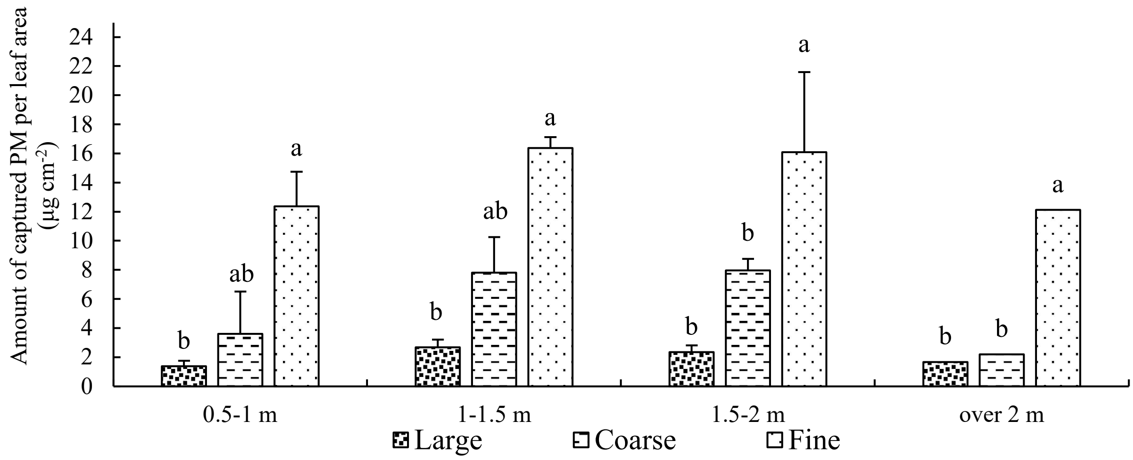
epicuticular wax showed its highest capturing efficiency for fine PM (16.367 ± 2.383 µg cm^{-2}). The value was 2 times as much as it for coarse PM and 6 times as it for large PM capture. There was significant efficiency difference between fine and large PM capturing. No statistical difference was found between large and coarse PM capturing.

Unlike leaf surface, for same sized PM, the amount of deposited PM by leaf epicuticular wax showed no obvious height-related variation (Fig. 4.10b). With the sampling height rising up, the efficiency to capture different sized PM all took on the trend increased first and then declined. For fine PM capturing, with the sampling height increasing from 0.5 m to 1.5 m, the leaf`s efficiency value increased from 12.370 ± 3.475 µg cm^{-2} to the peak value 16.367 ± 2.383 µg cm^{-2} , and held to be high (16.074 ± 0.753 µg cm^{-2})

at 1.5-2m. When the height increased to over 2 m, the value decreased slightly to its minimum (12.119 ± 5.524 μg cm^{-2}). For coarse PM capturing, the efficiency at the height range of 1-2 m was about twice as much as it of the sampling area with the height of 0.5-1 m and over 2 m. The efficiency for large PM capturing was always the lowest compared with it of the other two sized PM. Except to capture fine PM, leaf epicuticular wax played a very limited role for both large and coarse PM absorbing.

4.3.2.3 Distribution characteristics of captured PM on leaf surface and in leaf wax

Leaf surface and leaf epicuticular wax both showed absorbing preference for PM with different size fractions, and the distribution tendency of different sized PM on leaf surface and in epicuticular wax was also diverse (Fig. 4.11). Most large PM (with a diameter over 10 μm) tended to be concentrated on the leaf



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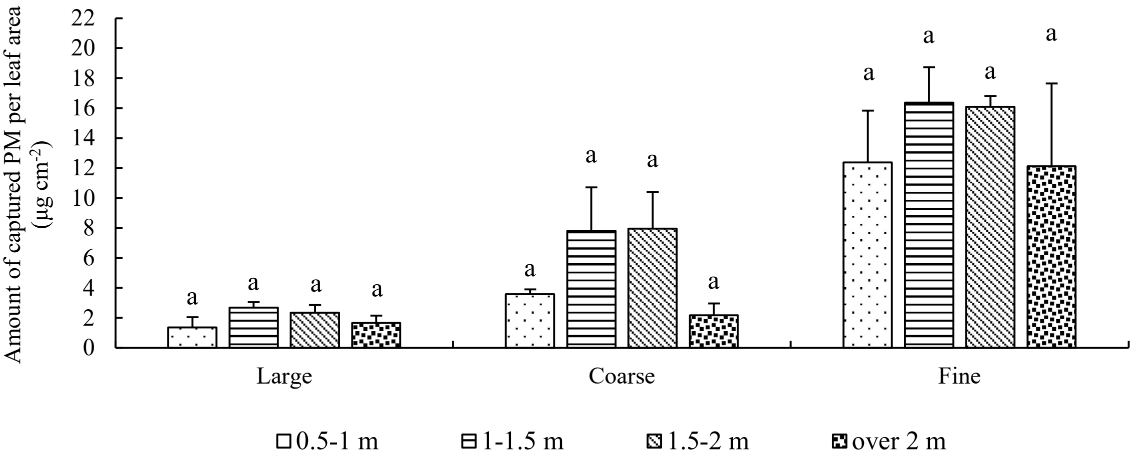

b

Fig. 4.10 Efficiency of leaf epicuticular wax to capture PM with different particle size fractions. Vertical bars represent the standard error; Statistic analysis by one-way ANOVA shows that there are significant differences between different species ($P < 0.05$); Data are mean ± SE. Within the same height range and height group, the same letter means there is no significant statistical difference at 0.05 level. a: for PM with different particle size fractions at the same sampling height, b: for PM with the same particle size fractions at different sampling heights. (Based on the original data from Table C-7, Appendix C)

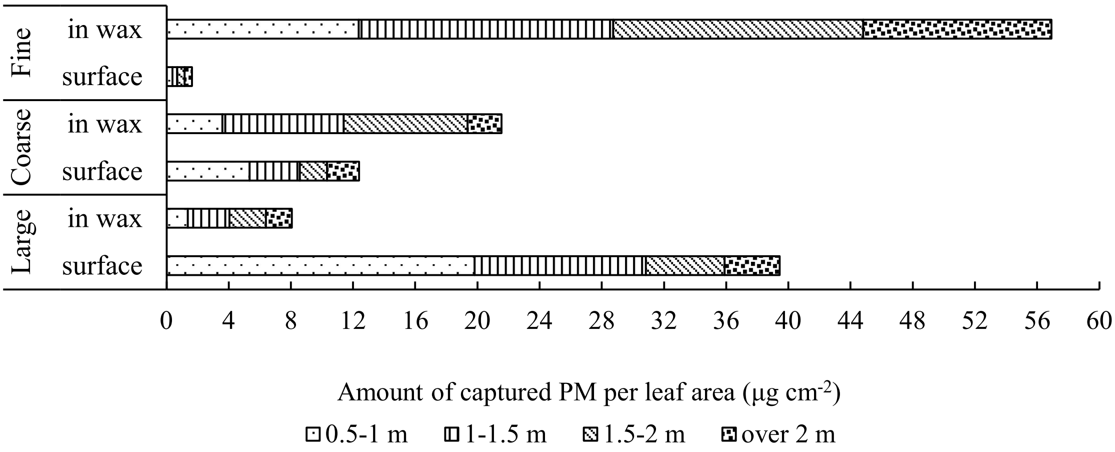

Fig. 4.11 Distribution tendency of different sized PM on leaf surface and in leaf epicuticular wax. Large: PM with a diameter over 10 μm, Corase: PM with a diameter 2.5-10 μm, Fine: PM with a diameter 0.2-2.5 μm. Bars represent the capturing efficiency of different height ranges. (Based on the original data from Table C-6 and Table C-7, Appendix C)

surface, the amount of the deposited large PM by leaf surface on the green wall was about 39.448 μg cm^{-2}, which was five times as much as it deposited by leaf epicuticular wax. The amount of coarse PM (with a diameter between 10 μm to 2.5 μm) captured by leaf surface and by leaf epicuticular wax was almost similar. But leaf epicuticular wax showed significantly high preference for fine PM than leaf surface, its capturing capacity for fine PM (with a diameter between 2.5 to 0.2 μm) was about 30 times as much as it of leaf surface. As most large PM was concentrated on leaf surface, it was the major area for large PM absorption, and leaf epicuticular wax was the area mainly for fine particle capture.

4.3.2.4 Distribution characteristics of captured PM on the green wall with different height ranges

At different sampling height ranges, the captured PM showed diverse size fractions (Fig. 4.12a). On leaf surface, 60%-70% was large PM at each sampling zone, and most large PM tended to be concentrated on leaf surface which was close to the ground. With the sampling height rising up, the percentage of the captured large particle declined sharply from 77.59% to 58.36%. About 20%-25% PM in each sampling zone was coarse PM, and the percentage rose up from 20.90% to 33.74% along with the sampling height. Although the percentage of captured fine PM on leaf surface also rose with sampling height, the value was only increased from 1.51% to 7.90% (Fig. 4.12a).

In leaf epicuticular wax, fine PM was the main component of captured PM, with sampling height rising up, the percentage of fine PM decreased first and then increased to its peak value when the height range was over 2 m. on the contrary, the percentage of coarse PM increased first along with heights and then decreased to its minimum at the height range over 2 m. The percentage of coarse PM on leaf surface and in epicuticular wax were almost equal (about 24%). Only a little amount of large PM was found in epicuticular wax, and its percentage remained stable and low at each sampling zones (about 9%). (Fig. 4.12b)

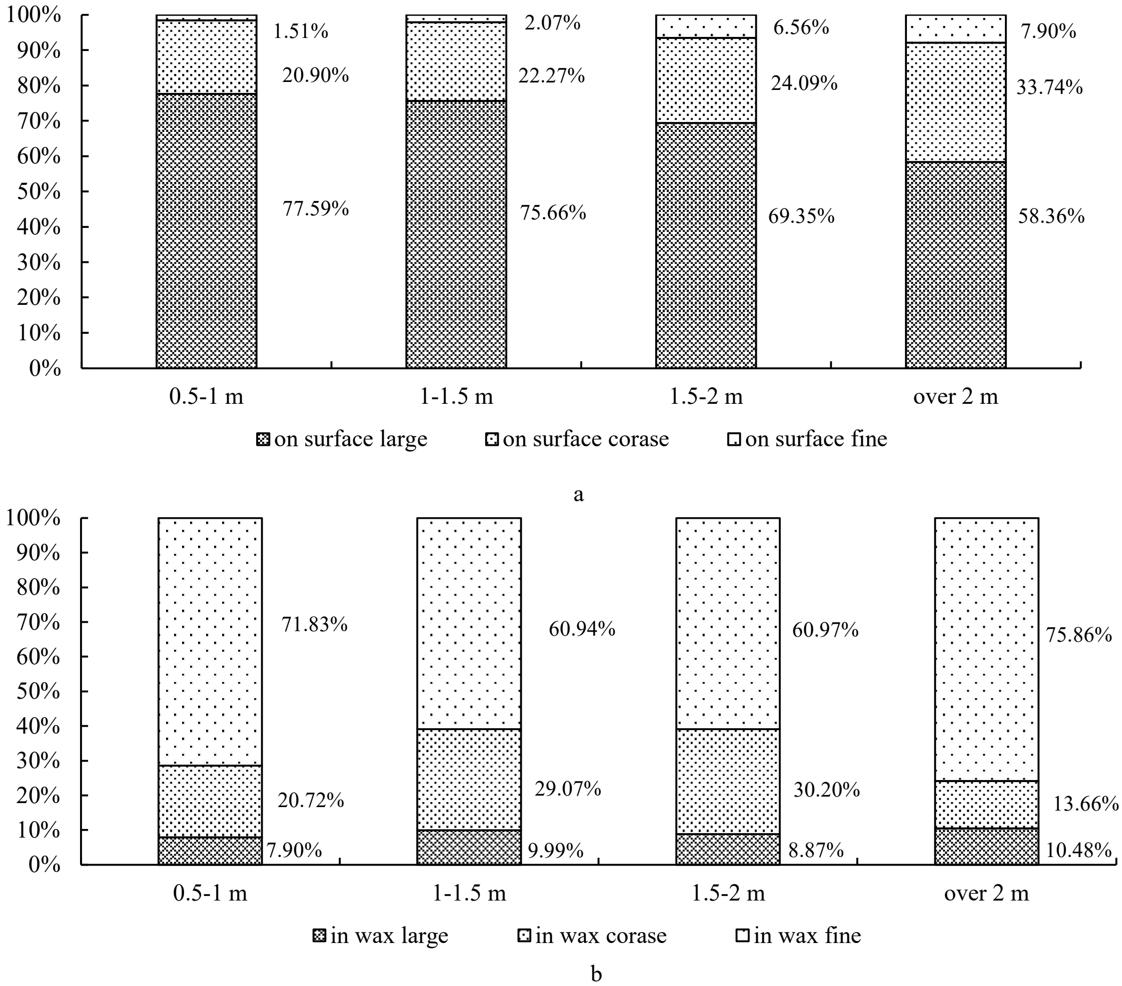

Fig. 4.12 Percentage of captured PM with different size fractions in sampling zones with different height ranges. a: captured PM on the leaf surface, b: captured PM in leaf epicuticular wax. (Based on the original data from Table C-6 and Table C-7, Appendix C)

4.4 Discussion

In this chapter, both tested roadside species showed a certain amount of PM retention efficiency under various traffic pressures. Agreed with former studies, different plant species showed various retaining capacities for PM with different aerodynamic diameters under the same traffic pressure (Freer-Smith *et al.* 2005, Ottelé *et al.* 2010). This variation may due to the aerodynamic properties of PM, and their interactions with different leaf surface structural characteristics (Petroff *et al.* 2008). Another factor caused the efficiency difference between species was the different deposition velocities (Slinn 1982). Depositing process of PM on leaf surface is mainly through dry deposition which includes processes such as sedimentation, impaction and interception (Sabin *et al.* 2006). Different process thus results in different deposition velocities. Besides, trapped PM on leaf surface could be removed again in some cases like rainfall flushing or wind blowing. Diverse remobilization rates of PM with different size fractions (Gregory 1973) may also influence its quantities captured on leaves (Weerakkody *et al.* 2017). Generally, needle-leaved species has been proved to have higher capturing efficiency than broad-leaved species (Sæbø *et al.* 2012, Gourdji 2018, Xu *et al.* 2018), This viewpoint is further verified by us under different traffic conditions. As needle-leaved species, *T. baccata* was much effective than broad-leaved species: *H. helix*, its average retaining efficiency for PM_{10} and $PM_{2.5}$ was about 1.5 times as much as it was for *H. helix* respectively. The reason for the high efficiency of needle-leaved species based on its several special properties. As tree species, *T. baccata* has a larger canopy, and its needle-shaped leaves provide overall a larger surface area for PM to settle on (Chen *et al.* 2017). In addition, PM concentration increases when trees are planted along the streets because air circulation is reduced (Salmond *et al.* 2013). More turbulent mixing of air is caused by large leaf surface area of tree species than by climbing vegetation, and PM has thus enough time and opportunities to be deposited on leaf surface (Beckett *et al.* 2000a). Besides, specific leaf morphology also enhances the efficiency of *T. baccata*. Plenty of grooves and wrinkles on its leaves increase its leaf surface roughness and provide sufficient room for PM to be embedded in. The thin boundary layers of its long leaves make PM much easily hit and then deposit on its flat leaves (Sæbø *et al.* 2012). Consistent with the results of Dzierzanowski *et al.* (2011), we also found large PM is more easily deposited on the leaf surface of both species. However, Przybysz *et al.* (2014) found small PM is much easier to be retained. This disparity may be attribute to different methods applied to quantify PM. The gravimetric method we use may cause a high weight/area value, while the SEM/image method used by Perini is to evaluate the PM capturing efficiency of plants by counting the number of different sized PM captured on the leaf surface. The proportion of different sized PM contained on leaf surface may also cause this disparity (Weerakkody *et al.* 2017).

Although both roadside species reached their own highest PM_{10} capturing efficiency under the high traffic pressure, the value of *T. baccata* (needle-leaved) was still higher than it of *H. helix* (broad-leaved). For $PM_{2.5}$ capturing, needle-leaved species was more efficient than broad-leaved species only under the high traffic pressure. As broad-leaved species, *H. helix* accumulated the highest amount of PM_{10} under the high traffic pressure and the amount of accumulated $PM_{2.5}$ reached the peak value under the middle pressure. For needle-leaved species: *T. baccata*, the retaining efficiency for both PM_{10} and $PM_{2.5}$ decreased with the mitigating of traffic pressure. However, the changing rate of needle-leaved species between traffic pressures was much significant than it of broad-leaved species. The results documented in our test partly confirm our first hypotheses: the PM capturing efficiency of roadside species increases with the growth of traffic pressure except for $PM_{2.5}$ absorbing process of broad-leaved species.

The efficiency disparity of different leaf-shaped species under various traffic pressures is mainly caused by the following factors: the first is the variation of PM concentration between roads under different traffic densities. As one of the main process for PM capture, dry deposition is accelerated by the increase of the concentration of air pollution in ambient atmosphere. Fleck *et al.* (2016) evaluated the air quality in areas near highways with heavy vehicular traffic in five Brazilian cities and found cities with heavy traffic density have a significantly high amount of accumulated $PM_{2.5}$ and NO_2 compared to those far from highway systems. Turkyilmaz *et al.* (2018) found a high amount of heavy metal accumulation on leaves of *Prunus cerasifera* in dense-traffic areas. Other studies also have confirmed a high correlation of high $PM_{2.5}$ density with areas which have high vehicular traffic (Bathmanabhan and Saragur Madanayak 2010, Lawson *et al.* 2011, Mukerjee *et al.* 2015). The changing of meteorological condition caused by diverse traffic densities is the second reason. Besides the concentration of air pollution, dry deposition velocity is also determined by meteorological conditions (Shahin *et al.* 2002, Petroff *et al.* 2008, Mammarella *et al.* 2011, Zhu *et al.* 2016). Wind speed is the first factor to affect dry deposition velocity. According to former studies, urban areas with a high traffic density tend to have an average high wind speed (Toja-Silva *et al.* 2013, Morbiato *et al.* 2014, Yang *et al.* 2016), and a higher wind speed then leads to both higher PM deposition velocity and higher PM capturing efficiency for roadside plants (Shahin *et al.* 2002). The higher temperature is also found indirectly contribute to accelerate the velocity of dry deposition. Areas with high vehicle exhaust emission usually show higher temperature, and the urban heat island effect is caused by the larger heat storage (Kalnay and Cai 2003, Oleson *et al.* 2013). An intense urban heat island effect allows a great momentum of air flux from atmospheric stable area with low traffic pressure to high temperature area with busy traffic (Lee 1979). Wind speeds up in area with heavy traffic and then the velocity of dry deposition is thus accelerated. The last factor is the change of leaf surface microstructures such as stoma, guard cells and trichome. Leaf surface with more trichomes is found more effective to capture PM (Freer-Smith *et al.* 2005). The number of deep grooves and wrinkled cuticles which can increase leaf surface roughness and PM absorbing capacity are found increased on leaf surface from area with high traffic density (Kupcinskiene and Huttunen 2005, Xie *et al.* 2014, Weerakkody *et al.* 2017). Yang *et al.* (2015b) compared the PM capturing efficiency on leaves in areas with different PM densities and found leaf surface of *Euonymus japonicus* from traffic area shows higher PM retaining efficiency, meanwhile more trichomes, massive grooves and protuberances are observed on its leaves compared with those from clean area. Leaf surface of *Fraxinus chinensis* in industrial areas has higher bar protuberances than it in clean area, and its PM capturing ability is considered to be highly improved. In addition, the grooves on the leaf surface of *G. biloba* are deeper in the industrial area, and thus its PM-retaining ability is thought to be enhanced.

Leaf surface CA varies under different traffic pressures. According to former researches, for different plant species, negative correlation is found between leaf surface contact angle and the amount of captured PM (Koch *et al.* 2009, Kardel *et al.* 2010, Wang *et al.* 2013). However, for the same plant species, although the leaf surface contact angle changed between different traffic pressures, this correlation was insignificant. This indicates that interspecies differences rather than leaf surface hydrophilicity might be more important for plants to have different PM capturing capacity under different traffic pressures. Between different traffic pressures, leaf surface contact angle of *T. baccata* changed significantly than it of *H. helix*, and this indicates that leaves of *T. baccata* might be more vulnerable to air pollution (Kardel *et al.* 2012) even though it showed a relatively high PM capturing capacity under high traffic pressure. The contact angle of *H. helix* changed slightly with the change of traffic pressure, and its leaves were more tolerant and effective under all traffic densities. Although *T. baccata* generally captured more amount of PM, a vertical green wall covered by *H. helix* could be more befitting and proper to be set along roads as PM absorber under diverse traffic pressures. In brief, leaf surface contact angle was different under different traffic pressures, but the change of surface contact angle had limited effects on plants` PM capturing capacity, and was not a major cause for the different PM capturing capacity under different traffic densities.

Green walls are originally developed for saving energy, reducing ambient temperature and other aesthetics purpose, recently it gets more concern because it is proved to be a proper method for urban air pollution cleaning. Green walls are vegetated surface where plants are attached to the wall surface through various mechanisms (Abhijith *et al.* 2017). They are classified into two types: green facades and living walls. Unlike green facades which attaches plants onto walls by special supporting features, living walls are vertical walls with growing media attached to (Manso and Castro-Gomes 2015, Susorova 2015). As a new tool for urban air pollution reduction, green walls reduce PM concentration without altering air exchange between streets (Litschke and Kuttler 2008). Its high PM capturing efficiency has been confirmed by former studies. Pugh *et al.* (2012) claimed up to 35% NO_2 concentration and 50% PM_{10} concentration is reduced by the green wall system. Dzierzanowski *et al.* (2011) found the green wall could act as a sink for PM capturing all year long, because the captured PM on the leaf surface could be later washed off by rain falls. Other studies also confirmed the high efficiency of green wall for PM reduction (Joshi *et al.* 2014, Jayasooriya *et al.* 2017). Common climbing plants are found suitable to cover green walls in Europe (Sternberg *et al.* 2010). The large leaf surface area which is up to over 14 cm^2, the high on-wall growth which is over 20 meters and relatively high amount of captured PM on its unit leaf surface area make English ivy (*Hedera helix*) an effective PM filter which has great potential for urban PM absorption (Heuzé *et al.* 2009). Agreed with former researchers, our test also found leaves of English ivy (*H. helix*) possess high efficiency as PM absorber at different height ranges on the green wall. It showed its highest PM_{10} capturing efficiency at the height range of 0.5-1 m above from the ground, and the highest efficiency for $PM_{2.5}$ at the height of 1-2 meters. According to Ottelé *et al.* (2010), the sampling height has no influence on the amount of accumulated PM by *H. helix*. Our results partly agreed with his conclusion. Except the condition that the amount of accumulated large PM had a sharp decreasing trend with the rise of height, the capturing capacity for other sized PM showed no obvious height-related relationship. As a result, our second hypothesis is partly rejected. Although large PM which has an aerodynamic diameter larger than 10 μm tended to be accumulated on the low-height zone of the green wall, the capacity of *H. helix* to capture other sized PM has no relationship with its sampling height.

Epicuticular wax has significant effects on PM absorption which has been claimed by former studies (Kaupp *et al.* 2000, Jouraeva *et al.* 2002). Sabin *et al.* (2006) reported that pine species with thicker epicuticular wax layer helps leaves to deposit more particles. Positive correlation is claimed by Sæbø *et al.* (2012) between the quantity of wax and the amount of accumulated PM with different size fractions, and similar positive correlation between the amount of captured coarse PM and the amount of wax on leaf surface has been claimed by Popek *et al.* (2013). Although both leaf surface and epicuticular wax have notable ability to capture PM from the air, the area of which surface is more effective remains a subject of some debate. According to Xu *et al.* (2018), the amount of captured PM on leaf surface is about 4 times higher than that of captured in epicuticular wax. After testing 13 woody species, Popek *et al.* (2013) also reported most PM is deposited on leaf surface other than in wax. However, other researchers presented the opposite outcomes. Sæbø *et al.* (2012) found 80% PM is accumulated in leaf wax of *Betula pendula*. Viecco *et al.* (2018) found generally 52% of the PM is fixed in leaf wax in their study, and for the most effective species, *Sedum album*, the percentage of captured PM in the leaf wax reaches almost 84%. More fine PM is observed in leaf wax of *Quercus ilex* than large PM in an industrial city of central Italy, and this finding confirms the significant major effect of wax for fine PM rather than large PM removal (Sgrigna *et al.* 2015). Sæbø *et al.* (2012) claimed most PM is captured in leaf wax of *B. pendula* because of the rich wax content of its leaves, and he reported the positive correlation between the content of leaf wax and the PM capturing efficiency. In our test, leaf surface was found to be the major functional area for large PM removal at different sampling heights, almost 70% of captured PM by leaf surface was large PM and only about 5% of captured PM was fine PM. While agreed with Viecco *et al.* (2018), epicuticular wax was more effective to capture fine PM. Almost 65% captured PM in leaf wax was fine PM while the percentage of captured large PM in leaf wax was only about 10%. The reasons leaf surface of different species showed various preference for PM with different size fractions are as follows: 1. The average background PM concentrations. As sedimentation under gravity is the process by which PM deposits onto leaves, different PM concentration may lead to the discrepancy of former studies. 2. Interspecific difference. As wax of different species had different physicochemical properties, some plant species might show distinctive PM retention efficiency (Jouraeva *et al.* 2002). 3. PM capturing capacity of leaves depends on the adhesion force between leaf surface and particles. This adhesion force is the intermolecular force which is determined by the chemical constitution of molecules and interfacial area (Wang *et al.* 2015d). However, epicuticular wax layer on the upper leaf surface is found to be eroded by captured PM at industrial and traffic regions (Singh *et al.* 2018). The different wax erosion degree between species with different background PM concentrations changes the interfacial area of different plant species, and then causes the change of adhesion force and the variation of capturing efficiency (Wang *et al.* 2015d). In addition, thin epicuticular wax layer has been reported to accelerate the efficiency for $PM_{2.5}$ capturing, while dense wax decreases the interface area for PM to settle on and reduces the capturing efficiency (Wang *et al.* 2015d, Singh *et al.* 2018). Our third hypothesis is accepted. As leaf wax captures a great amount of fine PM, and its high capturing capacity has no height-related changes , setting green walls which are covered by leaves of *H. helix* alongside city streets would maximize its potential health effects, and reduce the health risk from PM pollution, especially those caused by inhaled fine PM to the cardio-pulmonary system. Yet at the same time, the effects which brought by PM concentration in the air, and to what extent PM size distribution in the air will affect the size distribution of captured PM on the green wall need further study in the future.

4.5 Conclusions

Different roadside plant species tested in this chapter showed significant efficiency differences in PM capturing under different traffic pressures. Leaves of *H. helix* were most effective for PM_{10} and $PM_{2.5}$ capturing under the high and middle traffic pressure respectively. Leaves of *T. baccata* showed their highest PM_{10} and $PM_{2.5}$ efficiency under the high traffic pressure. With the traffic pressure mitigating, the efficiency value of *H. helix* changed slightly, while the value of *T. baccata* declined significantly. Although under the high traffic pressure, both needle-leaved and broad-leaved species had the peak value for PM_{10} capturing, the value of needle-leaved species was higher than it of broad-leaved species. Under middle and low traffic pressures, leaf shape had little effect on PM_{10} capturing. For $PM_{2.5}$ capturing, needle-leaved species showed the highest efficiency value under the high traffic pressure, and broad-leaved species was most effective under the middle traffic pressure. The efficiency values of the two test species were approximate under the middle pressure, but the value`s differences under the other two pressures were quite big. Besides, the PM_{10} capturing efficiency of the two species declined along with the mitigation of traffic density, but only needle-leaved species showed a positive relationship between its $PM_{2.5}$ capturing efficiency with the change of traffic pressure. In addition, the leaf surface of *H. helix* kept to be highly hydrophobic between different traffic pressures, while the leaf surface contact angle of *T. baccata* changed significantly. The relationship between leaf surface contact angle and PM capturing capacity was always nonlinear with the exception of the $PM_{2.5}$ capturing efficiency of *H. helix* and its leaf surface contact angle. More amount of large PM tended to be captured on leaf surface while epicuticular wax was the main absorber for fine PM. Leaf surface 0.5-1 m above from the ground was the major capturing zone on the green wall for large PM, and with the rise of sampling height, the efficiency value declined sharply. While the high efficiency of epicuticular wax was hardly affected by the change of heights. As the efficiency of roadside plants to capture PM was affected by the changes in traffic pressures and sampling heights, finding the relationship between traffic pressure and PM capturing capacity, exploring the specificity of PM capturing capacity between different height ranges will provide scientific and feasible options for city managers to arrange green belts along city roads, and maximize the capacity of roadside plants as phytoremediation for urban PM reduction.

Chapter 5 General discussion and Conclusions

As serious health risks have been posed by air pollution, especially by PM with various size fractions, increasing debates has risen up among the public and residents in the urban areas. Policy makers and researches are facing the need for an efficient and eco-friendly solution to alleviate the PM pollution in cities. Thus urban vegetation thus has attracted increasing attention since 20th century (Hennebo 1955, Guderian (1975), Mo *et al.* 2015). Although various sources contribute to PM generation, the urban one is mainly caused by urban transportation and traffic system (Kunzli *et al.* 2000). Hence, roadside plants are regarded as one of the most important phytoremediation. The main objectives of this research are to find some kinds of appropriate roadside plants from commonly cultivated urban species for both PM_{10} and $PM_{2.5}$ capture by comparing their PM capturing efficiency; to summarize the intercommunity of highly efficient roadside plant species; to explore the underlying reasons which make a certain roadside plant suitable for urban PM absorption; to explore feasible use patterns of highly effective roadside plant species and to evaluate the influence brought by different internal and external factors to urban vegetations` PM capturing efficiency.

5.1 General discussion

5.1.1 Variation of PM capturing efficiency of different roadside plant species and the apparent intercommunity of highly efficient leaves

Different plants have various abilities to absorb particulate matters (Dzierzanowski *et al.* 2011). To compare the PM capturing efficiency of different plants, 12 roadside species were selected and their capturing efficiency was measured in September, when all plant species reach their optimum growth condition and their leaves are all fully spread (Chapter 2). Among all tested species, *B. thunbergii* and *T. baccata* showed the highest absorbing efficiency for PM_{10}, while *C. betulus* and *P. laurocerasus* were the most inefficient species. The efficiency value for *B. thunbergii* was almost 14 times higher than that of *P. laurocerasus*. Moreover, *B. thunbergii*, *T. baccata*, *P. nigra* and *H. helix* were also found to present notably higher PM_{10} capturing efficiency than the other 8 tested species. Within the 4 most-efficient species, *T. baccata* and *P. nigra* are needle-leaved and *B. thunbergii* and *H.helix* are broad-leaved. According to independent samples T-test, no significant difference was found for PM_{10} capturing efficiency between shrub species and tree species ($P = 0.747 > 0.05$). No notable difference was found between evergreen species and deciduous species ($P = 0.188 > 0.05$). As for $PM_{2.5}$ capture, *T. baccata* was found to be the most efficient species, with a $PM_{2.5}$ capturing efficiency more than 21 times higher compared to the least effective species considered in this study (*C. betulus*). Among the top four roadside species with high $PM_{2.5}$ capturing efficiency, the two needle-leaved species (*T. baccata* and *P. nigra*) showed much higher efficiency value than the two broad-leaved ones (*B. thunbergii* and *H. helix*) (Fig. 2.4). Between the two most efficient broad-leaved species, the efficiency value of *B. thunbergii* which has very small leaf surface area was almost 1.5 times higher than that of *H. helix*d despite the smaller leaf surface. By considering all shrub species and tree species as a whole, the $PM_{2.5}$ absorbing efficiency was almost equal. Moreover, the T-test of independent samples found no significant efficiency variation between evergreen species and deciduous species ($P = 0.059 > 0.05$).

Leaf shapes and leaf surface area were identified as key factors for roadside plant species to show high PM_{10} and $PM_{2.5}$ capture efficiency. When taking all needle-leaved species and broad-leaved species as a while respectively, a statistical analysis showed that the PM_{10} capture efficiency of needle-leaved species was 0.244 ± 0.093 mg cm^{-2}, about 3 times higher than that of broad-leaved species. The efficiency of needle-leaved species for $PM_{2.5}$ capture was also about 4 times larger. However, for the plant species with species with the same leaf shape show no differences in PM_{10} and $PM_{2.5}$ capture efficiency (Fig. 2.5). On the other hand, significant statistical difference was found when considering leaf areas. Species with very small leaf surface area (0-10 cm^2 per blade) showed the highest capturing efficiency for both PM_{10} and $PM_{2.5}$. In particular, the PM_{10} and $PM_{2.5}$ capture efficiencies were about 6 and 10 times larger those the least efficiency species with intermediate leaf area (50-100 cm^2 per blade), see Fig. 2.6 and Fig. 2.7. Statistical analysis showed that only species group with small leaf surface area showed significant high PM capturing efficiency, while no notable difference was found within the other two tested species groups in this study.

The larger PM capturing of needle-leaved species and species with small leaf surface is mainly due to three factors: first, in the lower atmosphere, particulate matters, especially fine particles, are mainly transported by the aerodynamic processes such as turbulent eddies (Grantz *et al.* 2003). The high density of needle-shaped leaves on branches reduces the wind speed and makes the atmosphere more stable. This gives PM particles more time and chances to settle onto the leaf surface (Bunzl *et al.* 1989). Second, despite the relatively small surface area, needle-leaved species and other small-leaved plant species provide a relatively larger overall surface area for PM in the ambient air to be adhered to within the same dimensional range (McDonald *et al.* 2007, Chen *et al.* 2017). At last, some special leaf surface traits such as mucus oils and the leaf wax covered on conifers may also increase the PM capturing efficiency of some needle-leaved species (Tomasz *et al.* 1994, Shao and Zhang 2005, Zhang *et al.* 2015b, Shi *et al.* 2016).

Although evergreen species like *T. baccata*, *P. nigra* and *H. helix* all showed high PM_{10} and $PM_{2.5}$ capture efficiency in summer, when all roadside plant species reached their optimum growth condition respectively (see Chapter 2), whether they were highly efficient during winter months, when air pollution concentration is relatively high and most efficient deciduous species lost their PM absorbing ability, was rarely reported. Thus, four common roadside evergreen species (*T. baccata*, *P. nigra*, *H. helix* and *P. laurocerasus*) with different leaf traits were selected, and their PM capturing efficiency (for both PM_{10} and $PM_{2.5}$) during winter months (from November to March) was measured (Chapter 3). The most effective species changed throughout the winter months. In December, all tested species showed relatively high capturing efficiency for both PM_{10} and $PM_{2.5}$. *P. nigra* was the most effective species in this month and its efficiency for PM_{10} and $PM_{2.5}$ capture reached 0.3413 ± 0.0693 mg cm^{-2} and 0.3189 ± 0.0382 mg cm^{-2} respectively. In January, *T. baccata* showed the highest contribution rate among the four tested species for both PM_{10} and $PM_{2.5}$ absorption (48.23% and 51.10% for PM_{10} and $PM_{2.5}$ capture, respectively). In March, the most efficient species for PM_{10} and $PM_{2.5}$ capture was still *P. nigra* (0.0770 ± 0.0370 mg cm^{-2} and 0.0719 ± 0.0224 mg cm^{-2}, respectively). Although the most efficient roadside evergreen species varied between months, the two needle-leaved species were still found to be more effective during winter.

The time variation of PM capture efficiency of tested evergreen species showed a similar trend. *P. nigra* and *T. baccata* both had a relatively higher capturing efficiency for both PM_{10} and $PM_{2.5}$ in early winter. From November, their efficiency value increased fast to their peak value in December. However, the PM capturing efficiency of *P. nigra* declined quickly to its minimum value in February, while the value of *T. baccata* declined gently from December to its minimum in March. Although *H. helix* and *P. laurocerasus* had similar variation trends as the two tested needle-leaved species, *H. helix* had two peak values in December and February respectively, and the variation rate of the capturing efficiency of these two species was much gentle compared to that of *T. baccata* and *P. nigra*. The large PM density is the first reason for the general increase of PM capturing efficiency of the four tested evergreen species in early winter. In November, the leaves of deciduous species started to fall off, causing less vegetation to contributed to the higher PM concentration in the air (Wang *et al.* 2015b). The burden for leaves of evergreen species was increased in early winter and an increased density of ambient PM then promoted the amount of deposited PM on the leaf surface (Prusty *et al.* 2005). Przybysz *et al.* (2014) also confirmed the increase of deposited PM on leaves of *T. baccata, H. helix and P. sylvestris* when these are planted in heavily contaminated areas. Lower precipitation is another cause increasing the capture efficiency of evergreen plants (Rodriguez-Germade *et al.* 2014). In our study site, the average amount of precipitation was only 49.6 mm on average in November, and the relatively dry weather enhanced the dry deposition process for particulate matters. From late December, with the average precipitation increase to 62.2 mm, the efficiency value for PM capture of all tested evergreen species started to decrease. Generally, the PM capturing efficiency values of all tested species declined smoothly from December, with the exception of *P. nigra*. Unlike the other three species, leaf surface of *P. nigra* is covered with a layer of wax, where a large amount of PM was found to be concentrated. Former research found that a great number of pollution particles causes serious physiological damage to leaves of pines (Godzik *et al.* 1979), and the captured PM on leaves could also degrade epicuticular wax of pine species (Burkhardt and Pariyar 2014). This partly explains the drastically efficiency decrease of *P. nigra* for PM capture from late December and indicates pine species as the more sensitive to the rise of PM density in winter.

Although the most efficient species varied in each winter month, the variation rate of each tested species had specific features. When considering all winter months as a whole, a statistical analysis confirmed that *T. baccata* was still the most efficient evergreen species for both PM_{10} and $PM_{2.5}$ absorption (0.1477 ± 0.0454 mg cm^{-2} and 0.1379 ± 0.0450 mg cm^{-2}, respectively). *P. nigra* was the second most efficient evergreen species and its capturing efficiency for PM_{10} and $PM_{2.5}$ reached 0.1251 ± 0.0311 mg cm^{-2} and 0.1112 ± 0.0301 mg cm^{-2} respectively. *H. helix* had a moderate capture efficiency, while *P. laurocerasus* was the least efficient species for both PM_{10} and $PM_{2.5}$ reduction, with efficiency values of 0.0937 ± 0.0130 mg cm^{-2} and 0.0837 ± 0.0127 mg cm^{-2} respectively. Besides the leaf surface structural features such as stomata and trichomes, which increase the leaf`s efficiency for PM capture, the difference of crowns, leaf shape and leaf area were still key factors for species to gain a high capturing efficiency value. *T. baccata* and *P. nigra* showed higher efficiency than *P. laurocerasus* and *H. helix* because they are both tree species. Fowler *et al.* (2004) claimed tree species are typically more efficient than small vegetation, and tree species provides sufficient leaf surface area for PM to be adhered to within the same dimensional range because of its relatively large canopy (Chen *et al.* 2017). Beckett *et al.* (2000a) found that more turbulent air mixing is caused by tree species with large canopy other than small vegetation, Hence, more PM has enough time to be deposited on their leaf surface. According to Salmond *et al.* (2013), tree species could even increase the PM concentration by reducing air circulation when it is planted alongside urban streets. All these features allow the two tree species in this study to show relatively high PM capturing efficiency during winter. However, according to our results in chapter 2, insignificant difference was found between shrub species and tree species for PM capture. This difference may be due to the following two reasons: firstly, the test in chapter 2 was made in September, when most shrub species kept being effective as their leaves were still fully spread, the amount of leaves of shrub species was large enough to keep causing turbulent air mixing as tree species, and the advantage of tree species which had relatively large canopy was not as significant as it in winter. Second, as in winter the concentration of ambient PM was much higher than it in summer because the PM capturing efficiency of deciduous species decreased dramatically due to the leaves fall, and tree species with large canopy showed much higher probability than small shrub vegetation to be exposed to PM pollution in winter.

In conclusion, when leaf surface morphology is not taken into account, evergreen species with needle-shaped leaves like *T. baccata* and *P. nigra* are highly efficient at absorbing urban PM during both summer and winter. Thus, this kind of species of this kind is recommended as one of the most appropriate roadside species for future city planning and management. Evergreen species which have broad leaves such as *H. helix* are also a suitable choice for urban PM capture thanks to their long-lasting and moderate capturing efficiency. When using deciduous plants, only species with very small leaves such as *B. thunbergii* which average leaf surface area is smaller than 10 cm^2, are recommended as roadside phytoremediation for urban PM absorption.

5.1.2 Surface characteristics of leaves with high PM capturing efficiency

Besides leaf traits such as leaf shape and leaf surface area, which make both tested needle-leaved species quite efficient at PM capturing, differences of leaf surface characteristics are also an important factor for the different capture efficiency of roadside plant species.

B. thunbergii was the most efficient broad-leaved species tested in this study. The cells on the upper leaf surface are quite small in size and were densely arranged (Fig. 2.8 A-1, A-2). This arrangement resulted in the densely distributed wrinkles and grooves on the leaf surface, which became much wavier and rougher (Boize *et al.* 1976). PM tends to accumulate on rough leaf surface, as w reported by many previous researches (Beckett *et al.* 2000b, Freer-Smith *et al.* 2005, Dzierzanowski *et al.* 2011, Sæbø *et al.* 2012, Przybysz *et al.* 2019). By observing the leaf surface micro-morphology of *T. baccata* (the most efficient species tested in our study) with a scan electron microscope, many grooves were found to be widely distributed. Most of them were very narrow and deep, and PM with various size fractions was embedded and accumulated in these grooves. (Fig. 3.9). Leaf micro-morphology of *P. nigra* also showed the increasing PM capture effectiveness of high leaf surface roughness (Fig. 3.10). On the contrary, SEM observation revealed that the leaf surface of *P. laurocerasus* was quite smooth with a few grooves and wrinkles (Fig. 3.12). Its efficiency was low during both summer and winter. Our results that plant species with rough leaf surface tend to show higher efficiency at capturing PM in the air are consistent with Hwang *et al.* (2011).

Besides the level of leaf surface roughness, some structural traits like trichome and leaf hair also boost the effectiveness of PM capture (Sæbø *et al.* 2012). Directly adjacent to the surface, the leaf bound layer (LBL) represents the lowest part of the atmosphere where wind speed is reduced by the surface friction (Schuepp 1993). The thickness of the LBL ranges between a few micrometers and a few millimeters. The thickness of the boundary layer is increased by the pubescence with dense trichomes. Widely spaced hairs may be generated by viscous sublayer and create an "aerodynamically rough" surface (Reynolds 2000, Meyers *et al.* 2006). Hence, trichomes are highly effective at trapping aerosols (Martell 1974, Burkhardt 2010). Freer-Smith *et al.* (2005) claimed broad leaves with more trichome to be more effective at capturing PM compared smooth leaves. According to Yang *et al.* (2015b), a large amount of trichomes increase the $PM_{2.5}$ capturing efficiency of leaves of *E. japonicus* in the traffic areas, and the capturing efficiency of *F. chinensis* is increased thanks to a massive number of bar protuberances on its leaf surface. According to Hwang *et al.* (2011), the hairy lower side of leaves of *Platanus occidentalis* is more efficient at capturing PM than the upper smooth leaf surface. Consistently with former researches, trichomes have also been observed on the leaf surface of *B. thunbergii*, the species with the largest PM capturing efficiency among all broad-leaved plants in this study. The stomata on leaf surface are also considered as an important leaf related factor (Liu *et al.* 2013) and its presence on the mesophyll has also been reported as positively related to the leaf' s efficiency for PM capture (Xie *et al.* 2014, Yang *et al.* 2015a). Zhang *et al.* (2015b) reported that a high density of stoma allows leaves of *P. tabuliformis* to show higher PM adsorption capacity than *G. biloba*, the species which has low stoma density. PM was found to concentrate around the area close to the stoma on the leaf surface of *F. sylvatica*, consistently with the results of Rai *et al.* (2010). On the leaves of *P. nigra,* rows of stomata were observed where a big amount of PM was located. Zha *et* *al.* (2019) also proposed a positive correlation between the amount of retained PM and stomatal density and pore size. The fitting equation of stomatal density was R^2=0.837 and of pore size is R^2=0.979. Species with orderly stomatal arrangement has also been reported as more efficient for PM contamination absorption than disorderly arranged plants (Chen *et al.* 2003). Besides the increased leaf surface roughness, another reason why stoma accelerates the deposition efficiency of leaf surface is that the stomata increase the rate of leaf surface transpiration (Burkhardt *et al.* 2001). As PM is deliquescent, the increased of transpiration on leaf surface makes PM much easier to be captured onto leaf surface. Besides, with the increasing of transpiration, the leaf surface is cooled and more PM is deposited from relatively hot ambient air onto the relatively cold leaf surface as stomata enhance the thermophoresis process (Hinds 1999, Räsänen *et al.* 2013). As the velocity of dry PM deposition for PM is highly affected by changes of the surface humidity, foliar PM capturing efficiency is strongly affected by stomata.

Besides the level of leaf surface roughness and leaf surface structural features, epicuticular wax which is covered on leaf surface has also been reported as effective at increasing the PM capturing efficiency (Kaupp *et al.* 2000, Tallis *et al.* 2011). Consistently, with Sabin *et al.* (2006) who found that epicuticular wax promotes leaves of conifers to have a higher PM capturing efficiency, we found on the leaf surface of *P. nigra*, that captured PM was mainly distributed on its wax layer. Other studies have also confirmed the positive correlation between the epicuticular wax and the PM retaining efficiency (Sæbø *et al.* 2012, Sgrigna *et al.* 2015, Viecco *et al.* 2018). However, some studies claimed that leaf surfaces still show a higher efficiency than leaf surface wax for PM capture (Popek *et al.* 2013, Xu *et al.* 2018). In our study, 65% of fine PM was mainly absorbed by epicuticular wax and 70% of large PM was concentrated on the leaf surface. This result is consistent with Viecco *et al.* (2018). The reason causing the disparity among different researches might be as follows: as sedimentation under gravity is the main process leading to the deposition of PM from the air onto leaf surface, the difference of average background PM concentration in different researches might lead to the discrepancy of results; different physicochemical properties of tested plants in different researches is another reason for the disparity, as some plant species might have distinctive ability for PM capture (Jouraeva *et al.* 2002); the change of the adhesion force between leaf surface and particles might also cause the efficiency disparity. As capturing efficiency of leaves is determined by the adhesion force between the leaf surface and particulate matters, this force is determined by the chemical constitution of molecules and the interfacial area (Wang *et al.* 2015d). However, researchers have found that epicuticular wax can be eroded once a certain amount of PM is deposited

(Huttunen *et al.* 1981, Mengel *et al.* 1989, Sase *et al.* 1998, Singh *et al.* 2018). Different erosion degrees of the tested species under different average PM concentration results in the variation of the adhesion force (Wang *et al.* 2015d), and this in turn causes the disparity of results among different researches is generated.

Wettability and hydrophobicity of leaf surface are also regarded as important features for plant species for capturing particulate matters (Neinhuis and Barthlott 1998, Wichink Kruit *et al.* 2008, Koch *et al.* 2009). Contac angle (CA) measurement is the main method for the quantification of the surface hydrophilicity (Koch *et al.* 2009). Hydrophilicity is quantified by the contact angle of standardized water droplets on the leaf surface, and this parameter indicates the hydrophilicity which is determined by physical and chemical composition of leaf cuticle (Holloway 1969, Brewer *et al.* 1991). Leaf surfaces with CA lower than 40° are defined as "super-hydrophilic"; "highly-wettable" if 40° < CA < 90°; "wettable" when 90° < CA < 110°; "non-wettable" if 110° < CA < 130°; "highly non-wettable" when CA > 130° (Aryal and Neuner 2010); and leaf surface is defined as "super non-wettable" if CA is over 150° (Fig. 5.1) (Yoshimitsu *et al.* 2002). Negative correlation was found between the leaf surface PM capture efficiency and the CA (Chapter 3). The CA of wettable species *P. laurocerasus* was 105.1°, which was the largest value among the four tested species in our study while its PM efficiency was the smallest. The leaf surface CA of the most efficient species in our test, *T. baccata*, was only 85.95° and it was the only hydrophilic species we considered. Consistently with Koch *et al.* (2009), our results indicate that species with large CA have a better self-cleaning ability and that water droplets on such leaves would remove particles when moving over the leaf surface. Neinhuis and Barthlott (1998) have found that the low PM deposition efficiency of *G. biloba* is due to its low wettable leaves, and Kardel *et al.* (2012) indicate a negative correlation between the leaf surface wettability and its PM capture efficiency. This negative correlation could be explained in terms of the self-cleaning effect of some plant species. The leaves of Lotus (*Nelumbo nucifera*) are not only water repellent, but also anti-adhesive to particle contamination (Barthlott and Neinhuis 1997), and

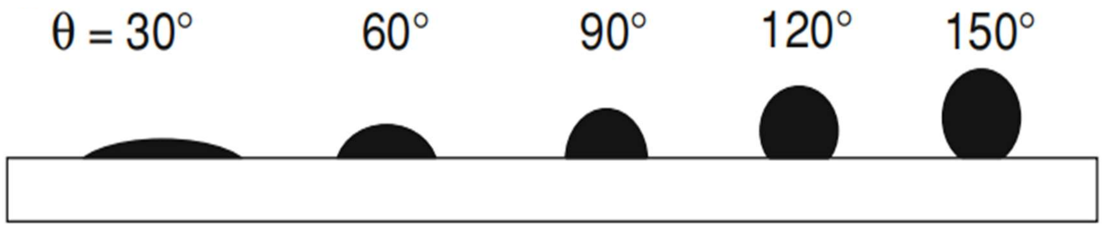

Fig. 5.1 Water droplets for different surface contact angles (CA). When CA < 110°, the leaf surface is defined as "wettable"; if CA > 110°, the leaf surface is considered "non-wettable" (adapted from Aryal *et al.* 2010, Changed)

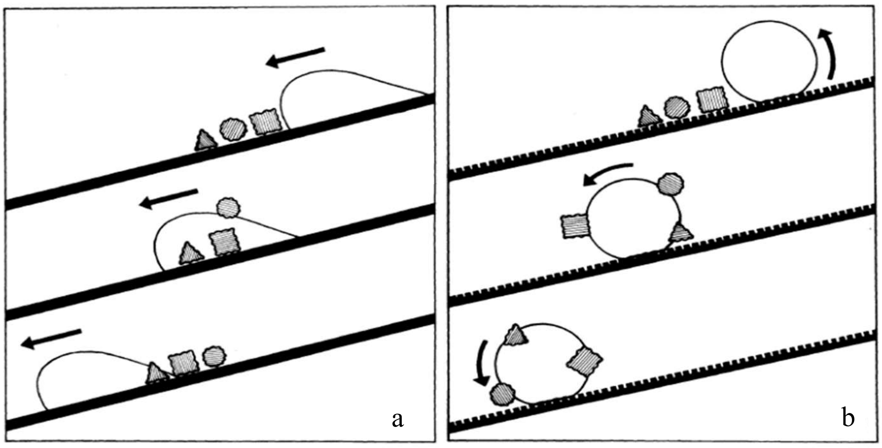

Fig. 5.2 Diagram summarizing the self-cleaning process of species with different wettability. Particles tend to stay on hydrophilic leaf surface due to strong adhesion force (a) and particles are removed off by water droplets on hydrophobic leaf surface because of the weak adhesion force (b) (by Barthlott and Neinhuis 1997, changed).

its leaf surface CA is as large as 160°, which is defined as "super non-wettable" (Koch *et al.* 2009). The contact area between a particle and the underlying leaf surface of *N. nucifera* is reduced, as a large CA causes more air to be enclosed between the particle surface and the leaf surface, leaf surface with large CA enlarged the water/air interface while minimized the solid/water surface and a composite surface is formed (Barthlott and Neinhuis 1997). As a result, the physical adhesion forces between the particle and the leaf surface are greatly reduced. With little adhesion area, contaminating particles could be easily picked up by the water droplet on such hydrophobic surface and then be removed from the leaves; on hydrophilic surfaces, particles tended to adhere to the surface because the adhesion force between the particle and the leaf surface is much greater than it between the particle and the water droplet, see summary in Fig. 5.2 (Barthlott and Neinhuis 1997). Zhang *et al.* (2018) compared the leaf surface characteristics of 6 tree species for PM capture at different parks in Beijing and concluded that on leaf surface of *G. biloba* and *P. tomentosa*, their hydrophobic property of leaf surface caused by the epicuticular wax greatly reduced the contact area between particles and the leaf surface (Xu *et al.* 2017). Hence, the reduced physical adhesion forces cause the low PM retaining ability of the two species. Overall, the weak van der Waals force which reduce the connection of particles with the leaf surface results in the low amount of captured PM onto the hydrophobic leaf surface (Chow 2003, 2007).

In conclusion, roadside plant species with relatively high PM capturing efficiency normally have some special leaf surface characteristics. Species such as *T. baccata* and *B. thunbergii* which have rougher leaf surfaces, were usually more efficient at capturing and to retain PM from the air. Leaf surface morphological structures like stoma and trichome would contribute to the high efficiency value for PM capture. In addition, epicuticular wax and leaf surface hydrophilicity would greatly affect the efficiency of roadside plants as phytoremediation for urban air pollution reduction. Morphological factors of leaf surface should be taken into consideration when choosing roadside plants as urban PM filter.

5.1.3 Recommended using pattern for efficient roadside plant species as urban PM filter and their efficiency variation under different external conditions

The efficiency variation of different roadside plant species for PM capture is caused not only by internal factors such as leaf shape, leaf surface area and different leaf surface micro-morphological traits like stomata and trichomes, but also by other external conditions such as different traffic pressures and different growth height ranges.

To investigate the influence of different traffic pressures, two relatively efficient plant species, *T. baccata* and *H. helix*, were selected in our third experiment and their efficiencies for both PM_{10} and $PM_{2.5}$ capture under different traffic pressures were tested (Chapter 4). Leaves of *H. helix* showed their highest efficiency for PM_{10} capture under the high traffic pressure. This efficiency decreased gently with the mitigation of traffic pressure and reached its minimum value under the low traffic pressure. For $PM_{2.5}$ capture, the leaves showed the highest efficiency when was under the middle traffic pressure, with similar values under the high and low traffic pressure were similar. For leaves of *T. baccata*, a positive relationship was found between its PM capturing efficiency and the traffic pressure. The efficiency for PM_{10} capture under the high traffic pressure was about 3.5 times larger than under the low traffic pressure. For $PM_{2.5}$, the absorption efficiency under the high traffic pressure was even about 19 times larger than under the low traffic pressure. The relative high PM capturing efficiency showed by roadside species under the heavy traffic pressure can be explained in terms of three factors: firstly, high concentration of air pollution accelerates the dry deposition process, which is the main channel for PM deposition. A large amount of accumulated $PM_{2.5}$ and NO_2 has been detected in the area near highways with heavy vehicular traffic than it in clean area in five Brazilian cities (Fleck *et al.* 2016). Turkyilmaz *et al.* (2018) have also reported the increasing amount of heavy mental elements accumulated on leaves of *P. cerasifera* in heavy-traffic area. Secondly, heavy traffic shifts meteorology. Average high wind speed has been measured in areas with high traffic density (Morbiato *et al.* 2014, Yang *et al.* 2016). This leads to both high dry deposition velocity and high PM capturing efficiency for roadside plants (Shahin *et al.* 2002). Besides wind speed, higher temperature has also been found in areas with heavy traffic. A larger heat storage is caused by strong vehicle emissions in heavy traffic areas, leading to the urban heat island effect (Oleson *et al.* 2013). The intense urban heat island effect causes an air flux from atmospheric stable areas with stable atmosphere and low traffic pressure to high-temperature areas with heavy traffic density (Lee 1979). Due to the faster winds, the dry deposition velocity is accelerated and thus plant species retains a larger amount of PM contaminants. At last, leaf surface microstructures are also found changed according to the traffic density. Leaves of *F. chinensis* in the industrial areas have been found have higher bar protuberances than it in the clean area. More trichomes, massive grooves and protuberances have been observed on leaves of *E. japonicus* in traffic areas than in clean ones (Yang *et al.* 2015a).

The needle-leaved species (*T. baccata*) was found to be more efficient than the broad-leaved species (*H. helix*) at capturing both PM_{10} and $PM_{2.5}$ only when they were under the heavy traffic pressure. In this case, the former showed an efficiency value about 2 times higher than the latter for both PM_{10} and $PM_{2.5}$ capture. Under the middle and the low traffic pressure, the efficiency for PM_{10} absorption of both leaf-shaped species was almost equal, whereas the broad-leaved species was more effective at reducing $PM_{2.5}$, its efficiency value for $PM_{2.5}$ capture was even 6 times larger than it of needle-leaved species under the low traffic pressure. Needle-leaved species were not only the most efficient for both PM_{10} and $PM_{2.5}$ capture under high traffic pressure, but also the most sensitive tested ones to changes of the traffic pressure. For decreasing traffic pressure, the efficiency of needle-leaved species declined sharply, while the changing rate of broad-leaved species between different traffic pressures was quite slight. In addition, leaf surface CA of *T. baccata* in our study changed significantly than that of *H. helix*. This indicated that *T. baccata* is more vulnerable to the air pollution (Kardel *et al.* 2012). Former researches also reported that the erosion of epicuticular wax on the leaf surface of pines leads to the decrease of the PM capturing efficiency for pine species (Haines *et al.* 1985). Hence, our results do not recommend roadside needle-leaved species as the only PM filter in all scenarios. As both PM capturing efficiency and leaf surface CA of *H. helix* showed limited variation under different traffic pressures, a vertical green wall covered by *H. helix* might be another appropriate alternate in different circumstances.

Green walls are vegetated surface where plants are attached onto wall surface through a variety of mechanisms (Abhijith *et al.* 2017). Although some researches have claimed that green walls are not as effective as trees (Tong *et al.* 2016), green walls have still been reported to show significant improvement for city air quality by city scale study (Jayasooriya *et al.* 2017). Green walls have been reported to absorb up to 35% of NO_2 and 50% of PM_{10} (Pugh *et al.* 2012), Dzierzanowski *et al.* (2011) claimed green walls as "PM sink" all year long, as PM on their surface could be flushed off by subsequent rain fall. *H. helix* is recommended as a cover plant for green wall because of its high efficiency for PM absorption, and in particularly for fine and ultra-fine PM in heavy-traffic areas. Its canopy influences air flow dynamics in front of the wall and increases the deposition of both large and small particles by slowing the air flow down and perhaps by triggering some turbulence (Sternberg *et al.* 2010). Morever, its large leaf surface area, high on-wall growth (over 20 m) also make it an appropriate choice for green wall covering.(Heuzé *et al.* 2009)

consistently with former studies, the high PM reducing efficiency of the green wall covered by *H. helix* was also confirmed by our analysis, Nevertheless, leaves at different height range showed a significant variation of the capturing efficiency variance for particles with different size fractions. The leaf surface was found to be the most effective channel for large PM absorption within by the growth-height range of 0.5-1 m. At this height range, leaves were about 4 times more effective at capturing large PM than compared coarse PM (aerodynamic diameter between 2.5μm to 10 μm), and was even 51 times more efficient than the case of fine PM (aerodynamic diameter smaller than 2.5μm). For larger heights, the efficiency of leaf surfaces for large PM absorption declined significantly, it remains stable for coarse PM capture. The efficiency of leaf surface for fine PM capture kept to be low at all growth-height ranges. Leaf wax was found to be most effective place for fine PM capture. The capturing efficiency remained relatively constant under height variations, with the height values showing the largest efficiency for fine PM capture ranging between 1 and 2 m. Relatively large amounts of coarse PM captured by leaf wax were also found in the same height range, whereas the amount of large PM captured by leaf wax was low at all height ranges.

Overall, on green walls the leaf surface of *H. helix* was the main absorbing place for large PM, and leaf epicuticular wax was the area with the highest capturing efficiency for fine PM. Its efficiency for fine PM absorption was almost 35 times as much as it of leaf surface. For coarse PM capture, no efficiency difference was found between leaf surface and leaf wax. As for the impact of height changes, large PM was captured onto leaf surface close to the ground, and significant negative height-related correlation was found for the PM capturing efficiency. Leaf wax showed relatively high efficiency for fine PM capture at all growth-height ranges.

An effective use of roadside plants with high PM capturing efficiency strongly depends on the actual traffic condition of the considered urban roads. Following aspects should be taken into account. Firstly, from the perspective of choosing roadside plants species for urban PM reduction, evergreen tree species with very small leaf area, densely arranged and needle-shaped leaves such as *T. baccata* and *P. nigra* are recommended as the priority of the selection by us. Small evergreen species like *H. helix* are also a good option. Deciduous vegetation which had very small and densely arranged leaves is suitable. However, broad-leaved deciduous species with very big and sparsely arranged leaves are not recommended as urban roadside PM filter by this study. When choosing roadside plant species, the micro-morphological characteristic of the leaf surface should also be taken into consideration. Species with rough hairy leaf surface with deep grooves, densely arranged stomata and a mass of trichomes are also highly recommended. As a negative relationship was found between the leaf surface CA and its PM capturing efficiency, plant species with hydrophilic leaf surface are also appropriate for PM reduction. Secondly, in order to ensure traffic safety, tree branches of trees close to the ground surface are usually cut off. A mixed use of both tree species and small vegetation is recommended by our analysis, with a belt of small vegetation under a line of trees alongside the urban street. This would maximize the efficiency for traffic-related PM absorption. Thirdly, as needle-leaved species were the most efficient at capturing both PM_{10} and $PM_{2.5}$ only under the high traffic pressure, and broad-leaved species were found to have larger $PM_{2.5}$ capturing efficiency under the middle and the low traffic pressure, specific planting strategy of efficient roadside plants should be developed based on actual traffic condition. At last, as tree species show some limitations when be used as the PM filter, for example *P. nigra* is sensitive to the changes of traffic pressure, pine species are reported not suitable for areas with high salt density, and leaf wax of pines can be corroded by air pollutant and leads to the decrease of its PM reducing efficiency, a vertical green wall or green hedge covered with efficient plants like *H. helix* could also be regarded as an effective approach. As large PM tended to be concentrated on leaf surface of green wall close to the ground, whereas no height-related difference was found for fine PM capture, a maximization of the PM capture efficiency of leaves at different height ranges on the green wall should also be considered.

5.2 General Conclusions

This study carried out a series of investigations on the role of roadside plant species as phytoremediation for air pollution reduction, compared the efficiency of different common roadside plants for traffic-related PM capture, and summarized the similarity of species with high capturing efficiency. Both the internal and external factors leading to the efficiency variations among different plant species with various leaf characteristics were discussed; Suitable using patterns with efficient roadside plant species under different external conditions were explored. Based on these results and on available study results and literatures, the general conclusions are put forward in the following four aspects.

5.2.1 Efficiency variation among roadside plants and the intercommunity of highly efficient plant species

Significant differences were found among different roadside plant species in terms of their PM capturing efficiency. Among all tested species in this study, *B.thunbergii* and *T. baccata* were the species with the largest PM_{10} capturing efficiency value, while *C. betulus* and *P. laurocerasus* were the least efficient plant species. *T. baccata* was also the most efficient species for $PM_{2.5}$ capture, with an efficiency value 21 times larger than that of *C. betulus,* the least efficient species. Intercommunity was found among the highly efficient species considered in this study. *T. baccata*, *B. thunbergii*, *P. nigra* and *H. helix* were the four species showing a significantly higher efficiency compared to the other eight tested species for both PM_{10} and $PM_{2.5}$ absorption. Within the top four efficient species, the two needle-leaved species (*T. baccata* and *P. nigra*) showed even higher efficiency value than it of the two broad-leaved species. Moreover, between the two efficient broad-leaved species, the efficiency value of species which had small leaves (*B. thunbergii*) was about 2 times higher than it of the species with relatively large leaf surface area (*H. helix*). In addition, evergreen green plants were generally more effective thanks to their long-lasting capturing efficiency even during winter. Their efficiency reached the peak value in December, the minimum one in March. Moreover, tree species were also found to be more efficient than shrub species in winter. Overall, evergreen tree species with needle-shaped leaves and very small leaf surface area are the most efficient roadside plants for both PM_{10} and $PM_{2.5}$ capture.

5.2.2 Leaf surface features which contributed to high PM diminishing efficiency

A number of leaf surface features have been found to affect the efficiency of roadside plant species for PM capture. Leaf surface roughness was the first factor which promoting the deposition process of particulate matters. On the leaf surface of *T. baccata*, the most efficient species in this study, plenty grooves and ridges were found widely distributed. Most grooves were very narrow and deep, and PM with various size fractions was embedded in these grooves. Leaves with low level of roughness were normally inefficient for PM reduction. One example was of *P. laurocerasus* which kept to show a low efficiency in during both its growth season and winter. Second, leaf surface micro-morphology like trichomes and stomata had a positive correlation with PM capturing efficiency. PM was found adhered to trichomes on the leaves of plant species with relatively high PM capture efficiency values such as *P. nigra* and *B. thunbergii*. Rows of stomata were found distributed on the leaf surface of *P. nigra* and a large amount of PM was observed concentrated around stomata. Third, epicuticular wax on leaf surface was considered to promote the amount of deposited PM on leaf surface. On leaves of *P. nigra*, a large number of PM was observed to be captured by leaf wax, and 65% fine PM was absorbed by leaf wax of *H. helix* on a green wall. consistently with former researches, our study also confirmed the positive effects of leaf wax at enhancing the PM capturing process of plants. At last, the wettability and hydrophobicity of leaf surface were also closely correlated with the efficiency of PM reduction. Plants with wettable and hydrophilic leaves showed higher PM capturing efficiency because hydrophilic leaf surface was considered to disperse the energy which removes particles from the leaf surface when water drops rolled over and make more PM adhered firmly on leaf surface. In this study, the most efficient species (*T. baccata*) had the most hydrophilic leaves and the CA of its leaf surface was the smallest among all tested roadside plant species.

5.2.3 Efficiency of roadside plant species under different traffic pressure and at different growth height

The efficiency value of different roadside plant species varies depending on the external conditions. Under different traffic pressures, the most efficient species in this study (*T. baccata*) showed a positive linear relationship between its PM capturing efficiency (for both PM_{10} and $PM_{2.5}$) and traffic pressures. Under the high traffic pressure, its PM_{10} capturing efficiency was about 3 times larger than that under the low traffic pressure, and its efficiency value for $PM_{2.5}$ capture under the high traffic pressure was even 19 times higher than it when was under then low traffic pressure. For *H. helix*, only the correlation between its efficiency for PM_{10} capture and traffic pressure was positive. For $PM_{2.5}$ capture, the efficiency was highest when was under the middle traffic pressure, and no notable differences were found between high and low traffic pressures. Considering the leaf shape, needle-leaved species were more efficient than broad-leaved ones for both PM_{10} and $PM_{2.5}$ capture only when was under the high traffic pressure. Under middle and low traffic pressure, both leaf-shaped species showed comparable efficiency values for PM_{10} reduction. Broad-leaved species were more efficient at capturing $PM_{2.5}$, with an efficiency value 6 times higher than that of needle-leaved species when was under the low traffic pressure. Although needle-leaves species had a better performance for both PM_{10} and $PM_{2.5}$ absorption under the high traffic pressure, they were also quite sensitive to the changes of the traffic pressure. On green walls, the leaf surface was found to be most suitable at absorbing large PM. The most efficient height range was 0.5-1 m above from the ground. Within this height range, leaves were 4 and 51 times more efficient at absorbing large PM than coarse and fine PM, respectively. But with height rising up, only the efficiency for large PM absorption declined significantly. Leaf epicuticular wax was the most suitable for fine PM absorption. The efficiency value to capture fine PM was almost 35 times higher than that for large PM capture. The most effective height range was 1-2 m above from the ground, and the efficiency value showed limited variations at different height ranges. The amount of captured coarse PM by leaf wax and by leaf surface was almost similar, whereas the amount of large PM captured by leaf wax at different height ranges remained small.

5.2.4 Recommended using pattern of highly efficient roadside plant species as urban PM filter

As the efficiency of roadside plant species was strongly influenced by many external and internal factors, the using pattern of highly efficient species should be coincident with various actual traffic conditions in the urban area. As for the choice of roadside plants, evergreen tree species with small, needle-shaped and densely arranged leaves is recommended as the first preference. Evergreen plants with small leaves are also suitable. When selecting deciduous vegetations, species with small-sized and densely arranged leaves should be taken into consideration. We consider deciduous plants with big, broad and sparsely arranged leaves as the least optimal selection. Leaf surface micro-morphological characteristics should also be considered as selection criteria. As deep grooves and ridges increase the level of leaf surface roughness, densely arranged stomata accelerate the transpiration and thermophoresis process on the leaf surface, and trichomes and leaf hair facilitate on PM capturing, plant species with rough, hairy leaf surface and a large number of distributed trichomes and stomata are an appropriate choice. In addition, plant species with hydrophilic leaf surface are also highly efficient for PM absorption. As for the planting pattern of efficient plant species, given that tree branches close to the ground are usually cut off for traffic safety, mixed utilization that a belt of small vegetation is planted under a line of trees would maximize the advantage of both plant types. Needle-leaved species were found to be very efficient at capturing PM_{10} and $PM_{2.5}$ only under the high traffic pressure. Moreover, broad-leaved species had higher efficiency for $PM_{2.5}$ reduction under middle and low traffic pressures. Hence, the usage pattern and planting strategy of efficient roadside plants should also fit actual traffic conditions. Besides, due to some limitations in the use of tree species such as its special limitation in narrow streets, sensitivity to salt density and to the change of traffic pressure, a green hedge of a green wall systems coved with efficient plant species is also recommended. However, specificity was found for the deposition for PM with different size fractions by leaves at different height ranges, it is also quite crucial to maximize the effectiveness of leaf surface and leaf wax at different height ranges on the green walls to absorb PM with different size fractions.

Chapter 6 Prospective study directions

Based on the present analysis and the summary from former literatures, the prospective study directions from following aspects are suggested:

6.1 Further internal factors causing the efficiency variation among different plant species

Besides the internal factors such as leaf surface roughness, number of stomata and trichomes which will have significant influence on the efficiency of roadside plant species for PM capture, other leaf features should also be taken into consideration for future studies. The angle of leaves on branches is reported as correlated with the leaf`s efficiency for PM absorption. Leaves with larger angle typically show higher capturing efficiency (Lu *et al.* 2016). Other physiological features such as the amount of chlorophyll, phyllotaxis and branch hardness are also perceived to impact the capturing efficiency among species, and more studies on these aspects are needed in the future.

Although the leaf surface is broadly regraded as the highly efficient area for air pollution absorption, whether other parts of the plants such as trunks and branches are also useful for PM capture. The factors influencing such efficiency needs further study.

In addition, the leaf surface is reported to be efficiently absorb the chemical elements which adhered to particulate matters, and especially to absorb heavy metal elements. But whether the captured chemical elements have negative effects on the plant`s health and hence reduce its PM capturing efficiency has not been sufficiently investigated yet.

Finally, most researches focused on the efficiency of leaves or on the PM capturing capacity of individual plants. However, studies on the efficiency of plant communities, or on the efficiency of different plant community combinations could offer another future investigation line.

6.2 Efficiency under different meteorological conditions and its change with time

The vegetation works as efficient phytoremediation for PM capture by regulating the microenvironment and promoting the formation of turbulence. Moreover, meteorological factors could also change the PM capturing efficiency of plants by affecting their phenological period. Temperature,

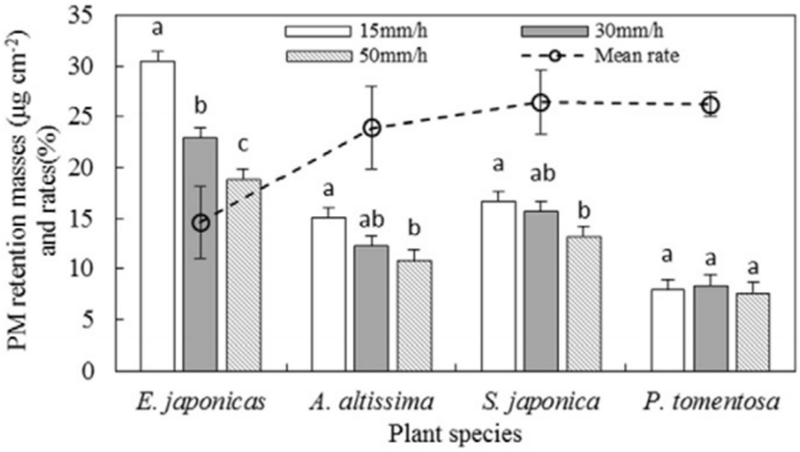

Fig. 6.1 PM retention masses under three intensities (mm h^{-1}) and mean PM retention rate for three intensities after 17.5 mm of rain for different plant species: *Euonymus japonicus, Ailanthus altissima*, *Sophora japonica* and *Populus tomentosa.* difference significant at 0.05 level. (adapted from image in Xu *et al.* 2017, changed)

wind speed, precipitation and humidity are considered as four main meteorological factors related to the PM capturing efficiency of plants. Studies have revealed that the highest impact on PM removal is exerted by relative humidity, followed by the wind speed and the temperature at the least (Chen *et al.* 2015b). Although the correlation has been explored by former researches, more detailed studies are still needed.

High temperatures accelerate the diffusion of particulate matters because they promotes the formation of a strong atmospheric vertical turbulences (Dawson et al. 2007). However, high temperatures favor PM capture and the best temperature range for plants to absorb PM is rarely reported. High wind speed is perceived to decrease the amount of captured PM on leaves of *Ligustrum lucidum* by 30% (Wang *et al.* 2015a), but other researchers have claimed the PM could be resuspended by wind at a speed of 5 m s^{-1} (Wang *et al.* 2015b), and the high wind speed would promote the deposition of PM (Freer-Smith et al. 2004). Brantley *et al.* (2014) and Morakinyo and Lam (2016) also indicate a positive correlation between the concentration of air pollutant and the wind speed. In addition, a study in China found that the variation of captured PM on leaves is insignificant before and after a strong wind event (<10.4 m s^{-1}) (Wang *et al*. 2006). Furthermore, the diameter of particles greatly affects the amount of the PM blown off by wind. Large and coarse PM are more easily blown off than fine PM (Wang *et al.* 2015b). Besides wind speed, the wind direction has also been reported as an important factor when taking roadside vegetation as PM filter. An oblique wind direction is identified as the worst scenario which could increase the density of air pollution on both sides of the city canyon (Buccolieri *et al.* 2009, Gromke and Ruck 2012, Abhijith and Gokhale 2015). while the greatest reduction is found take place behind the vegetation barrier

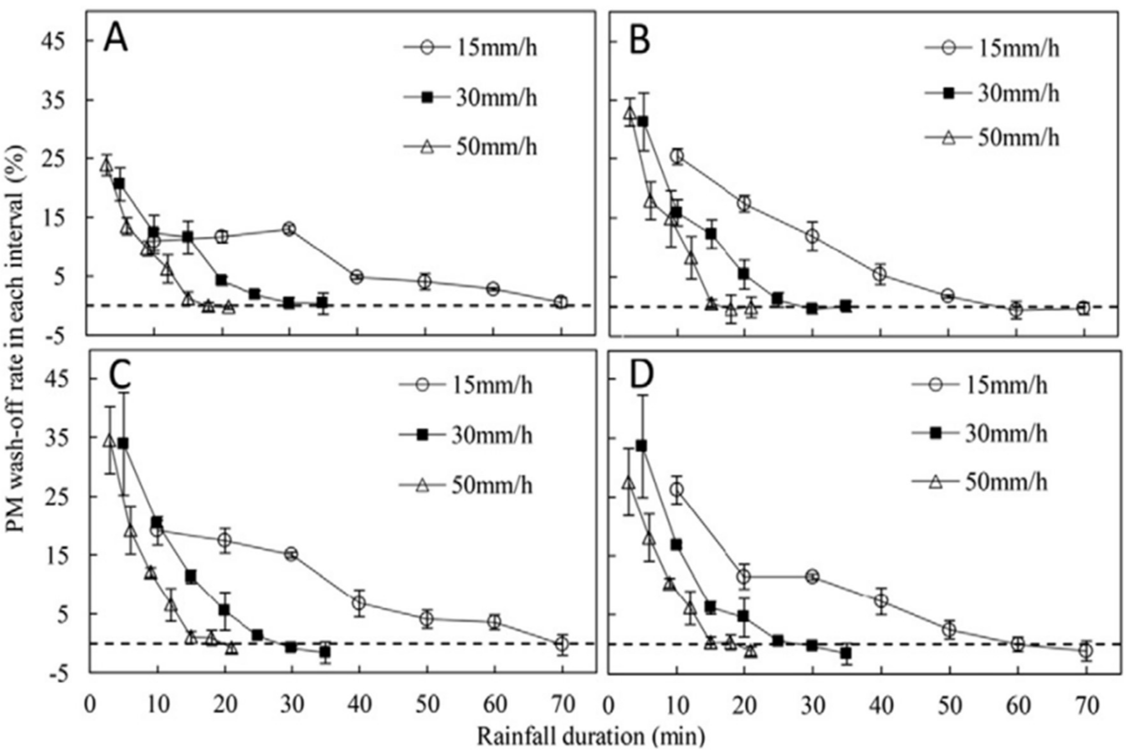

Fig. 6.2 Percent PM wash-off rate for several rainfall intervals as a function of different rainfall intensities (mm h^{-1}) for (A) *Euonymus japonicus* (B) *Ailanthus altissima* (C) *Sophora japonica* (D) *Populus tomentosa* (adapted from Xu *et al.* 2017, changed)

if the wind direction is perpendicular to the barrier (Brantley *et al.* 2014). More information about the influence brought by wind should be provided in the future. As rain water would flush the captured PM off the leaves, precipitation is very important for leaves to recover their capacity after a period of PM absorption. The indoor experiment conducted by Xu *et al.* (2017) investigated the relationship between the amount of retained PM on the leaf surface and the duration and intensity of the rainfall. They found that the PM wash-off rates are not only determined by the amount of rainfall, but also by the number of days of PM accumulation and the PM capturing capacity of plants. Typically, plant species with rough leaf surface which have and higher PM capturing efficiency have also shown greater PM wash-off masses, and deciduous species exhibit better PM removal than the coniferous species. Increasing diameter and kinetic energy of simulated raindrops associated with the higher rainfall intensity causes less PM retention (Fig. 6.1). The final wash-off rate lies between 51% and 70% of the initial accumulation. The amount of washed-off PM increases with the duration of rainfall. The PM wash-off rates increase for larger rainfall intensity during the first interval, but its influence during the later intervals is quite insignificant (Fig. 6.2). However, the amount of precipitation required to maximize the cleaning of the leaf surface to maximum extent and the percentage of PM washed off the leaf surface through rain water is still controversial. At last, environments with low humidity are reported as not suitable for the absorption of PM. Fantozzi *et al.* (2015) observed a high NO_2 concentration under a high relative humidity and low temperature. According to this study, high average air humidity is beneficial for PM capture, but whether a positive linear correlation exists between the air humidity and PM capturing efficiency requires further analysis.

In consideration of time, plant species may show different PM capturing efficiency at different time points. whether daily variation exists because of the change of temperature; whether monthly variation exists because of different meteorological factors and plant growth conditions; and whether seasonally variation exists because due to different leaf densities. All these aspects require further investigation in the future.

6.3 Efficiency of roadside plant species with complex planting patterns

Most former studies have mainly investigated the efficiency of single planting pattern with tree species or shrubs. Besides using trees, vegetation hedges are found to also reduce wind velocity with-in the street canyon (Wania *et al.* 2012, Li *et al.* 2016), and they are now widely discussed as a planting pattern for roadside plant species as city PM filter. The main research focus of this planting pattern is mainly on four aspects. First is the thick of the hedge. An increasing hedge thickness could result in a reduction of PM concentration in the street, with a linear correlation to increasing capturing efficiency (Neft *et al.* 2016). Green belts with a minimum thickness of 5 m and optimum thickness of 10 m which are recommended by Shan *et al.* (2007), and Islam *et al.* (2012) reported this thickness removes a minimum rate of 50% for total suspended particles and nano-particles (20 nm). Second is the density of the vegetation belt. This is commonly expressed in term of leaf area density (LAD), the canopy density (CD), which is defined as the ratio between the projected area of the canopy and the total ground area of the green belt; and the shelterbelt porosity (Abhijith *et al.* 2017). Normally, the amount of PM removal increases with the increase of CD and LAD and decreases with an increase in shelterbelt porosity (Islam *et al.* 2012). An optimum CD of 70-85% and 20-40% of shelterbelt porosity are recommended for TSP reduction and for maintaining a healthy green belt (Shan *et al.* 2007, Islam *et al.* 2012). However, if the CD is over 85% and the porosity is over 40%, the green hedge would act more like a solid barrier, and the PM removal process is decreased or maintained unchanged (Shan *et al.* 2007). The third aspect is the height of vegetation of green hedges. The maximum PM reduction occurs at the breathing height along the foot path with a hedge of 2 m height, and with a hedge of 1.1 m in regular street canyon. The optimum height of the green hedge is considered to be between 1 m to 2 m in both regular and shallow street canyons (Li *et al.* 2016). The last aspect is the location of the green hedge. Compared to the hedgerow along both sides of the street, a central hedgerow which located in the middle of the street has been reported to be more effective as a PM filter (Gromke *et al.* 2016).

Other planting patterns such as green roofs have also shown significant PM removal ability (Speak *et al.* 2012). However, its removal rate is influenced by wind conditions, species characteristics and the location of the roof (Currie and Bass 2008, Speak *et al.* 2012). Hence, the reduction ability is lower than trees at both local scale (Speak *et al.* 2012) and city scale (Currie and Bass 2008). The low surface roughness and distance away from pollutant sources also weakened its impact as an effective urban PM filter (Speak *et al.* 2012).

As a result, complex planting patterns maximizing the combined PM capture efficiency could be another line of investigation.in particular, the following aspects should be considered: At first, the combination of multiple plant communities for complex planting pattern need further investigation. Between "tree-shrub type", "tree-grass type", "shrub-grass type" and "tree-shrub-grass type", which combination type shows the highest efficiency for PM absorption. Secondly, as for the most efficient complex planting pattern, what species composition is the most effective, and what is the best horizontal and vertical structure. At last, the cultivated area and the planting density of complex planting pattern which would maximize its PM capturing efficiency could also be explored by future studies.

6.4 The endurance of roadside plants to traffic-related pollution and its durability as PM filter

Former researches mainly focused on the efficiency of different vegetation species at mitigating the PM pollution level in urban areas. However, the damage cause to plants by particulate matters, and the endurance and durability of roadside vegetation as a urban PM filter were rarely reported. Typically, the PM absorbed on leaf surface could take part in the plant metabolism via three mechanisms. Firstly, PM on the leaf surface could be swept off the leaves and brought to soil by raindrops, and then be absorbed by roots; Secondly, some ultra-fine PM could get into plants by passing through stomata and then take part in plant`s cycle process; At last, PM could even be directly absorbed by the cuticles of plant. If too much particulate matters are deposited on the leaf surface, damages such as ambustion of leaf surface, blocking of the stomata, and reduction of the photosynthetic intensity have been claimed by former researches (Tomašević *et al.* 2005, Katiyar *et al.* 2000).

The damage caused by PM to plants consists mainly of chlorosis and necrosis. Chlorosis refers to the degradation of green parts of the plants. It is the most common and important consequence of air pollutants in plants. The content of chlorophyll and carotene has been reported to change with the variation of the amount of captured PM on the leaf surface, with the total amount of chlorophyll of leaves which retaining lot of PM being much lower than in common leaves (Prusty *et al.* 2005). When a great amount of copper particles is captured on the leaf surface, symptoms of chlorosis are also observed. With the decreasing of the ratio of chlorophyll a and chlorophyll b, the photosynthetic system of leaves is less able to transfer electrons, the rate of photosynthesis is reported to decrease (Vinit-Dunand *et al.* 2002). Necrosis is the progressive decrease away of physiological function after the leaves are under a long-term negative environment. If too much PM adheres on the leaf surface for a long time, air exchange is prevented due to the block of stoma (Hirano *et al.* 1995). The temperature of the leaf surface increases due to the extra amount of radiation absorbed by the captured particles, and enzymes in plants are thus damaged to varying degrees (Hirano *et al.* 1995). All these damages accelerate the aging process of the plants themselves. In addition, ultra-fine PM which gets directly into the plants through stomata (Fernández Espinosa and Oliva 2006) could result in the accumulation of harmful heavy metal elements inside plants, and leads to serious damages such as metabolic disorder, stunted plant growth and even heritable variation (Hirano *et al.* 1995, Burzyński and Kłobus 2004).

Because of the aforementioned damages to plants caused by captured PM, to maintain a high endurance and durability of roadside plants used as PM filter, it is quite important to take the resistance to contaminants as a species selection factor. Further investigation on this topic is recommended.

6.5 Innovation of new experimental methods

Eco-friendly methods to absorb air particulate matters in urban areas has recently become a hot research topic. As limitations of existing weighing methods has been reported, new experimental methods are required. Zhang *et al.* (2014) have proposed a new method called EWPA (elution-weighing-particle size-analysis) and measure the particle size distribution accurately with the help of LPSA (Laser Particle Size Analyzer) and balance. SEM-EDX analysis has also been used recently to analyze particle size characteristics and particle chemical features of PM captured on leaf surface (Megido *et al.* 2016). By making use of the magnetic susceptibility of particles, researches now use thermomagnetic and electro-microscopy measurements to analyze road dust samples (Rodriguez-Germade *et al.* 2014). SIRM (saturation isothermal remanent magnetization) is also conducted as a substitution when the magnetic aspects of particle samples are weak (Kardel *et al.* 2011). With multifarious analysis methods, the role of plants as urban PM filter can be comprehensively explored in the future.

The efficiency of roadside plants to capture urban particulate matter is a synthetic effect of multiple internal and external factors. The key factor impacting the capturing efficiency of roadside plant species varies depending on the region, area, and different practical situations. The study of roadside vegetation as phytoremediation for air particulate matter absorption should also adapt to the actual local conditions.

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Appendices

Appendix A: Photos of main experiment instruments

Photo A.1 Vacuum Freeze Drier (Alpha 1-2 LD plus Entry Freeze Dryer package, Martin Christ, Australia)

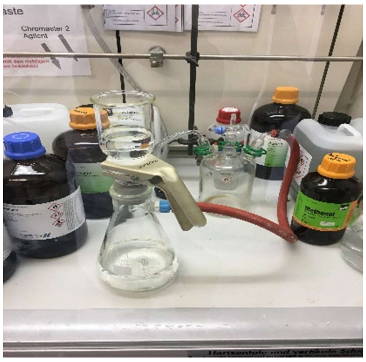

Photo A.2 Extraction filtration apparatus which equipped with 47 mm glass filter funnel connected to a vacuum pump

Photo A.3 Polytetrafluoroethylene vacuum desiccator

Photo A.4 Filter paper (Pore diameter 2.5 μm).

Photo A.5 Nylon hydrophilic membrane filter (Pore diameter 10 μm)

Photo A.6 Scanner for leaf area measurements (Mp C300 exS, Ricoh, Tokyo, Japan)

Photo A.6 Scanning electron microscope (JSM 6700F, JEOL, Japan)

Photo A.7 High vacuum sputter coater (EM SCD 500, Leica, Germany)

Photo A.8 Drop contact angle measuring system (OCA 15EC Dataphysics, Germany)

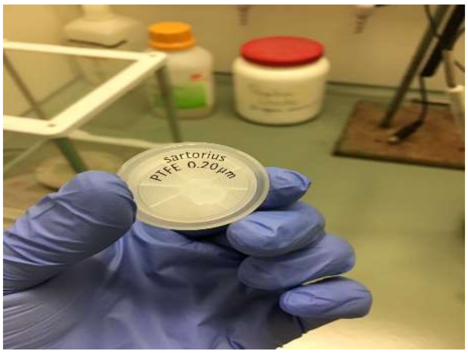

Photo A.9 PTFE membrane filter with pore diameter of 0.2 µm to filtrate chloroform solution

Appendix B: Photos of main tested samples

Photo B.1 Samples for filtration by extraction filtration apparatus (Beakers covered by aluminum foil) and for drying by Vacuum Freeze Drier (Plastic tubes with orange caps)

Photo B.2 The after dried nylon hydrophilic membrane filter with particulate matters

Photo B.3 Samples of chloroform solution for filtration by filter unit with PTFE membrane filter (pore diameter 0.2μm)

Photo B.4 Samples leaf surface which was covered by carbon for SEM scanning

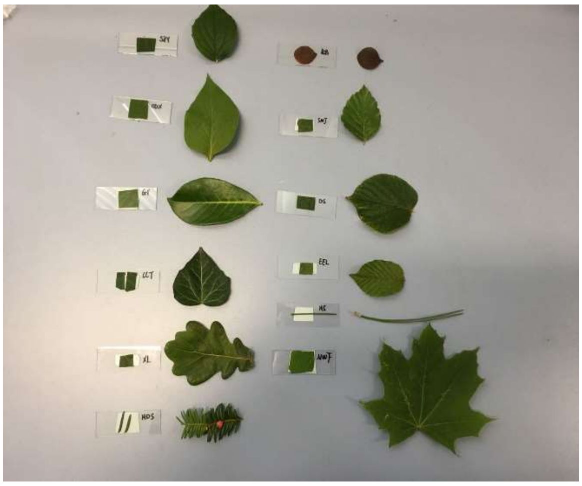

Photo B.5 Leaf samples for surface contact angle measurements. (left side, from up to down: *Philadelphus incanus*; *Syringa vulgaris*; *Prunus laurocerasus*; *Hedera helix*; *Quercus robur*; *Taxus baccata*; right side, from up to down: *Berberis thunbergii*; *Fagus sylvatica*; *Tila cordata*; *Carpinus betulus*; *Pinus nigra*; *Acer platanoides*;

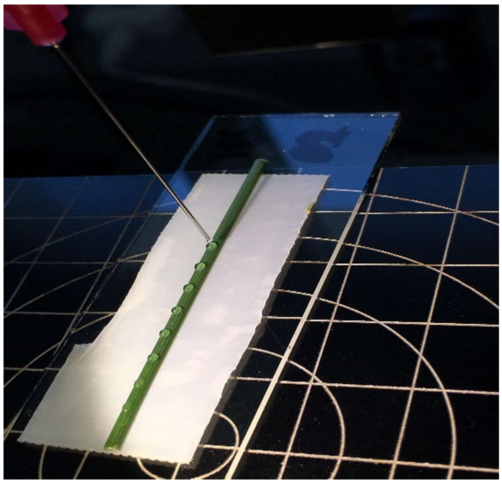

Photo B.6 leaf surface contact angle measuring process for *Pinus nigra* (with water drops on its leaf surface)

Appendix C: Tables of important original data

Table C-1 Original data for PM capturing efficiency of 12 tested roadside plants in September. (Original data for Fig. 2.2 – Fig. 2.6)

Number	Sample	M_{TP} (g)	$M_{Tpm>10}$ (g)	$M_{Tpm2.5\text{-}10}$ (g)	$M_{Tpm2.5}$ (g)	M_{Tpm10} (g)	Total leaf surface area (cm^2)	Captured PM_{10} per leaf area (mg/cm^2)	Captured $PM_{2.5}$ per leaf area (mg/cm^2)
1	*H. helix*-09-01	0.0439	0.0002	0.0016	0.0421	0.0437	276.3520	0.1580	0.1522
2	*H. helix*-09-02	0.0562	0.0009	0.0034	0.0519	0.0553	298.0200	0.1856	0.1741
3	*H. helix*-09-03	0.0510	0.0020	0.0035	0.0454	0.0490	428.9460	0.1141	0.1060
4	*S. vulgaris*-09-01	0.0274	0.0025	0.0075	0.0175	0.0250	573.5940	0.0436	0.0305
5	*S. vulgaris*-09-02	0.0281	0.0024	0.0050	0.0207	0.0257	503.9640	0.0510	0.0410
6	*S. vulgaris*-09-03	0.0270	0.0026	0.0041	0.0204	0.0244	738.4400	0.0331	0.0276
7	*F. sylvatica*-09-01	0.0192	0.0033	0.0048	0.0110	0.0158	362.1120	0.0438	0.0305
8	*F. sylvatica*-09-02	0.0112	0.0021	0.0027	0.0064	0.0090	367.3100	0.0246	0.0174
9	*F. sylvatica*-09-03	0.0318	0.0020	0.0138	0.0160	0.0298	375.0400	0.0794	0.0427
10	*P. incanus*-09-01	0.0176	0.0042	0.0051	0.0083	0.0134	364.7000	0.0367	0.0227
11	*P. incanus*-09-02	0.0314	0.0068	0.0049	0.0197	0.0246	492.0840	0.0500	0.0400
12	*P. incanus*-09-03	0.0239	0.0045	0.0062	0.0132	0.0194	326.0800	0.0594	0.0405
13	*T. cordata*-09-01	0.0208	0.0026	0.0032	0.0150	0.0182	455.6740	0.0400	0.0330
14	*T. cordata*-09-02	0.0469	0.0071	0.0099	0.0298	0.0397	663.5880	0.0598	0.0449
15	*T. cordata*-09-03	0.0351	0.0038	0.0113	0.0200	0.0313	632.8580	0.0494	0.0316
16	*B. thunbergii*-09-01	0.0136	0.0020	0.0120	-0.0004	0.0116	128.0820	0.0906	-0.0031
17	*B. thunbergii*-09-02	0.0645	0.0017	0.0157	0.0471	0.0628	168.5640	0.3727	0.2796
18	*B. thunbergii*-09-03	0.0325	0.0015	0.0115	0.0195	0.0310	101.1700	0.3066	0.1929

Number	Sample	M_{TP} (g)	$M_{Tpm>10}$ (g)	$M_{Tpm2.5\text{-}10}$ (g)	$M_{Tpm2.5}$ (g)	M_{Tpm10} (g)	Total leaf surface area (cm^2)	Captured PM_{10} per leaf area (mg/cm^2)	Captured $PM_{2.5}$ per leaf area (mg/cm^2)
19	*A. platanoides*-09-01	0.0573	0.0062	0.0091	0.0420	0.0511	1144.1580	0.0446	0.0367
20	*A. platanoides*-09-02	0.0465	0.0052	0.0118	0.0295	0.0413	661.3100	0.0624	0.0446
21	*A. platanoides*-09-03	0.0388	0.0121	0.0131	0.0136	0.0267	882.8260	0.0303	0.0154
22	*P. nigra*-09-01	0.0335	0.0049	0.0109	0.0178	0.0286	468.3491	0.0611	0.0379
23	*P. nigra*-09-02	0.0550	0.0061	0.0035	0.0454	0.0489	423.8742	0.1153	0.1070
24	*P. nigra*-09-03	0.1006	0.0031	0.0055	0.0921	0.0975	382.0296	0.2553	0.2410
25	*C. betulus*-09-01	0.0206	0.0069	0.0149	-0.0012	0.0137	646.8260	0.0211	-0.0019
26	*C. betulus*-09-02	0.0216	0.0033	0.0062	0.0121	0.0183	667.8520	0.0274	0.0182
27	*C. betulus*-09-03	0.0207	0.0044	0.0127	0.0036	0.0163	484.9260	0.0337	0.0075
28	*T. baccata*-09-01	0.1062	0.0019	0.0142	0.0901	0.1043	384.3340	0.2715	0.2344
29	*T. baccata*-09-02	0.0212	0.0030	0.0077	0.0105	0.0182	280.6110	0.0648	0.0372
30	*T. baccata*-09-03	0.0919	0.0070	0.0090	0.0760	0.0849	253.5380	0.3350	0.2997
31	*Q. robur*-09-01	0.0257	0.0100	0.0066	0.0090	0.0156	681.9220	0.0229	0.0133
32	*Q. robur*-09-02	0.0376	0.0088	0.0070	0.0218	0.0288	394.7480	0.0731	0.0552
33	*Q. robur*-09-03	0.0449	0.0112	0.0119	0.0218	0.0337	670.8200	0.0502	0.0326
34	*P. laurocerasus*-09-01	0.0128	0.0023	0.0036	0.0069	0.0105	399.1320	0.0263	0.0172
35	*P. laurocerasus*-09-02	0.0147	0.0039	0.0048	0.0059	0.0107	462.8380	0.0232	0.0128
36	*P. laurocerasus*-09-03	0.0162	0.0052	0.0068	0.0042	0.0110	455.6180	0.0241	0.0091

Table C-2 Original data for PM capturing efficiency of 4 tested evergreen plants during winter. (Original data for Fig. 3.3- Fig. 3.8)

Table C-2-1 Data of November

Number	Sample	M_{TP} (g)	$M_{Tpm>10}$ (g)	$M_{Tpm2.5\text{-}10}$ (g)	$M_{Tpm2.5}$ (g)	M_{Tpm10} (g)	Total leaf surface area (cm^2)	Captured PM_{10} per leaf area (mg/cm^2)	Captured $PM_{2.5}$ per leaf area (mg/cm^2)
1	*H. helix*-11-01	0.0248	0.0009	0.0013	0.0227	0.0240	165.0670	0.0726	0.0687
2	*H. helix*-11-02	0.0112	0.0010	0.0021	0.0081	0.0103	136.8300	0.0375	0.0297
3	*H. helix*-11-03	0.0176	0.0009	0.0018	0.0150	0.0168	164.3900	0.0511	0.0456
4	*P. nigra*-11-01	0.0819	0.0086	0.0055	0.0678	0.0733	315.2234	0.1162	0.1075
5	*P. nigra*-11-02	0.0360	0.0200	0.0112	0.0048	0.0160	281.2112	0.0285	0.0085
6	*P. nigra*-11-03	0.0878	0.0139	0.0037	0.0702	0.0739	284.4369	0.1299	0.1234
7	*T. baccata*-11-01	0.0125	0.0010	0.0011	0.0104	0.0115	168.9290	0.0340	0.0309
8	*T. baccata*-11-02	0.0151	0.0017	0.0017	0.0117	0.0134	226.4390	0.0295	0.0258
9	*T. baccata*-11-03	0.0336	0.0048	0.0034	0.0254	0.0288	177.1720	0.0813	0.0718
10	*P. laurocerasus*-11-01	0.0398	0.0027	0.0034	0.0337	0.0371	219.4070	0.0845	0.0768
11	*P. laurocerasus*-11-02	0.0474	0.0043	0.0032	0.0399	0.0431	237.4860	0.0907	0.0841
12	*P. laurocerasus*-11-03	0.0417	0.0007	0.0038	0.0372	0.0410	217.8470	0.0941	0.0853

Table C-2-2 Data of December

Number	Sample	M_{TP} (g)	$M_{Tpm>10}$ (g)	$M_{Tpm2.5\text{-}10}$ (g)	$M_{Tpm2.5}$ (g)	M_{Tpm10} (g)	Total leaf surface area (cm^2)	Captured PM_{10} per leaf area (mg/cm^2)	Captured $PM_{2.5}$ per leaf area (mg/cm^2)
1	*H. helix*-12-01	0.0555	0.0032	0.0015	0.0508	0.0523	167.1240	0.1563	0.1519
2	*H. helix*-12-02	0.0512	0.0026	0.0017	0.0469	0.0486	137.3140	0.1768	0.1707
3	*H. helix*-12-03	0.0405	0.0013	0.0016	0.0376	0.0392	130.2200	0.1506	0.1445
4	*P. nigra*-12-01	0.0789	0.0082	0.0046	0.0661	0.0707	91.6490	0.3857	0.3605
5	*P. nigra*-12-02	0.0743	0.0062	0.0042	0.0639	0.0681	90.3880	0.3769	0.3537
6	*P. nigra*-12-03	0.0693	0.0065	0.0045	0.0582	0.0628	120.0270	0.2614	0.2426
7	*T. baccata*-12-01	0.0613	0.0013	0.0016	0.0642	0.0626	201.2974	0.1555	0.1595
8	*T. baccata*-12-02	0.1590	0.0004	0.0017	0.1569	0.1586	134.4264	0.5898	0.5835
9	*T. baccata*-12-03	0.0526	0.0003	0.0019	0.0504	0.0523	189.4047	0.1380	0.1330
10	*P. laurocerasus*-12-01	0.0319	0.0012	0.0019	0.0288	0.0307	107.0640	0.1436	0.1346
11	*P. laurocerasus*-12-02	0.0417	0.0005	0.0025	0.0387	0.0412	96.9920	0.2122	0.1996
12	*P. laurocerasus*-12-03	0.0450	0.0005	0.0022	0.0422	0.0445	151.6910	0.1466	0.1392

Table C-2-3 Data of January

Number	Sample	M_{TP} (g)	$M_{Tpm>10}$ (g)	$M_{Tpm2.5-10}$ (g)	$M_{Tpm2.5}$ (g)	M_{Tpm10} (g)	Total leaf surface area (cm^2)	Captured PM_{10} per leaf area (mg/cm^2)	Captured $PM_{2.5}$ per leaf area (mg/cm^2)
1	*H. helix*-01-01	0.0267	0.0021	0.0031	0.0215	0.0246	146.4860	0.0840	0.0735
2	*H. helix*-01-02	0.0260	0.0018	0.0031	0.0211	0.0242	119.4180	0.1014	0.0885
3	*H. helix*-01-03	0.0240	0.0027	0.0040	0.0173	0.0213	143.1400	0.0744	0.0606
4	*P. nigra*-01-01	0.0262	0.0117	0.0069	0.0076	0.0145	312.6072	0.0232	0.0121
5	*P. nigra*-01-02	0.0731	0.0106	0.0038	0.0586	0.0625	289.6110	0.1078	0.1012
6	*P. nigra*-01-03	0.0452	0.0028	0.0098	0.0326	0.0424	308.0995	0.0688	0.0529
7	*T. baccata*-01-01	0.0064	0.0019	0.0034	0.0010	0.0045	109.9340	0.0203	0.0048
8	*T. baccata*-01-02	0.1090	0.0028	0.0037	0.1025	0.1063	99.9170	0.5318	0.5131
9	*T. baccata*-01-03	0.0365	0.0016	0.0030	0.0319	0.0349	139.0150	0.1255	0.1148
10	*P. laurocerasus*-01-01	0.0644	0.0029	0.0060	0.0556	0.0615	205.5660	0.1497	0.1352
11	*P. laurocerasus*-01-02	0.0296	0.0039	0.0062	0.0195	0.0257	241.7780	0.0532	0.0404
12	*P. laurocerasus*-01-03	0.0337	0.0077	0.0064	0.0197	0.0260	239.6580	0.543	0.0410

Table C-2-4 Data of February

Number	Sample	M_{TP} (g)	$M_{Tpm>10}$ (g)	$M_{Tpm2.5\text{-}10}$ (g)	$M_{Tpm2.5}$ (g)	M_{Tpm10} (g)	Total leaf surface area (cm^2)	Captured PM_{10} per leaf area (mg/cm^2)	Captured $PM_{2.5}$ per leaf area (mg/cm^2)
1	*H. helix*-02-01	0.0696	0.0015	0.0036	0.0645	0.0681	164.9270	0.2064	0.1954
2	*H. helix*-02-02	0.0851	0.0019	0.0025	0.0807	0.0832	262.2070	0.1586	0.1539
3	*H. helix*-02-03	0.0620	0.0016	0.0050	0.0554	0.0604	276.6980	0.1092	0.1002
4	*P. nigra*-02-01	0.0512	0.0050	0.0178	0.0284	0.0462	260.7370	0.0886	0.0544
5	*P. nigra*-02-02	0.0148	0.0017	0.0007	0.0124	0.0131	277.0695	0.0237	0.0224
6	*P. nigra*-02-03	0.0276	0.0034	0.0149	0.0093	0.0242	350.2980	0.0345	0.0132
7	*T. baccata*-02-01	0.0205	0.0012	0.0033	0.0160	0.0193	140.8380	0.0686	0.0568
8	*T. baccata*-02-02	0.0213	0.0015	0.0032	0.0166	0.0198	84.9610	0.1164	0.0976
9	*T. baccata*-02-03	0.0398	0.0012	0.0060	0.0327	0.0387	100.2810	0.1927	0.1629
10	*P. laurocerasus*-02-01	0.0411	0.0037	0.0093	0.0280	0.0374	250.5270	0.0746	0.0559
11	*P. laurocerasus*-02-02	0.0553	0.0028	0.0085	0.0440	0.0526	277.2050	0.0948	0.0794
12	*P. laurocerasus*-02-03	0.0582	0.0019	0.0106	0.0457	0.0563	350.2980	0.804	0.0653

Table C-2-5 Data of March

Number	Sample	M_{TP} (g)	$M_{Tpm>10}$ (g)	$M_{Tpm2.5-10}$ (g)	$M_{Tpm2.5}$ (g)	M_{Tpm10} (g)	Total leaf surface area (cm^2)	Captured PM_{10} per leaf area (mg/cm^2)	Captured $PM_{2.5}$ per leaf area (mg/cm^2)
1	*H. helix*-03-01	0.0168	0.0030	0.0009	0.0130	0.0138	242.2530	0.0286	0.0268
2	*H. helix*-03-02	0.0237	0.0016	0.0005	0.0216	0.0221	208.8590	0.0530	0.0517
3	*H. helix*-03-03	0.0186	0.0030	0.0015	0.0141	0.0156	234.4150	0.0333	0.0301
4	*P. nigra*-03-01	0.0263	0.0017	0.0033	0.0213	0.0246	254.7199	0.0483	0.0419
5	*P. nigra*-03-02	0.0589	0.0028	0.0015	0.0546	0.0561	236.0402	0.1187	0.1156
6	*P. nigra*-03-03	0.0357	0.0046	0.0029	0.0283	0.0311	243.0296	0.0640	0.0581
7	*T. baccata*-03-01	0.0339	0.0042	0.0022	0.0275	0.0297	269.4500	0.0551	0.0510
8	*T. baccata*-03-02	0.0177	0.0018	0.0020	0.0138	0.0159	215.9570	0.0368	0.0321
9	*T. baccata*-03-03	0.0257	0.0054	0.0054	0.0148	0.0203	252.5120	0.0401	0.0294
10	*P. laurocerasus*-03-01	0.0249	0.0017	0.0014	0.0218	0.0232	339.4610	0.0342	0.0321
11	*P. laurocerasus*-03-02	0.0370	0.0014	0.0011	0.0345	0.0356	258.5590	0.0688	0.0668
12	*P. laurocerasus*-03-03	0.0147	0.0038	0.0015	0.0094	0.0109	232.5610	0.0233	0.0201

Table C-3 Original data for leaf surface contact angle of 4 tested evergreen plants. (Original data for Fig. 3.14- Fig. 3.15)

Species: *H. helix*	Contact angle (°)								
Repetition	initial			1s later			4s later		
	left angle	right angle	mean angle	left angle	right angle	mean angle	left angle	right angle	mean angle
1	102.54	101.44	101.99	101.85	100.89	101.37	101.54	100.57	101.05
2	99.48	99.49	99.49	99.01	98.81	98.91	98.55	98.23	98.39
3	106.49	105.99	106.24	106.49	105.99	106.24	106.49	105.99	106.24
4	97.16	96.74	96.95	97.11	96.50	96.81	97.19	96.97	97.08
5	93.05	92.19	92.62	93.09	91.96	92.53	92.04	91.17	91.61
6	103.09	103.12	103.11	101.87	101.92	101.90	99.47	100.00	99.74
7	108.02	107.94	107.98	106.91	106.97	106.94	105.21	104.96	105.08
8	98.90	98.70	98.80	98.44	98.27	98.36	97.97	97.64	97.80
9	106.46	106.17	106.31	107.61	106.90	107.26	103.53	103.31	103.42
10	109.76	109.27	109.52	108.66	108.16	108.41	107.57	107.41	107.49
11	99.23	99.25	99.24	96.11	93.87	94.99	93.44	91.97	92.71
12	106.30	105.62	105.96	105.77	105.10	105.44	103.37	103.74	103.56

Species: *P. nigra*	Contact angle (°)								
Repetition	initial			1s later			4s later		
	left angle	right angle	mean angle	left angle	right angle	mean angle	left angle	right angle	mean angle
1	95.57	94.79	95.18	97.14	94.87	96.01	102.69	105.08	103.89
2	104.75	103.85	104.30	91.41	91.74	91.58	95.64	99.17	97.41
3	100.97	100.36	100.67	100.15	99.57	99.86	99.85	99.47	99.66
4	88.39	88.12	88.26	86.92	86.94	86.93	86.10	86.09	86.10
5	88.97	91.41	90.19	94.92	96.68	95.80	96.13	97.94	97.04
6	102.11	103.92	103.02	102.83	105.61	104.22	98.73	97.91	98.32
7	90.06	90.23	90.15	89.47	89.58	89.53	86.13	87.95	87.04
8	89.75	89.47	89.61	89.46	89.19	89.32	88.86	88.64	88.75
9	86.63	87.24	86.93	86.33	86.85	86.59	86.01	86.49	86.25
10	99.00	99.49	99.25	98.07	98.63	98.35	97.71	98.36	98.04
11	96.78	96.57	96.68	95.85	95.55	95.70	95.16	94.83	95.00
12	90.15	90.65	90.40	88.32	88.41	88.36	88.05	88.00	88.03

Species: *T. baccata*	Contact angle (°)								
Repetition	initial			1s later			4s later		
	left angle	right angle	mean angle	left angle	right angle	mean angle	left angle	right angle	mean angle
1	84.27	83.73	84.00	83.18	83.06	83.12	88.04	85.36	86.70
2	103.79	102.99	103.39	92.01	93.06	92.53	98.45	98.93	98.69
3	66.14	60.72	63.43	63.93	63.93	63.93	62.27	62.27	62.27
4	78.78	76.70	77.74	77.19	74.86	76.02	75.05	73.17	74.11
5	87.97	85.33	86.65	85.61	83.48	84.54	84.53	82.57	83.55
6	89.50	88.24	88.87	88.06	86.76	87.41	87.36	86.16	86.76
7	70.19	68.12	69.15	80.97	85.06	83.02	79.69	80.66	80.17
8	87.72	90.46	89.09	87.67	94.29	90.98	77.17	83.74	80.45
9	85.96	87.72	86.84	86.72	88.11	87.41	86.99	88.22	87.61
10	94.09	93.11	93.60	93.31	91.81	92.56	93.16	91.62	92.39
11	94.31	93.22	93.76	94.40	93.04	93.72	93.02	92.12	92.57
12	82.08	79.97	81.02	81.01	79.54	80.28	80.37	82.78	81.57

Species: *P. laurocerasus*	Contact angle (°)								
Repetition	initial			1s later			4s later		
	left angle	right angle	mean angle	left angle	right angle	mean angle	left angle	right angle	mean angle
1	107.87	105.88	106.88	109.03	108.40	108.72	108.78	108.14	108.46
2	110.69	109.06	109.88	106.49	109.89	108.19	109.59	107.66	108.63
3	107.17	106.09	106.63	106.58	105.34	105.96	106.46	105.27	105.86
4	106.84	105.76	106.30	106.67	105.54	106.10	106.31	105.23	105.77
5	103.92	103.68	103.80	103.78	103.46	103.62	103.55	103.30	103.43
6	106.62	105.52	106.07	106.46	105.36	105.91	106.30	105.23	105.77
7	107.69	109.36	108.52	105.33	106.87	106.10	105.00	106.74	105.87
8	101.70	100.48	101.09	102.93	101.76	102.34	103.75	101.73	102.74
9	101.71	104.00	102.85	93.73	94.84	94.28	100.46	103.03	101.75
10	103.56	103.26	103.41	103.54	103.29	103.42	103.32	103.07	103.19
11	100.62	100.28	100.45	99.60	100.32	99.96	103.80	103.53	103.66
12	106.13	105.42	105.77	106.23	105.47	105.85	105.83	105.14	105.49

Table C-4 Original data for PM capturing efficiency of roadside plants under different traffic pressures. (Original data for Table 4.1, Fig. 4.5- Fig. 4.6)

Number	Sample	M_{TP} (g)	$M_{Tpm>10}$ (g)	$M_{Tpm2.5\text{-}10}$ (g)	$M_{Tpm2.5}$ (g)	M_{Tpm10} (g)	Total leaf surface area (cm^2)	Captured PM_{10} per leaf area (mg/cm^2)	Captured $PM_{2.5}$ per leaf area (mg/cm^2)
1	*H. helix*-high-01	0.0306	0.0076	0.0116	0.0114	0.0230	140.9370	0.0816	0.0404
2	*H. helix*-high-02	0.0265	0.0071	0.0118	0.0076	0.0194	174.6020	0.0555	0.0218
3	*H. helix*-high-*03*	0.0268	0.0047	0.0079	0.0141	0.0221	170.4430	0.0648	0.0415
4	*H. helix*-middle-01	0.0194	0.0018	0.0048	0.0129	0.0177	194.7990	0.0454	0.0331
5	*H. helix*-middle-02	0.0259	0.0057	0.0078	0.0123	0.0201	223.0670	0.0451	0.0276
6	*H. helix*-middle-03	0.0351	0.0068	0.0071	0.0212	0.0284	162.1100	0.0875	0.0655
7	*H. helix*-low-01	0.0184	0.0035	0.0043	0.0106	0.0149	154.5790	0.0483	0.0343
8	*H. helix*-low-02	0.0208	0.0031	0.0044	0.0132	0.0177	198.0740	0.0447	0.0334
9	*H. helix*-low-*03*	0.0200	0.0034	0.0050	0.0116	0.0166	221.6120	0.0374	0.0262
10	*T. baccata*-high-01	0.0151	0.0007	0.0040	0.0104	0.0144	81.9800	0.0880	0.0636
11	*T. baccata*-high-02	0.0178	0.0014	0.0020	0.0144	0.0164	47.7600	0.1717	0.1508
12	*T. baccata*-high-03	0.0119	0.0003	0.0040	0.0075	0.0115	40.0100	0.1440	0.0939
13	*T. baccata*-middle-01	0.0124	0.0019	0.0041	0.0064	0.0105	102.7360	0.0510	0.0310
14	*T. baccata*-middle-02	0.0083	0.0004	0.0030	0.0049	0.0078	57.5030	0.0682	0.0423
15	*T. baccata*-middle-03	0.0111	0.0011	0.0078	0.0022	0.0100	60.6580	0.0825	0.0185
16	*T. baccata*-low-01	0.0055	0.0012	0.0033	0.0010	0.0043	54.8530	0.0390	0.0094
17	*T. baccata*-low-02	0.0079	0.0023	0.0066	-0.0009	0.0056	70.7460	0.0397	-0.0067
18	*T. baccata*-low-03	0.0072	0.0011	0.0039	0.0021	0.0060	77.5950	0.0389	0.0135

Table C-5 Original data for leaf surface contact angle of roadside plants under different traffic pressures. (Original data for Table 4.3 and Fig. 4.7)

Species: *H. helix* — Contact angle under high traffic pressure (°)

Repetition	initial			1s later			4s later		
	left angle	right angle	mean angle	left angle	right angle	mean angle	left angle	right angle	mean angle
1	100.80	99.75	100.27	96.53	95.38	95.96	95.87	95.00	95.43
2	103.30	103.84	103.57	101.52	102.57	102.05	97.47	97.81	97.64
3	94.02	92.31	93.17	90.84	89.21	90.03	88.95	87.10	88.02
4	103.70	102.29	102.99	98.83	97.11	97.97	99.78	102.48	101.13
5	96.21	94.55	95.38	97.96	97.29	97.62	99.51	98.44	98.97
6	110.73	110.60	110.67	110.13	110.17	110.15	109.61	109.63	109.62
7	105.54	106.32	105.93	105.35	105.55	105.45	92.61	96.22	94.42
8	87.36	90.13	88.75	94.72	95.64	95.18	92.57	93.17	92.87
9	98.65	98.81	98.73	98.72	98.43	98.57	96.71	96.44	96.58
10	102.79	102.80	102.80	103.06	102.22	102.64	100.12	99.92	100.02
11	103.46	102.29	102.88	103.19	101.98	102.59	102.68	101.35	102.02
12	111.72	112.68	112.20	104.88	108.85	106.87	109.34	109.34	109.34

Species: *H. helix*	Contact angle under middle traffic pressure (°)								
Repetition	initial			1s later			4s later		
	left angle	right angle	mean angle	left angle	right angle	mean angle	left angle	right angle	mean angle
1	104.57	105.05	104.81	107.50	107.15	107.32	98.14	99.42	98.78
2	100.07	100.90	100.48	95.25	96.70	95.97	94.70	95.69	95.20
3	106.24	106.09	106.16	106.07	106.08	106.07	104.22	104.22	104.22
4	98.54	98.89	98.71	94.67	95.08	94.87	96.91	97.17	97.04
5	88.77	88.82	88.79	85.11	84.75	84.93	80.62	80.86	80.74
6	103.61	103.35	103.48	98.90	98.95	98.93	91.57	93.25	92.41
7	98.55	98.76	98.65	96.67	96.83	96.75	95.74	95.85	95.79
8	101.60	101.38	101.49	99.01	98.51	98.76	95.49	94.48	94.98
9	99.10	98.74	98.92	98.26	98.12	98.19	93.95	94.13	94.04
10	97.80	96.70	97.25	96.86	95.63	96.24	96.44	95.28	95.86
11	98.61	98.28	98.45	96.30	95.97	96.13	94.41	94.08	94.25
12	106.39	106.38	106.39	106.59	106.61	106.60	104.01	103.71	103.86

Species: *H. helix*	Contact angle under low traffic pressure (°)								
Repetition	initial			1s later			4s later		
	left angle	right angle	mean angle	left angle	right angle	mean angle	left angle	right angle	mean angle
1	109.93	109.58	109.76	107.60	107.32	107.46	107.35	107.14	107.24
2	111.95	112.09	112.02	109.37	109.34	109.36	113.13	112.69	112.91
3	96.51	96.48	96.49	87.66	87.25	87.45	94.41	93.87	94.14
4	107.74	107.60	107.67	107.00	107.06	107.03	103.51	106.78	105.15
5	109.86	109.43	109.64	107.82	108.15	107.98	100.56	97.23	98.90
6	103.09	104.44	103.77	101.43	103.30	102.37	100.70	102.70	101.70
7	102.66	102.23	102.45	102.62	102.24	102.43	102.35	102.00	102.18
8	106.75	106.03	106.39	104.95	103.80	104.38	104.68	103.58	104.13
9	115.15	110.48	112.81	98.00	97.39	97.69	96.49	95.83	96.16
10	100.20	98.76	99.48	100.34	98.72	99.53	99.37	97.57	98.47
11	99.66	99.06	99.36	99.52	98.86	99.19	99.28	98.76	99.02
12	94.78	94.22	94.50	92.41	92.91	92.66	90.22	90.66	90.44

Species: *T. baccata*	Contact angle under high traffic pressure (°)								
Repetition	initial			1s later			4s later		
	left angle	right angle	mean angle	left angle	right angle	mean angle	left angle	right angle	mean angle
1	91.41	91.03	91.22	86.83	86.80	86.81	86.46	85.63	86.04
2	92.93	93.34	93.14	95.71	95.97	95.84	92.01	91.89	91.95
3	92.64	97.84	95.24	93.31	95.04	94.17	91.89	86.90	89.40
4	94.55	97.68	96.12	88.99	96.60	92.80	90.55	93.63	92.09
5	84.99	81.50	83.25	82.66	77.50	80.08	83.03	77.35	80.19
6	98.68	97.88	98.28	95.50	94.64	95.07	94.20	93.36	93.78
7	101.66	101.83	101.75	99.40	98.54	98.97	101.37	100.54	100.95
8	110.82	111.72	111.27	87.83	85.37	86.60	97.98	98.87	98.43
9	101.28	100.02	100.65	94.53	94.09	94.31	86.12	93.49	89.80
10	98.69	98.23	98.46	97.17	95.95	96.56	96.12	94.68	95.40
11	94.45	93.85	94.15	92.63	92.49	92.56	91.33	90.28	90.80
12	101.05	100.92	100.98	99.51	98.86	99.19	98.29	96.86	97.57

Species: *T. baccata*	Contact angle under middle traffic pressure (°)								
Repetition	initial			1s later			4s later		
	left angle	right angle	mean angle	left angle	right angle	mean angle	left angle	right angle	mean angle
1	119.13	118.39	118.76	118.80	118.08	118.44	115.47	115.36	115.42
2	118.68	118.36	118.52	118.83	118.39	118.61	117.40	117.07	117.24
3	122.31	122.53	122.42	125.22	123.78	124.50	116.97	116.95	116.96
4	105.81	107.30	106.56	102.86	105.92	104.39	101.94	101.13	101.54
5	97.78	96.77	97.27	98.72	98.64	98.68	100.72	100.05	100.39
6	111.33	110.78	111.05	101.30	107.08	104.19	93.46	97.96	95.71
7	103.11	106.38	104.75	93.99	101.21	97.60	97.46	100.63	99.05
8	112.38	111.74	112.06	117.62	117.51	117.56	126.67	126.10	126.39
9	99.89	99.07	99.48	89.27	89.70	89.48	115.86	117.35	116.60
10	115.29	120.28	117.79	123.17	122.40	122.78	124.07	122.51	123.29
11	115.24	115.20	115.22	117.18	117.67	117.42	110.37	111.80	111.08
12	111.47	109.12	110.29	116.87	112.24	114.56	97.99	97.87	97.93

Species: *T. baccata*	Contact angle under low traffic pressure (°)								
Repetition	initial			1s later			4s later		
	left angle	right angle	mean angle	left angle	right angle	mean angle	left angle	right angle	mean angle
1	86.04	83.96	85.00	88.67	86.64	87.66	84.08	85.33	84.70
2	97.68	98.14	97.91	79.77	81.08	80.42	83.76	89.92	86.84
3	106.90	109.33	108.12	114.11	111.05	112.58	96.33	92.75	94.54
4	94.65	92.60	93.62	72.90	69.29	71.09	65.29	63.19	64.24
5	91.22	93.29	92.26	92.39	89.65	91.02	90.26	96.50	93.38
6	108.97	108.57	108.77	108.21	110.41	109.31	107.23	107.93	107.58
7	89.12	82.26	85.69	92.33	88.11	90.22	91.22	88.17	89.69
8	91.17	92.68	91.92	91.62	94.18	92.90	83.96	84.93	84.44
9	100.28	94.41	97.35	106.25	102.73	104.49	79.64	82.79	81.22
10	90.70	92.20	91.45	91.12	93.68	92.40	83.56	84.53	84.05
11	81.76	81.97	81.86	75.26	75.94	75.60	84.31	86.18	85.25
12	96.07	95.66	95.87	81.07	86.91	83.99	92.97	90.66	91.81

Table C-6 Original data of PM capturing efficiency of leaf surface with different height range on the green wall

(Original data for Fig. 4.8, Fig 4.10 and Fig. 4.12)

Number	Sample	Weight of large PM (10-100 μm) M_{fA} (g)	Leaf area (cm^2)	Weight of large PM per leaf area $M_{PM\text{-}Large}$ (mg cm^{-2})	Weight of coarse PM (2.5-10 μm) M_{fB} (g)	Leaf area (cm^2)	Weight of coarse PM per leaf area $M_{PM\text{-}Coarse}$ (mg cm^{-2})	Weight of fine PM (0.2-2.5 μm) M_{fC} (g)	Leaf area (cm^2)	Weight of fine PM per leaf area $M_{PM\text{-}Fine}$ (mg cm^{-2})
1	H1-01	0.0157	367.9290	0.0213	0.0035	367.9290	0.0048	0.0003	367.9290	0.0004
2	H1-02	0.0123	304.5960	0.0202	0.0029	304.5960	0.0048	0.0002	304.5960	0.0003
3	H1-03	0.0127	353.3930	0.0180	0.0046	353.3930	0.0065	0.0003	353.3930	0.0004
4	H2-01	0.0082	382.5850	0.0107	0.0016	382.5850	0.0021	0.0002	382.5850	0.0003
5	H2-02	0.0079	351.9930	0.0112	0.0026	351.9930	0.0037	0.0002	351.9930	0.0003
6	H2-03	0.0062	279.3580	0.0111	0.0022	279.3580	0.0039	0.0002	279.3580	0.0004
7	H3-01	0.0036	311.4920	0.0058	0.0011	311.4920	0.0018	0.0002	311.4920	0.0003
8	H3-02	0.0027	312.0730	0.0043	0.0011	312.0730	0.0018	0.0003	312.0730	0.0005
9	H3-03	0.0032	316.1790	0.0051	0.0011	316.1790	0.0017	0.0004	316.1790	0.0006
10	H4-01	0.0030	419.4780	0.0036	0.0009	419.4780	0.0011	0.0005	419.4780	0.0006
11	H4-02	0.0027	306.2570	0.0044	0.0017	306.2570	0.0028	0.0003	306.2570	0.0005
12	H4-03	0.0015	281.5670	0.0027	0.0013	281.5670	0.0023	0.0002	281.5670	0.0004

Note: H1: height range 0.5-1 m; H2: height range 1-1.5m; H3: height range 1.5-2 m; H4: height range over 2 m. Each height range contains 3 repetitions.

Table C-7 Original data of PM capturing efficiency of leaf wax with different height range on the green wall

(Original data for Fig. 4.10, Fig 4.10 and Fig. 4.12)

Number	Sample	Weight of large PM (10-100 μm) M_{fA} (g)	Leaf area (cm^2)	Weight of large PM per leaf area $M_{PM\text{-}Large}$ ($mg\ cm^{-2}$)	Weight of coarse PM (2.5-10 μm) M_{fB} (g)	Leaf area (cm^2)	Weight of coarse PM per leaf area $M_{PM\text{-}Coarse}$ ($mg\ cm^{-2}$)	Weight of fine PM (0.2-2.5 μm) M_{fC} (g)	Leaf area (cm^2)	Weight of fine PM per leaf area $M_{PM\text{-}Fine}$ ($mg\ cm^{-2}$)
1	H1-01	0.0020	367.9290	0.0027	0.0022	367.9290	0.0030	0.0040	367.9290	0.0054
2	H1-02	0.0005	304.5960	0.0008	0.0025	304.5960	0.0041	0.0099	304.5960	0.0163
3	H1-03	0.0004	353.3930	0.0006	0.0026	353.3930	0.0037	0.0109	353.3930	0.0154
4	H2-01	0.0016	382.5850	0.0021	0.0020	382.5850	0.0026	0.0107	382.5850	0.0140
5	H2-02	0.0018	351.9930	0.0026	0.0057	351.9930	0.0081	0.0132	351.9930	0.0188
6	H2-03	0.0019	279.3580	0.0034	0.0071	279.3580	0.0127	0.0852	279.3580	0.1525
7	H3-01	0.0008	311.4920	0.0013	0.0019	311.4920	0.0030	0.0101	311.4920	0.0162
8	H3-02	0.0019	312.0730	0.0030	0.0065	312.0730	0.0104	0.0108	312.0730	0.0173
9	H3-03	0.0017	316.1790	0.0027	0.0066	316.1790	0.0104	0.0093	316.1790	0.0147
10	H4-01	0.0017	419.4780	0.0020	0.0010	419.4780	0.0012	0.0010	419.4780	0.0012
11	H4-02	0.0014	306.2570	0.0023	0.0023	306.2570	0.0038	0.0099	306.2570	0.0162
12	H4-03	0.0004	281.5670	0.0007	0.0009	281.5670	0.0016	0.0107	281.5670	0.0190

Note: H1: height range 0.5-1 m; H2: height range 1-1.5m; H3: height range 1.5-2 m; H4: height range over 2 m. Each height range contains 3 repetitions.

Curriculum Vitae

Personal information

Name: Chen He

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Education

10.2015 – 11.2019	Leibniz Universität Hannover, Institut für Geobotanik	Ph.D candidate
Thesis Title:	Role of roadside vegetation as a passive method for urban air particulate matter absorption and its capturing efficiency under different conditions	
Supervisor:	Prof. Dr. Richard Pott	
09.2012 – 07.2015	Ningxia University, Institute for Grassland science and protection	Master
Thesis Title:	Study on the main pathogen identification and chemical control for *Astragalus* root rot disease in Ningxia	
Supervisor:	Prof. Dr. Shi Juan and Prof. Dr. Xie Yingzhong	
09.2008 – 07.2012	Huanggang normal university	Bachelor
Thesis Title:	Preparation and properties of chloroprene grafted adhesive	
Supervisor:	Prof. Dr. Zhang Kai	

Awards

09.2015-09.2019	Scholarship from China Scholarship Council	China Scholarship Council
2015	Excellent Master thesis	Ningxia University
2013	Reward for outstanding student cadres	Ningxia University
2012	Excellent Bachelor thesis	Huanggang Normal University

List of publications

Published:

- **Chen He**, Kaiyang Qiu*, Richard Pott (2020) Reduction of traffic-related particulate matter by roadside plants: Effect of traffic pressure and sampling height. International Journal of Phytoremediation 22(02): 184-200. DOI: https://doi.org/10.1080/15226514.2019.1652565. (* corresponding author).

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Published online:

- **Chen He**, Kaiyang Qiu*, Richard Pott (2019) Reduction of urban traffic-related particulate matter — Leaf trait matters. Environmental Science and Pollution Research (Published online) DOI: https://link.springer.com/article/10.1007/s11356-019-07160-0.

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- **Chen He**, Kaiyang Qiu*, Richard Pott (2018) Advances in plant effects on particulate matter decreasing caused by public transportation in urban area: A review. International Journal of Environment and Pollution.

- Hongqian Yu, Wendong Peng*, **Chen He**, Fengmao Ma, Xuening Tian, Fengqiao Hu, Dingxing Liu, Bo Ji (2019) Seed germination characteristics of three native forage grass of desert steppe in Ningxia. Acta Prataculturae Sinica.