UNIVERSIDADE FEDERAL DO CEARÁ

CENTRO DE CIÊNCIA E TECNOLOGIA

DEPARTAMENTO DE ENGENHARIA DE TRANSPORTES

PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA DE TRANSPORTES

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EVALUATION OF LEAF PROPERTIES FOR THE MITIGATION OF NON-EXHAUST EMISSIONS FROM TRANSPORTATION THROUGH GREEN CORRIDORS

FORTALEZA

2024

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EVALUATION OF LEAF PROPERTIES FOR THE MITIGATION OF NON-EXHAUST EMISSIONS FROM TRANSPORTATION THROUGH GREEN CORRIDORS

M.Sc. Thesis presented to the Graduate Program in Transport Engineering of the Universidade Federal do Ceará, as a partial fulfillment of the requirements for the Master's Degree in Transport Engineering. Concentration Area: Transport Infrastructure.
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FORTALEZA
2024

To my beloved family, friends, boyfriend and to every individual who refused to let me relinquish this dream, your encouragement has been the fuel propelling me forward. Thank you, from the depths of my heart.

Dados Internacionais de Catalogação na Publicação
Universidade Federal do Ceará
Sistema de Bibliotecas
Gerada automaticamente pelo módulo Catalog, mediante os dados fornecidos pelo(a) autor(a)

R37 Ribeiro, Marilia Nunes Freire.
EVALUATION OF LEAF PROPERTIES FOR THE MITIGATION OF NON-EXHAUST EMISSIONS FROM TRANSPORTATION THROUGH GREEN CORRIDORS / Marilia Nunes Freire Ribeiro. – 2024.
123 f. : il. color.

Dissertação (mestrado) – Universidade Federal do Ceará, Centro de Tecnologia, Programa de Pós-Graduação em Engenharia de Transportes, Fortaleza, 2024.
Orientação: Profa. Dra. Verônica Teixeira Franco Castelo Branco.
Coorientação: Profa. Dra. Manuela Gennesseaux.

1. Leaf surface properties. 2. Non-exhaust emissions transportation particles. 3. ISO volumetric parameters. 4. Green corridors. 5. Air pollution. I. Título.

CDD 388

-

"Às vezes eu tropeço, caio e me quebro em pedaços. Isso me fortalece.Oxe, se um de mim já é forte, imagine vários!" (Bráulio Bessa)

ABSTRACT

In the ongoing battle against air pollution, tackling atmospheric particulate matter (PM) remains a pivotal challenge. One promising strategy is the establishment of green corridors, offering potential improvements in urban air quality, especially around road infrastructure. A fundamental aspect of this endeavor is understanding how plants effectively capture PM, which is essential for selecting the most appropriate species. Previous studies have delved into quantifying leaf roughness and micromorphological traits without establishing a direct correlation with PM adherence. This research employs several approaches: (1) MountainsMap leaf 3D surface analysis to identify key performance indicators (KPIs) in green corridor planning, (2) exploring the relationship between surface characterization and pollutant retention from transportation infrastructure, and (3) assessing real-scale applications based on laboratory findings. Quantitative analysis highlights Core Void Volume (Vvc) and Core Material Volume (Vmc) as significant parameters, with a high correlation between them. Qualitative observations underscore *Cupressus leylandii* and *Vanhouttei de spirala* as effective retainers of non-exhaust transportation particles. When correlating these findings with data collected on-site behind green barriers at different distances, notably, while most species showed similar particle retention correlation patterns, *Euonymus Europaeus* exhibited a singular difference in pollutant capture within its foliage. Incorporating multiple plant species in green barriers is advocated for their diverse leaf micromorphologies, enhancing the range of mechanisms for particulate matter capture.

Keywords: Leaf surface properties; Non-exhaust emissions transportation particles; ISO volumetric parameters; Green corridors; Transport infrastructure, Air pollution.

RESUMO

Na busca contínua pela mitigação da poluição do ar, lidar com os níveis elevados de material particulado (MP) continua sendo um desafio crucial. Uma estratégia promissora é estabelecer corredores verdes, que oferecem melhorias potenciais na qualidade do ar urbano, especialmente em torno da infraestrutura rodoviária. Um aspecto fundamental desse esforço é compreender como as plantas retêm efetivamente o MP, o que é essencial para a seleção de espécies mais adequadas. Estudos anteriores se concentraram na quantificação da rugosidade foliar e nas características micromorfológicas, sem estabelecer uma correlação direta com a aderência do MP. Esta pesquisa utiliza várias abordagens: (1) análise de superfície 3D das folhas com o MountainsMap para identificar indicadores-chave de desempenho (KPIs) no planejamento de corredores verdes, (2) explorar a relação entre a caracterização da superfície e a retenção de poluentes da infraestrutura de transporte e (3) avaliar aplicações em escala real com base em descobertas laboratoriais. A análise quantitativa destaca o Volume do Vazio Central (Vvc) e o Volume do Material Central (Vmc) como parâmetros significativos, com uma alta correlação entre eles. Observações qualitativas destacam *Cupressus leylandii* e *Vanhouttei de spirala* como retentores eficazes de partículas de transporte de não-combustão. Ao correlacionar essas descobertas com dados coletados no local, atrás de barreiras verdes em diferentes distâncias, nota-se que, enquanto a maioria das espécies apresentava padrões de correlação de retenção de partículas semelhantes, *Euonymus Europaeus* exibiu um padrão de retenção de poluentes dentro de sua folhagem diferenciado das outras plantas. A incorporação de várias espécies vegetais em barreiras verdes é defendida por suas diversas micromorfologias foliares, ampliando o leque de mecanismos de captura de matéria particulada.

Keywords: Propriedades da superfície foliar; Partículas de transporte de não combustão; Parâmetros volumétricos; Corredores verdes; Infraestrutura de transporte; Poluição do ar.

RÉSUMÉ

Dans la lutte continue contre la pollution de l'air, la prise en charge des particules atmosphériques en suspension (PM) demeure un défi crucial. Une stratégie prometteuse est la création de corridors verts, offrant des améliorations potentielles de la qualité de l'air urbain, notamment autour des infrastructures routières. Un aspect fondamental de cette entreprise est de comprendre comment les plantes capturent efficacement les PM, ce qui est essentiel pour sélectionner les espèces les plus appropriées. Des études antérieures se sont penchées sur la quantification de la rugosité des feuilles et des caractéristiques micromorphologiques sans établir de corrélation directe avec l'adhérence des PM. Cette recherche utilise plusieurs approches : (1) l'analyse de surface en 3D des feuilles avec MountainsMap pour identifier les indicateurs de performance clés (KPI) dans la planification des corridors verts, (2) explorer la relation entre la caractérisation de la surface et la rétention des polluants des infrastructures de transport, et (3) évaluer les applications à l'échelle réelle en se basant sur les résultats de laboratoire. L'analyse quantitative met en évidence le Volume de Vide Central (Vvc) et le Volume de Matériau Central (Vmc) comme des paramètres significatifs, avec une forte corrélation entre eux. Les observations qualitatives soulignent que *Cupressus leylandii* et *Vanhouttei de spirala* sont des retenues efficaces des particules de transport non échappement. Lors de la corrélation de ces résultats avec les données collectées sur le terrain derrière les barrières vertes à différentes distances, il est à noter que, alors que la plupart des espèces présentaient des motifs de corrélation de rétention des particules similaires, *Euonymus Europaeus* présentait une différence singulière dans la capture de polluants au sein de son feuillage. L'incorporation de plusieurs espèces végétales dans les barrières vertes est préconisée pour leurs diverses micromorphologies foliaires, améliorant ainsi la gamme de mécanismes de capture des particules.

Mots clés: Propriétés de surface des feuilles ; Particules de transport non échappement ; Paramètres volumétriques ISO ; Corridors verts ; Infrastructure de transport ; Pollution de l'air.

LIST OF FIGURES

Figure 1 – Research structure 19
Figure 2 – PM Deposition 23
Figure 3 – Leaf micromorphology description. 25
Figure 4 – Research gap 1 - Leaf surface assessment. 29
Figure 5 – Databases and author's search about leaf surface characterization. 31
Figure 6 – VOSViewer clusters network visualization for the leaf surface characterization. 32
Figure 7 – Paper's year of publication - Leaf surface characterization. 33
Figure 8 – Authors publication density - Leaf surface characterization. 34
Figure 9 – Leaf species selected for the investigation - collected samples. 38
Figure 10 – Collect leaves for scanning, microscopical analysis, and experiment procedure. 39
Figure 11 – Leaf cleaning protocol. 40
Figure 12 – Step-by-step for the parameters obtention. 42
Figure 13 – 3D models of leaf surface processing with Mountainsmaps®. 42
Figure 14 – Pre-experiment leaf data storage. 43
Figure 15 – Graphical explanation of Mountains Map volumetric parameters. 45
Figure 16 – Adaxial observations of a cleaned Leaf 1. 46
Figure 17 – *Vanhouttei de spirala* 3D image of the scanned surface with its volumetric parameters graphic 47
Figure 18 – Abaxial observations of a cleaned Leaf 1 48
Figure 19 – *Vanhouttei de spirala* abaxial side parameters 49
Figure 20 – Clean adaxial side of *Euonymus Europaeus* leaf. 51
Figure 21 – *Euonymus Europaeus* adaxial side parameters 52
Figure 22 – Clean abaxial side of leaf 2. 53
Figure 23 – *Euonymus Europaeus* abaxial side parameters. 54
Figure 24 – Clean adaxial side of leaf 3. 55
Figure 25 – *Cotoneaster aspressus* adaxial surface paramters 56
Figure 26 – Clean abaxial side of leaf 3. 57
Figure 27 – *Cotoneaster aspressus* abaxial surface paramters 58
Figure 28 – Clean leaf 4. 59
Figure 29 – Surface 3D Leaf 4 60
Figure 30 – Volumetric parameters of Leaf 4 61

Figure 31 – Principal Component Analyses (Principal component analysis (PCA)) for volumetric parameters 65
Figure 32 – Correlation matrix (Pearson) p-value 66
Figure 33 – Graphic representation of interval estimates 68
Figure 34 – Research gap 2. 72
Figure 35 – Papers scanned in each scientific database for the non-exhaust transportation particles characterization. 73
Figure 36 – Database and author's papers search for the non-exhaust transportation particles. 74
Figure 37 – VOSViewer keywords clusters network visualization for the non-exhaust transportation particles. 75
Figure 38 – VOSViewer keywords clusters network visualization for the non-exhaust transportation particles. 76
Figure 39 – Non-exhaust transportation particles samples. 78
Figure 40 – Drying experimental particles in the oven, vacuum dessicator 79
Figure 41 – Bottles polluted air experiment preparation 80
Figure 42 – Exposure of particles to leaves at a laboratory scale 81
Figure 43 – Particle separation after laboratory experiment and analysis 81
Figure 44 – Procedure to retained laboratory experiment particles weigh determination . 82
Figure 45 – Leaf 1 exposed to three kinds of pollutants 84
Figure 46 – Leaf 2 exposed to three kinds of pollutants 86
Figure 47 – Leaf 3 exposed to three kinds of pollutants 87
Figure 48 – Leaf 4 exposed to three kinds of pollutants 89
Figure 49 – Particles retention per leaf weight unit 91
Figure 50 – Variables displayed on a multi-factor principal component analysis graphic . 92
Figure 51 – Research gap 3 97
Figure 52 – Carrousel of fatigue in the NEMO project, Nantes - France 98
Figure 53 – April 2023 Nantes, France weather caracterization 99
Figure 54 – Clusters network visualization for the effectiveness of the entire vegetative system in retaining pollutants 101
Figure 55 – Clusters density visualization for the effectiveness of the entire vegetative system in retaining pollutants 102
Figure 56 – Experiment setting scheme for outside air quality 104

Figure 57 – Experiment execution for outside air quality 105
Figure 58 – Data comparation from the 17th April 2023 measurements. 107
Figure 59 – Data comparation from the 18th April 2023 measurements. 108
Figure 60 – Pearson correlation matrix - Correlation (p-value) 109
Figure 61 – PCA groups distribution according to leaf type and Mini-wras position inside the plant 113
Figure 62 – Bottles polluted air entire experiment preparation 123

LIST OF TABLES

Table 1 – Summary of criteria used in the systematic review for leaf surface properties 30

Table 2 – Leaf roughness of plant species measured by 3D optical profilometry. 36

Table 3 – Leaf species selected for the investigation. 38

Table 4 – Mountains Maps® output relevant functional volume parameters meaning and units 44

Table 5 – Mountains Maps® output relevant height parameter meaning and units . . . 44

Table 6 – Leaf 1 - *Vanhouttei de spirala* surface parameters 50

Table 7 – Leaf 2 - *Euonymus Europaeus* surface parameters 54

Table 8 – Leaf 3 - *Cotoneaster aspressus* surface parameters 59

Table 9 – Leaf 4 - *Cupressus leylandii* surface parameters 61

Table 10 – Adaxial result 62

Table 11 – Abaxial result 62

Table 12 – P-values test results 63

Table 13 – Summary of criteria used in the systematic review for non-exhaust transportation PM characterization. 73

Table 14 – Particles retained by leaves 90

Table 15 – Multi-factor Linear Regression results for dirt index values 93

Table 16 – Summary of criteria used in the systematic review for green corridors and transportation air pollution. 100

Table 17 – Timetable for the air quality external measurement. 106

Table 18 – Multiple Linear Regression results for PM_1 measured value 110

Table 19 – Multiple Linear Regression results for $PM_{2.5}$ measured value 111

LIST OF ACRONYMS

μm	Micrometer
μm^2	Squared micrometer
μm^3	Cubic micrometer
6PPD	N-phenyl-N'-(1,3-dimethylbutyl)-p-phenylenediamine
ANOVA	Analysis of variance
APTI	Air Pollution Tolerance Index
HMMM	hexamethoxymethylmelamine
kHz	kilohertz
LE	Life Expectancy
mL	milliliter
mm	Millimiter
NO_2	Nitrogen dioxide
O_3	Ozone
PCA	Principal component analysis
PM	Particulate Matter
PM_1	Particles with an aerodynamic diameter of up to 1 µm
$PM_{2.5}$	Particles with an aerodynamic diameter of up to 2.5 µm
PM_{10}	Particles with an aerodynamic diameter of up to 10 µm
SEM	Scanning Electron Microscopy
TWP	Tire Wear Particles
V_{mc}	Core material volume
V_{mp}	Peak material volume
V_{vc}	Core void volume
V_{vv}	Valley void volume
WHO	World Health Organization
WRS	World Road Statistics

CONTENTS

1 INTRODUCTION 16

1.1 Research problem 16

1.2 Research justification 18

1.3 Research questions 18

1.4 Research objectives 19

1.4.1 Main objective 19

1.4.2 Specific objectives 20

1.5 Thesis structure 20

1.6 Theoretical background 21

1.6.1 Non-exhaust particles 21

1.6.2 Leaf surface properties 23

1.6.3 State of the art development 25

2 LEAF MICROMORPHOLOGY VOLUMETRIC PARAMETER STUDY FOR AIR POLLUTANT CAPTURE IN GREEN CORRIDORS 28

2.1 Introduction 28

2.1.1 Chapter objective 28

2.2 State of the art 30

2.2.1 Systematic literature review 30

2.2.2 Bibliographic review 34

2.3 Methodology 37

2.3.1 Leaves species 38

2.3.2 Collecting Leaves 39

2.3.3 Samples cleaning 39

2.3.4 Pre-experiment surface analyse 41

2.3.5 Mountains Maps® surface analyse parameters 43

2.4 Results 45

2.4.1 Leaf micromorphology analysis 45

2.4.1.1 Vanhouttei de spirala *45*

2.4.1.2 Euonymus Europaeus *50*

2.4.1.3 Cotoneaster aspressus *55*

2.4.1.4 Cupressus leylandii *59*

2.4.2	*Statistical analyses*	62
2.5	**Conclusion**	69
3	**IMPACT OF LEAF SURFACE VOLUMETRIC PARAMETERS ASSESSMENT ON NON-EXHAUST TRANSPORTATION PARTICLE RETENTION**	70
3.1	**Introduction**	70
3.1.1	*Chapter objective*	71
3.2	**State of the art**	72
3.2.1	*Systematic literature review*	72
3.2.2	*Bibliographic review*	77
3.3	**Methodology**	78
3.3.1	*Materials preparation*	79
3.3.2	*Experiment preparation*	79
3.3.3	*Particles exposure*	80
3.3.4	*Particle separation and analysis*	81
3.3.4.0.1	Measurement of particle weight removed from leaves surfaces	82
3.4	**Results**	83
3.4.1	*Vanhouttei de spirala*	83
3.4.2	*Euonymus Europaeus*	84
3.4.3	*Cotoneaster aspressus*	85
3.4.4	*Cupressus leylandii*	88
3.4.5	*Statistical analyse*	90
3.5	**Conclusion**	94
4	**ANALYZING THE CORRELATION BETWEEN LEAF VOLUMETRIC TRAITS AND POLLUTANT RETENTION ACROSS THE ENTIRE VEGETATIVE SYSTEM**	95
4.1	**Introduction**	95
4.1.1	*Chapter objective*	96
4.1.2	*Experiment location*	97
4.1.3	*Weather*	98
4.2	**State of the art**	99
4.2.1	*Systematic literature review*	99

4.2.2 *Bibliographic review* 102

4.3 **Methodology** 104

4.4 **Results** 106

4.4.1 *Statistical analyse* 108

4.5 **Conclusion** 114

5 **CONCLUSION AND SUGGESTIONS** 115

5.0.1 *Future works* 115

BIBLIOGRAPHY 117

1 INTRODUCTION

1.1 Research problem

According to the European Environmental Agency (2020), air pollutants play a crucial role in health problems in the European population, mainly in urban areas. Poor air quality is related to respiratory diseases, cardiovascular diseases, asthma, and allergies. In Brazil, for instance, Testa (2015) pointed out that more than three thousand deaths per year are related to air pollution in the metropolitan region of São Paulo. Between the most severe pollutants, they list the Particulate Matter (PM), Nitrogen dioxide (NO_2), and Ozone (O_3) from the ground level. Due to the increased medical costs of dealing with illnesses and reduced life expectancy, those pollutants also have an economic impact. The exact entity mentioned that premature deaths due to long-term exposure to air pollution smaller than 2.5 µm corresponded to 417 hundred deaths in Europe. The World Health Organization (WHO) estimates that around 3% of cardiopulmonary and 5% of lung cancer deaths are attributable to PM, globally.

Querol *et al.* (2004) used data from several European cities to show that exhaust and non-exhaust sources can contribute nearly equal amounts to total traffic-related emissions of PM (ASMA *et al.*, 2020). Ribeiro *et al.* (2019) observed that high NO_2 concentrations, for example, were observed in areas with higher entropy, indicating a direct link to vehicular flow and the emission of atmospheric pollutants, specifically NO_2 in their study. When looking at non-exhaust sources, Harrison *et al.* (2001) already mentioned that non-exhaust sources summarize almost an equal concentration to that from engine exhaust emissions on a heavily trafficked London road.

In Brazil, Rocha *et al.* (2020) assessed that a short-term reduction in the concentration of PM 10 by 20 µg m^{-3} could have the potential to avoid over 400 hospitalizations per year connected to cardiorespiratory diseases. The long-term reduction of the same concentration would avoid over 580 hospitalizations in the state of Ceará.

Forouzanfar *et al.* (2016) ranked PM air pollution exposure as the sixth most significant risk factor worldwide among 79 behavioral, environmental, and occupational factors. This emphasizes the importance of reducing PM levels. Encouragingly, aggressive emission control measures implemented in China through the Action Plan from 2013-2017 yielded positive outcomes. A study assessing air quality changes reported a 32% reduction in PM2.5 concentration, resulting in a 14% decrease in premature deaths attributed to long-term exposure (CHEN; HOEK, 2020). Lastly, the studies by Pires *et al.* (2022) and Adolfo *et al.* (2022) highlighted the hazardous chemical composition of air PM resulting from asphalt mixture production. These discoveries underscore the significance of examining the particulate matter (PM) leaves' capture potential.

1.2 Research justification

As mentioned previously, PM emissions have become a public health problem worldwide due to several different sources of emissions, one of which is related to transportation engineering and, more specifically, to the transport infrastructure (EUROPEAN ENVIRONMENTAL AGENCY, 2020). The significance of the transport infrastructure for today's dynamic population is unquestioned. According to the World Road Statistics (WRS) database (2020), the total road length worldwide is 26 million km, connecting cities and countries and providing access to schools, hospitals, and parks, for example. According to the World Population Review (2024), Brazil has the 4th largest road network in the world, behind the United States, India, and China. In 2023, the (WORLD HEALTH ORGANIZATION (WHO), 2023) estimated that around 3% of cardiopulmonary and 5% of lung cancer deaths are attributable to PM, globally.

When evaluating the population and environmental health, the relevance of appropriate plants adapted to the local climate and with the proper potential to improve the air quality and atmospheric depollution is generally only considered after several connected disease scenarios added to high direct and indirect costs of air pollution. Nonetheless, a pertinent approach has been aimed at improving the quality of life in the road's surroundings since the initial plan. At the moment, green paths have been an increased hope solution to decrease the severity of already developed problems. Due to this planning, transport engineers must proactively consider the positive health and social impacts of employing appropriate leaves and local greenery in the road vicinity since the plan. According to Corada *et al.* (2020), decision-markers should consider multidisciplinary groups when a green infrastructure in an urban area, including air pollution experts, architects, and botanists, for example.

1.3 Research questions

Considering the presented scenario concerning the selection of plants with the highest potential for particle retention from urban road transport, the following research questions emerged.

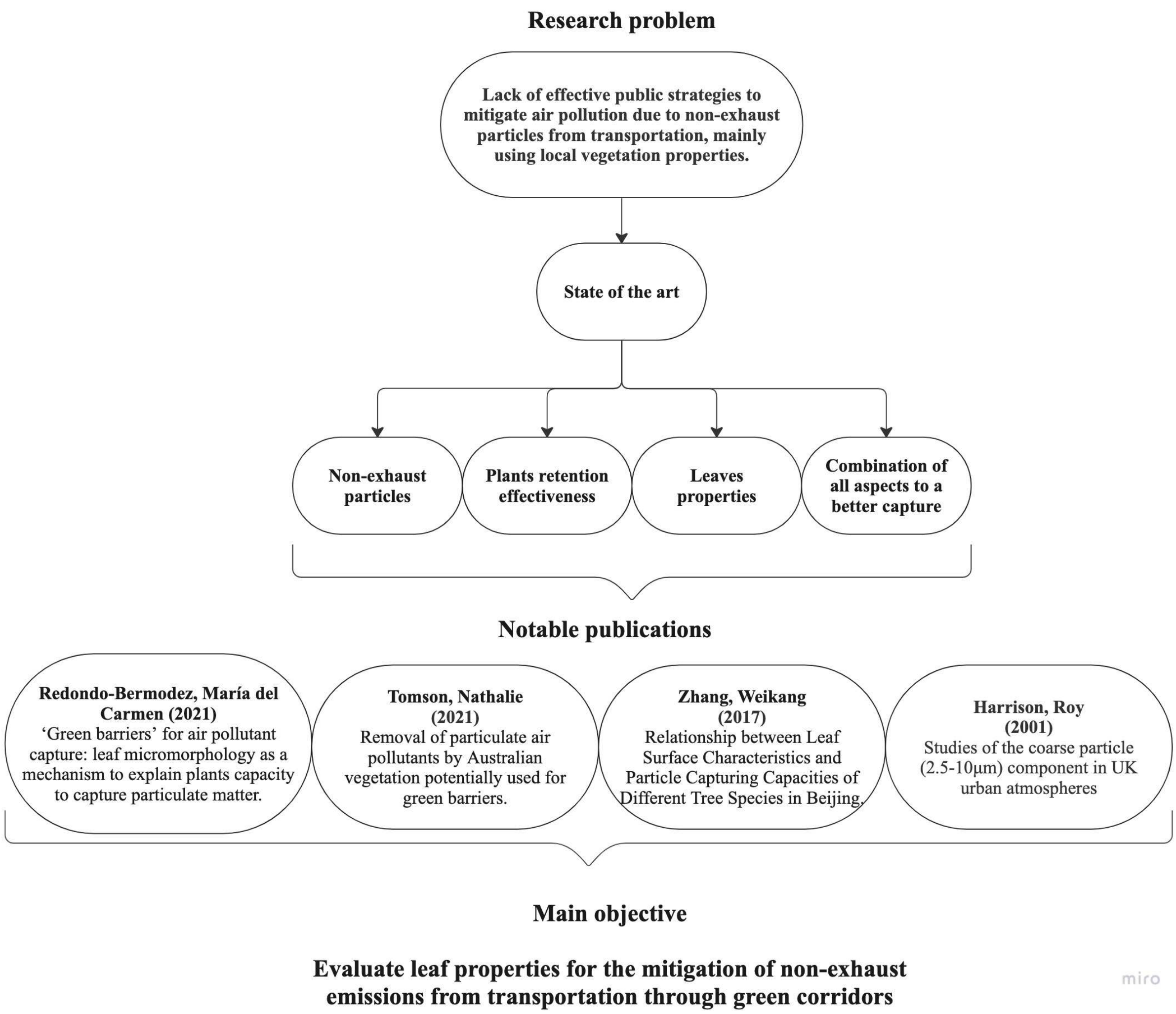
i How does leaves' surface texture could influence the retention of particles?

ii How are different transportation non-exhaust particles retained in leaves' surfaces?

iii Are the properties of the entire vegetative system in capturing pollutants as effective as the leaf volumetric properties?

Figure 1 shows those research gaps and some of the studies which based this research problem and objective design.

Figure 1 – Research structure



Source: Author

1.4 Research objectives

1.4.1 Main objective

This research aims to evaluate leaf properties to mitigate non-exhaust emissions from transportation through green corridors.

1.4.2 Specific objectives

A series of specific objectives will be examined individually to accomplish the primary objective. Those specific objectives are as follows:

i Evaluate surface parameters of the leaves to assess their characteristics;

ii Assess the relation between particle origination, leaf traits, and particle retention;

iii Determine the plant species that exhibit the highest particle retention when exposed to real-size particle exposure.

1.5 Thesis structure

This thesis comprises five chapters, each serving a distinct purpose within the research framework. The initial chapter provides a comprehensive overview of the research topic, delineating the definition of the research problem and its rationale and elucidating the principal and specific objectives of the study. This chapter incorporates a foundational theoretical framework (Section 1.6) to enhance readers' understanding without specialized expertise, elucidating fundamental concepts.

The ensuing three chapters—namely, the second, third, and fourth—individually address distinct research inquiries. Each chapter includes an introduction, a review of contemporary literature, a detailed methodology, results, and a conclusion pertinent to the research question.

Chapter 2 is dedicated to examining leaf characteristics (environmental), serving as a foundational exploration within the thesis. Leaf volumetric surface parameters will be studied and qualitatively analysed to elect the more appropriate one to represent these surfaces trait.

Chapter 3 focuses on assessing transportation particles (infrastructure) within the context of the preceding chapter's analysis of leaf characteristics. Integrating these factors is critical to understanding the retention mechanisms of particles.

Furthermore, Chapter 4 delves deeper into the evaluation of green corridors and the interconnection of plant features in the surrounding road infrastructure (planning/operation). This chapter serves as a bridge between the preceding chapters, providing a real-world application and experimental exploration of plant behavior when situated near non-exhaust emission sources, thereby synthesizing the findings from the prior sections.

Lastly, the fifth chapter presents the preview findings in a singular conclusion.

Additionally, this chapter brings suggestions for future works.

In summary:

i Chapter 1: "Introduction";

ii Chapter 2: "Leaf Micromorphology Volumetric Parameter Study for Air Pollutant Capture in Green Corridors";

iii Chapter 3: "Impact of Leaf Surface Volumetric Parameters Assessment on Non-Exhaust Transportation Particle Retention";

iv Chapter 4: "Analyzing the Correlation Between Leaf Volumetric Traits and Pollutant Retention Across the Entire Vegetative System";

v Chapter 5: "Conclusion and suggestions";

vi Bibliography and appendix.

1.6 Theoretical background

1.6.1 Non-exhaust particles

This section intends to provide clear definitions for concepts pertaining to non-exhaust tire-pavement friction emissions. These definitions encompass various terms used in this study, such as PM, inhalable particles, thoracic particles, alveolic particles, and non-exhaust emissions. The following definitions elucidate these concepts within the context of this research:

- Particulate Matter: The acronym PM encompasses a combination of solid particles and liquid droplets in the atmosphere (SUWANWAIPHATTHANA *et al.*, 2009). Certain particles, including dust, dirt, soot, or smoke, possess a size or color that makes them readily visible to the unaided eye. These particles can vary in size, composition, and origin and have diverse effects on human health and the environment (PROTECTION AGENCY, 2022).
- PM_{10}: Refers to Particles with an aerodynamic diameter of up to 10 µm (PM_{10}). In turn, PM_{10} can be subdivided into "coarse particles" ($PM_{2.5}$–PM_{10}, diameter 2.5–10 µm), "fine

particles" ($PM_{2.5}$, diameter <2.5 µm), and "ultrafine particles" (UFPs diameter <0.1 µm). These particles are small enough to be inhaled into the respiratory system, potentially reaching the lungs (PROTECTION AGENCY, 2022) & (POLICHETTI *et al.*, 2009).

– $PM_{2.5}$: Denotes fine inhalable Particles with an aerodynamic diameter of up to 2.5 µm (PM $_{2.5}$). These particles are even smaller than PM_{10} particles and can penetrate deeper into the respiratory system, posing potential health risks (PROTECTION AGENCY, 2022).

– PM_1: Defines Particles with an aerodynamic diameter of up to 1 µm (PM $_1$), quoted as the most dangerous fraction to human health, as it can achieve lungs alveoli (PRAžNIKAR; PRAžNIKAR, 2012).

– Inhalable Particles: Refers to small particles to be inhaled into the respiratory system. Typically, they have a diameter of 10 (µm) or less (coarse particles) and can penetrate the upper respiratory tract, potentially reaching the lungs. Have been found that they induce a mild inflammatory response. This initial inflammation can trigger subsequent inflammatory reactions in both the alveolar region of the lungs and the systemic circulation (SEATON W MACNEE, 1995).

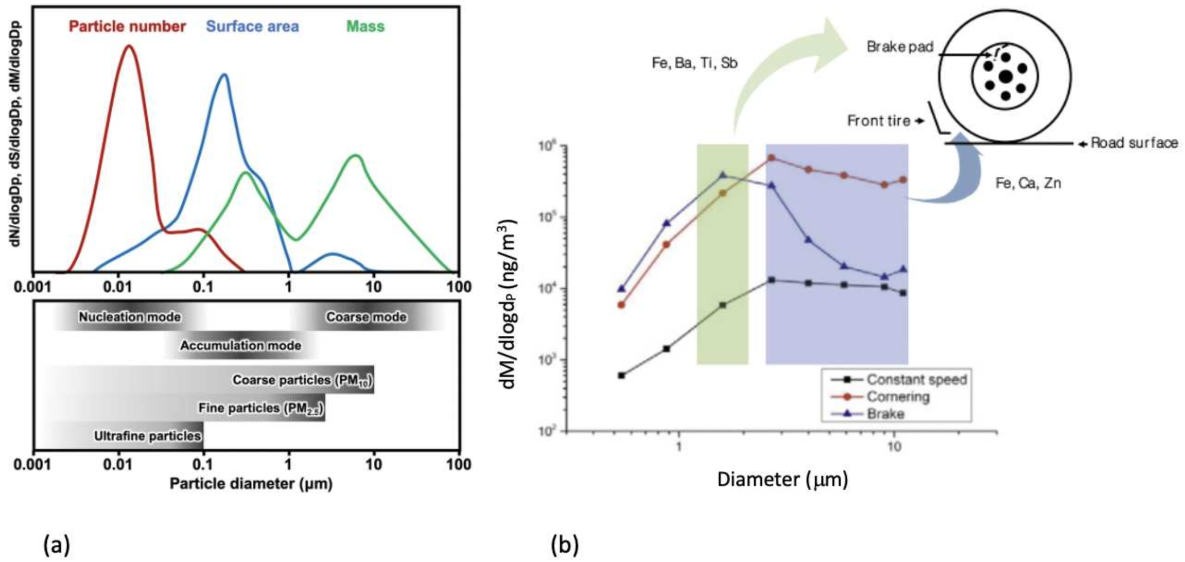
– Thoracic Particles: Denotes particles that are small enough to enter the thoracic region of the respiratory system beyond the larynx, the area of the throat containing the vocal cords used for breathing, swallowing, and talking. These particles generally have a diameter of 2.5 µm or less (fine particles) and can penetrate deeper into the respiratory system compared to inhalable particles (ESTHER; JUSTIN, 2022).

– Alveolic Particles: Describes particles that are fine enough to reach the alveoli, which are the tiny air sacs in the lungs where gas exchange occurs. Alveolic particles are typically ultrafine, with a diameter of 0.1 µm or less, and they have the potential to cause significant health effects due to their ability to enter the bloodstream (PRAžNIKAR; PRAžNIKAR, 2012).

– Non-Exhaust Emissions: Predominantly originate from abrasive sources, notably brake wear, tire wear, and abrasion of the road surface. These sources contribute to releasing particles into the environment (ABU-ALLABAN *et al.*, 2003) & (THORPE; HARRISON, 2008).

By clarifying these terms, this section establishes a common understanding of the concepts associated with non-exhaust tire-pavement friction emissions, as seen in Figure 2, facilitating effective communication and comprehension within the context of this research.

Figure 2 – PM Deposition



a. Representation of a typical ambient particle-size distribution of the number concentration, surface area concentration, and mass concentration (dN/dLog Dp, particle number per cubic millimeter; dS/dLog Dp, particle surface area per cubic millimeter; and dM/dLog Dp, particle mass per cubic millimeter, respectively). b. Characterization of non-exhaust coarse and fine particles from on-road driving and laboratory measurements.
Source:(PRAžNIKAR; PRAžNIKAR, 2012) & (KWAK *et al.*, 2013)

1.6.2 Leaf surface properties

The leaves' surface texture is pivotal in delineating their capacity to intercept airborne pollutants. Leaves endowed with rough surfaces hold the potential to serve as natural filters, adept at trapping airborne particles through a confluence of physical mechanisms, including interception, impact, and diffusion. Furthermore, the coarse texture of leaf surfaces augments the available surface area for particle adherence, thus potentially amplifying their efficacy in particle capture (TOMSON *et al.*, 2021). Additionally, the presence of trichomes and other surface structures may further enhance the particle capture potential of leaves. However, the efficacy of leaves in particle capture is contingent upon various factors such as leaf morphology, surface area, maturation, and prevailing environmental conditions encompassing wind velocity and humidity levels (BERMúDEZ *et al.*, 2021), (ZHANG *et al.*, 2018).

This section endeavors to offer precise elucidations of concepts about leaf surfaces. This encompasses terminology such as "adaxial," "abaxial," and "grooves," as they will be explored within the confines of this thesis.

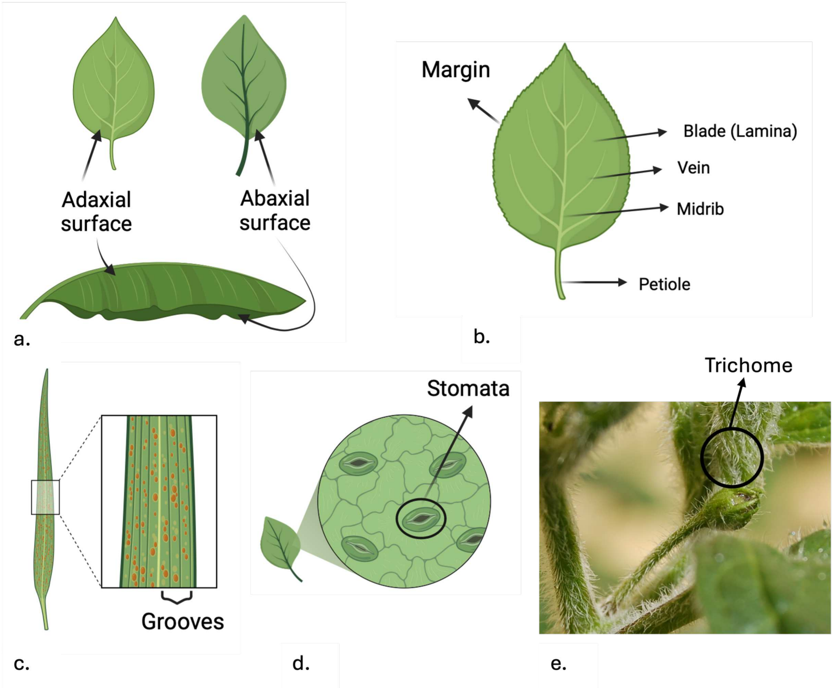
- Abaxial: Represents the lower leafs' domain surface with an epidermis with abundant stomata. In botanical terms, the side away from the axis (YAMAGUCHI *et al.*, 2012).
- Adaxial: It consists of the upper domain of the leaf surface of a relatively thick cuticle (YAMAGUCHI *et al.*, 2012).
- Blade (Lamina): The blade, also known as the lamina, is the broad, flat, typically green part of a leaf. It is the primary site for photosynthesis, where chlorophyll absorbs and converts sunlight into chemical energy (SOLANO *et al.*, 2012).
- Grooves: A cut or indentation as a line across the wood grain or leaf surface or anisotropic longitudinal flow (XU *et al.*, 2021).
- Epicuticular wax: A cuticle layer which creates a seemingly smooth layer on the leaf's surface (MUHAMMAD *et al.*, 2019).
- Leaf roughness: This is frequently estimated as the quantification of grooves and ridges by their width (2D distance measure), morphology, or the proportion they cover the leaf surface. This foliar characteristic is considered to have strong positive correlations with PM capture ((BERMúDEZ *et al.*, 2021), (DAN *et al.*, 2016), (SHAO *et al.*, 2018)).
- Midrib: Is the central vein running along the center of a leaf. It provides structural support to the leaf and contains vascular tissues that transport water and nutrients to the leaf blade (Oxford University Press, 2024).
- Petiole: This stalk or stem-like structure attaches the leaf blade to the plant's stem. It provides support and allows for flexibility and movement of the leaf in response to environmental factors (Master Gardeners of Northern Virginia, 2024).
- Stomata: These are tiny pores or openings primarily found on the underside of leaves. They regulate gas exchange, allowing carbon dioxide uptake for photosynthesis and releasing oxygen and excess water vapor through transpiration. Stomata also play a role in controlling water loss and regulating internal leaf temperature. The length can be between 10-70 μm (Study Smarter, 2024), (TAYLOR *et al.*, 2012).
- Trichomes: These are small hair-like outgrowths or appendages that protrude from the surface of leaves. They can serve various functions, including protection against herbivores, regulation of leaf temperature, and reduction of water loss through transpiration

(SIMPSON, 2019).

– Vein: These vascular tissues within a leaf facilitate the transport of water, nutrients, and sugars to and from the leaf. They provide structural support to the leaf and serve as conduits for the distribution of resources (SIMPSON, 2019).

– Venule: These are small veins within the leaf that branch off from more prominent veins. They distribute water, nutrients, and sugars to the leaf cells and are integral to the overall vascular system of the leaf, similar to stems (SIMPSON, 2019).

Figure 3 – Leaf micromorphology description.



a. Facets name b. Parts of a simple leaf c. Monocot leaf surface with grooves observation d. Stomatas e. Trichomes in a leaf surface.
Source: Author

1.6.3 State of the art development

According to Torres-Carrion *et al.* (2018), a systematic literature review is crucial for identifying research questions and justifying future research. However, it can be challenging for novice researchers lacking search, filtering skills, and knowledge of relevant databases. He proposed an adapted method in his work, dividing the process into planning, conducting, and reporting stages. It begins with defining research questions and a "mentefacto conceptual" framework.

A systematic literature review serves as a comprehensive tool for aggregating existing research, encompassing the methods employed, the obtained results, the presented proposals, the prominent authors in a given field, research groups into clusters, the distribution of the databases, and publications utilized to disseminate their work. This approach enables researchers to acquire up-to-date and enduring information regarding published findings from various laboratories, research centers, and educational institutions, facilitating access to a broad range of knowledge in a specific area. A preliminary study identifies existing literature, while inclusion/exclusion criteria are established during the planning phase. The rigorous approach yields relevant journals and articles for each research question, as assessed by Torres-Carrion *et al.* (2018) and Schaefer e Siluk (2021).

In this research, the systematic literature review methodology was employed to support the research questions addressed and provide scientific guidance and prior experiences in selecting and applying the methods and data analysis techniques.It was utilized a targeted search approach, focusing on recent references within a comprehensive global database. The chosen research topic exhibits considerable significance and innovation within the academic sphere, highlighting the limited correlation observed thus far between transportation infrastructure, planning, and the environment.

The primary objective during this review phase was to showcase the diverse research domains encompassing environmental, social, and urban transportation issues and highlight the key scientific findings already present within the field. As previously mentioned, the systematic review in this study consists of three distinct phases: planning, conducting the review, and reporting the findings. The Vosviewer software was used to aid in this process (XIAO; WATSON, 2017).

The primary motivation for conducting the systematic review is identified in the planning phase. A review protocol is established as a crucial component. This planning phase involves specifying the research questions, determining the conduction strategy, defining the selection criteria, establishing the quality assessment criteria for the included studies, outlining the data extraction methodology, and selecting the relevant journals for the review.

Subsequently, the conduction phase is carried out, wherein an extensive search strategy is employed to identify relevant studies. The inclusion and exclusion criteria are then applied to select appropriate articles. Once selected, the accepted articles undergo data extraction and synthesis.

The final phase aims to evaluate the obtained results. The objective of this systematic review established a priory, is to investigate the most pertinent studies conducted within the last five years and explore the interconnection of various significant research themes, mainly focusing on the surface characteristics of leaves, relevant to the pollutant retention.

This study will conduct three systematic reviews, as the research encompasses two significant areas of investigation. For the review presented in this chapter, the search was initiated using keywords such as "air pollution," "transportation," "deposition," and ("leaf" or "leaves") and various combinations of keywords to capture a broad range of relevant studies. To conclude, for each state-of-the-art analysis, the bibliographic review will summarize the preview step.

2 LEAF MICROMORPHOLOGY VOLUMETRIC PARAMETER STUDY FOR AIR POLLUTANT CAPTURE IN GREEN CORRIDORS

2.1 Introduction

In recent decades, there has been a growing focus within the scientific community on the potential of urban vegetation to play a crucial role in mitigating air pollution. However, as highlighted by Sgrigna *et al.* (2020), our understanding of the mechanisms underlying particulate matter (PM) retention by vegetation remains incomplete and requires further clarification.

The study of different contact mechanisms between the PM and leaf has steeply increased in the last few years, isolating different environmental aspects. For instance, Xie *et al.* (2017) studied this phenomenon under various wind conditions. Simultaneously, Baldacchini *et al.* (2017) examined leaf traits of the same plant species, *Platanus acerifolia*, in various geographical locations where they were situated.

In a parallel line of research, several papers have been published focusing on specific leaf characteristics. In 2021, for instance, Muhammad *et al.* (2019) identified leaf trichomes and specific leaf areas as significant traits for categorizing selected plant species as low, medium, or high net particle accumulators. A more recent 2023 study demonstrated that particulate matter (PM) primarily deposits onto the leaf surface, highlighting the importance of considering canopy-to-leaf aerodynamics-related characteristics such as branch/shoot complexity, leaf size, leaf surface roughness, and hairiness. Furthermore, characteristics influencing PM retention capacity, resuspension, and wash-off include leaf surface roughness, hairiness, and wax content (LINDéN *et al.*, 2023).

These previous studies contribute to our understanding that the topic addressed in this chapter results from multiple combined phenomena, which collectively contribute to PM retention. Simultaneously, the individual examination of each aspect represents an essential piece of the broader puzzle in understanding these phenomena.

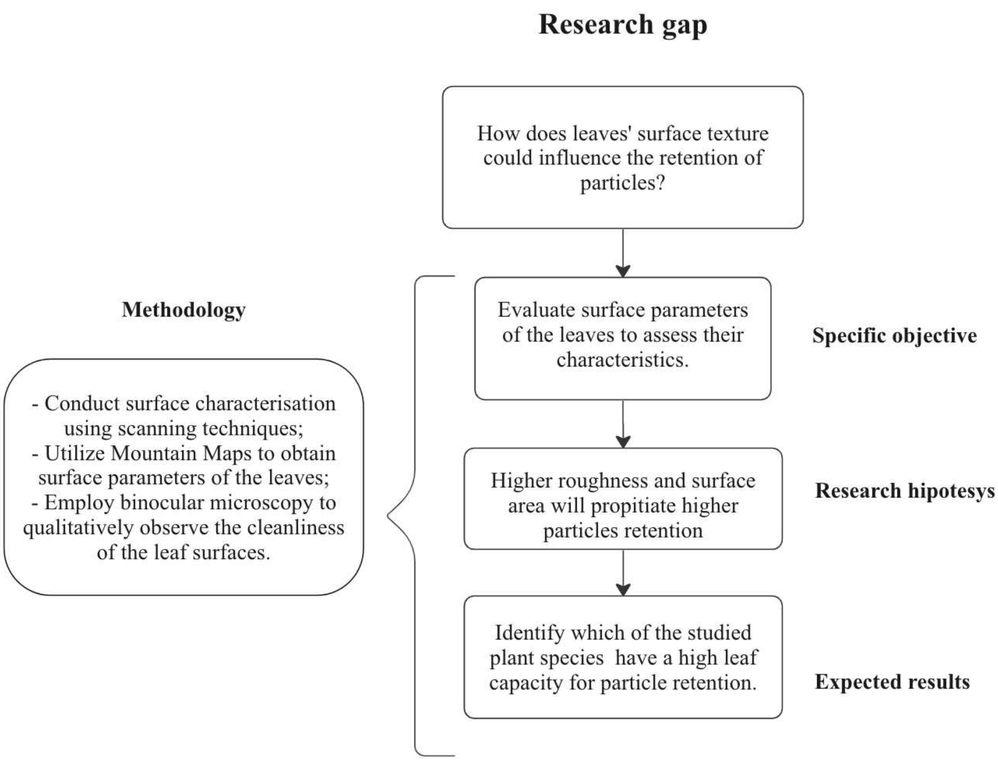
2.1.1 Chapter objective

In the context of an expanded database encompassing diverse locations worldwide and their corresponding data on leaves' surface properties, this chapter seeks to ascertain the plant species exhibiting the most remarkable leaf capacity for particulate retention. The specific objective entails evaluating the surface parameters of the leaves to assess their characteristic attributes.

Through a comprehensive analysis of the surface parameters, this research aims to elucidate the specific leaf characteristics that contribute to superior particulate retention. By examining fundamental surface properties such as volumetric surface parameters, morphology, and other relevant factors, the study aims to identify and quantify the leaf attributes that are most conducive to effective particulate retention.

The outcomes of this investigation will shed light on the local leaf surface properties, already chosen to be used near French roads, that correlate with enhanced particulate retention capabilities. These findings will contribute to understanding plant-based air pollution mitigation strategies and aid in selecting and implementing appropriate plant species in diverse geographic locations for optimal environmental benefits. The visual representation of the strategic approach adopted in this chapter can be observed in Figure 4.

Figure 4 – Research gap 1 - Leaf surface assessment.



Source: Author

2.2 State of the art

2.2.1 Systematic literature review

The databases selected for this chapter review were Scopus, Web of Science, and Science Direct. Initial exclusion criteria were established and applied as filters provided by the platforms, aiming to refine the search results and import the most pertinent data into Vosviewer. Initially, 1,954 studies were obtained based on the defined search strings. Applying the first filter, which focused on studies published within the last five years, 1,246 surveys were excluded. Additionally, with the implementation of the second filter to remain only review and research articles, excluding encyclopedias and book chapters, for example, 204 studies were eliminated, resulting in 504 studies.

Additionally, due to the high number of articles, an additional filter was used, criteria 3, to maintain only open-source papers. For further analysis remained, 127 papers. The numbers of studies obtained after each filter application are summarized in Table 1.

Table 1 – Summary of criteria used in the systematic review for leaf surface properties

Keywords	Database	Total papers	Criteria 1	Criteria 2	Criteria 3	Final papers
"air pollution" AND "transportation" AND "Deposition" AND ("leaf" OR "leaves")	Scopus	13	6	6	2	2
"air pollution" AND "transportation" AND "Deposition" AND ("leaf" OR "leaves")	Science Direct	6	6	6	6	6
"air pollution" AND "transportation" AND "Deposition" AND ("leaf" OR "leaves")	Web of science	1,935	696	492	119	119
					Total	127

Source: Author

The table above depicts the number of papers scanned in each scientific database, revealing that Web of Science yielded the highest quantity of relevant documents for the applied keywords, as the methodology used by Pereira (2021).

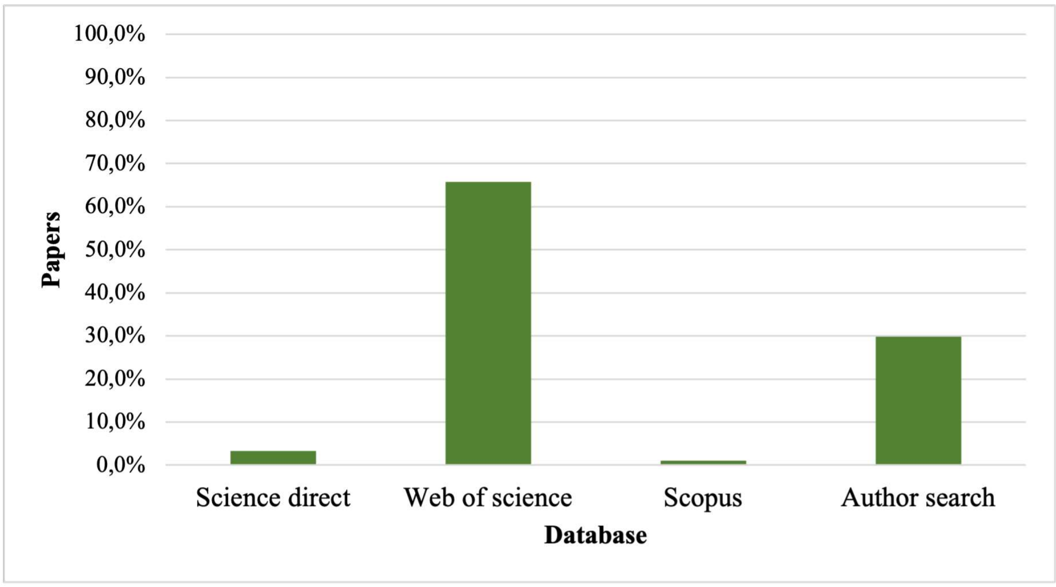
The initial searches yielded 127 studies, which were exported in .bibTeX format. In the subsequent analysis using the software Zotero, the following criteria were applied:

- Exclusion of duplicated/repeated articles;
- Exclusion of articles whose title and abstract did not align with the research focus.

After applying these criteria, it was determined that 15 articles were duplicates, and 90 articles did not meet the requirements based on their title and abstracts. Consequently, 22 articles were left for the next stage of analysis.

In addition, to ensure the inclusion of relevant papers not selected by the database, the author manually added 55 additional documents to the system, beyond the ones found with the keyword search, and added to the Vosviwer. The percentage can be seen in the following image:

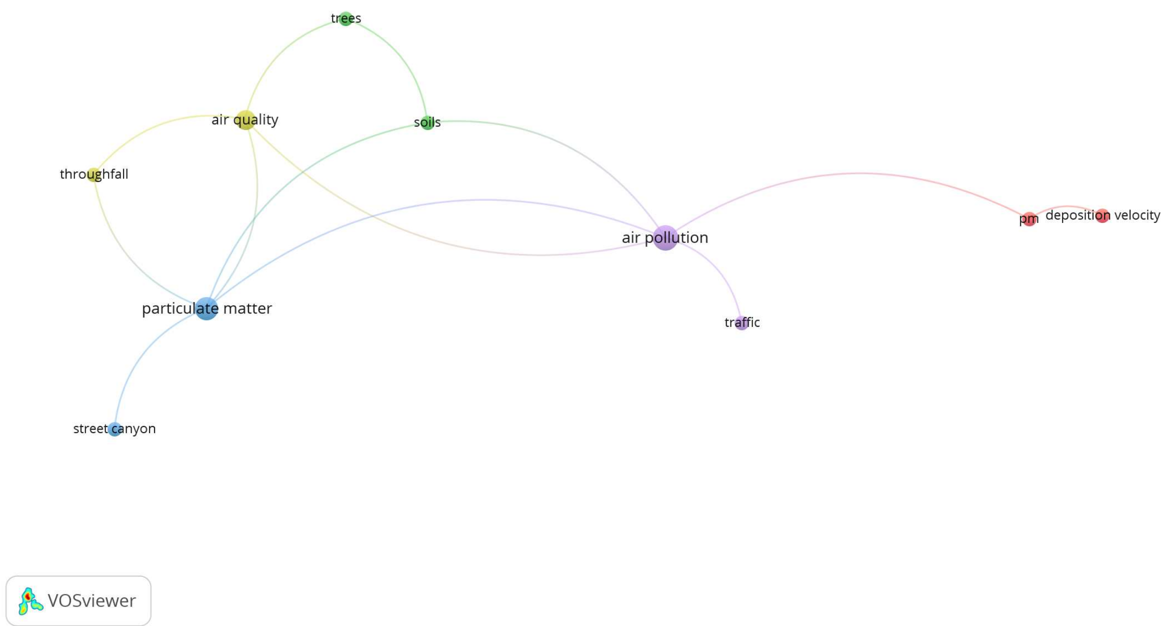
Figure 5 – Databases and author's search about leaf surface characterization.



Source: Author

The data from these 77 articles were then imported into the Vosviewer program for further analysis and summarizing; according to Eck e Waltman (2010), VOSviewer is a software tool for bibliometric analysis that has been collaboratively developed by scholars Nees Jan van Eck and Ludo Waltman from Leiden University (PRASETYO, 2019). Its primary purpose is to create knowledge maps by conducting various analyses, such as co-word, co-citation, and literature coupling analyses. With its visual representation capabilities, VOSviewer enables researchers to explore and interpret research results visually. Notably, the tool offers distinct advantages regarding clustering technology and map displays, enhancing the effectiveness of data visualization and analysis. The network produced using the keywords used in those 77 articles can have their connection seen in Figure 6.

Figure 6 – VOSViewer clusters network visualization for the leaf surface characterization.



Source: Author

The keyword cluster map generated by VOSViewer, seen in Figure 6, provides a clear illustration of the interconnections between the words used in the titles, keywords, and abstracts of articles about the study of leaf surfaces in the transportation cluster. The map reveals distinct clusters of words representing different research aspects.

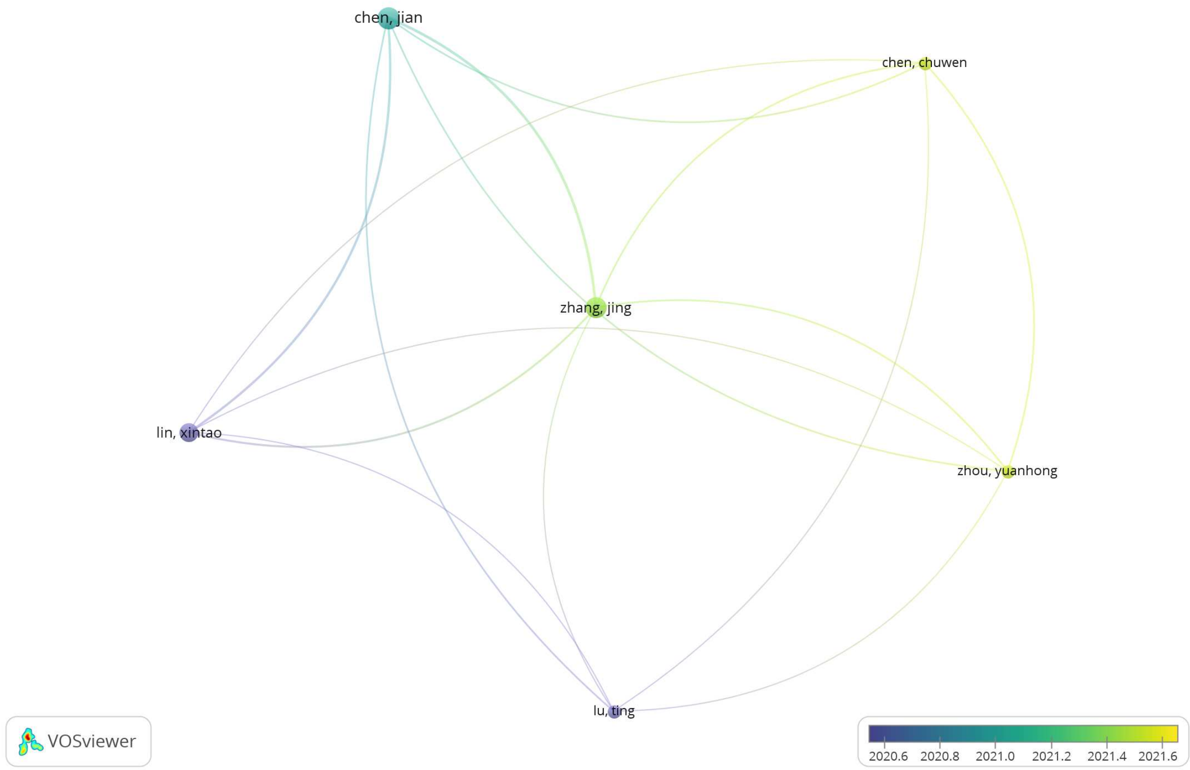
One prominent cluster, depicted in green, primarily encompasses papers focusing on vegetative aspects related to leaves. Another cluster, represented in blue, revolves around "green corridors" and their influence on particulate matter (PM). Additionally, the yellow and purple clusters highlight the close relationship between air quality and air pollution from traffic.

Lastly, the map displays the mechanical aspects of the phenomenon, symbolized by clusters of words that allude to deposition velocity. These clusters serve as a reminder of the significance of particles' physical characteristics and behavior in their interaction with leaf surfaces.

Figures 7 and 8 propitiate the reader to see which author has published more and which data spectrum was released. This example shows that Chen, Jian, Zhang, and Jing are the ones more frequently referenced lately and with newer papers. Both papers are from the quality monitoring area and non-exhaust transportation emission.

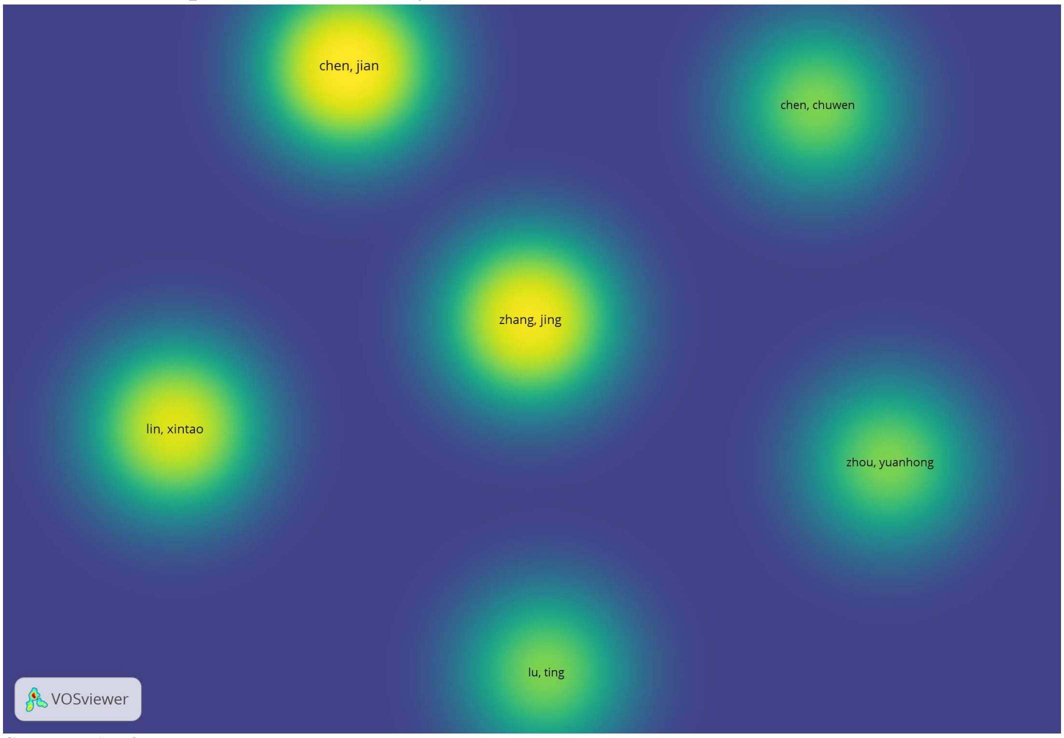
Following the step-by-step approach, each article was carefully read and analyzed to determine its relevance to the content. Subsequently, the accompanying table extracted and documented each article's key points and findings.

Figure 7 – Paper's year of publication - Leaf surface characterization.



Source: Author

Figure 8 – Authors publication density - Leaf surface characterization.



Source: Author

During the extraction phase, a set of four questions were defined:

- Which plant characteristics are favorable to PM retention?
- Was an experiment conducted to evaluate the effectiveness of leaves in retaining particles? If yes, which?
- Which leaves species demonstrated higher levels of particle retention?
- Which plant species had better retention results?

These questions served as a guideline for extracting relevant information from the selected articles, as chosen by Pereira (2021) in her work field. Those results will be compiled in a summarized table in the following research step.

2.2.2 Bibliographic review

In the initial work by Bermúdez *et al.* (2021), the author highlights the significance of detailed knowledge concerning how plants capture particulate matter (PM) to inform plant selection processes. The study observed that the depth and frequency of grooves on leaf surfaces are essential factors that contribute to PM deposition. Additionally, the presence of superficial wax on the leaf surface was found to play a crucial role in PM adherence.

However, Dzierzanowski *et al.* (2011) emphasized in their research on the role of wax in PM retention that it should not be assumed that high PM retention will always be observed. The extent of PM retention can vary depending on the plant species and other leaf surface traits. Building upon the insights from these previous studies, this chapter will delve into a comprehensive characterization of leaf traits to further elucidate their influence on PM retention. By examining a more extensive range of leaf characteristics, a more nuanced understanding of the mechanisms behind PM retention can be obtained for French leaves used in road areas.

In simultaneous, Chiam *et al.* (2019) assessed the leaves' hairy roll in the retention mechanism. For that, the author used parameters such as average leaf area (ALA) and specific leaf area (SLA) combined with leaf hairness for PM deposition. The researcher concluded that a higher quantity of hairs and low SLA propitiate a more incredible PM deposition velocity, which means that the hairs work like a physical barrier, while the low SLA results in a denser leaf compared to its area, as the SLA formula is the ratio of leaf area to dry weight per batch. When analyzing stomata density and waxy rolles, Zhang *et al.* (2018) concluded that PM retention was highly impacted. Still, the wax presence in the leaf surface was directly proportional to the stomata density.

Last but not least, when looking deeper into the leaves species, Chen e Hoek (2020) concluded that, in general, conifers exhibited higher efficiency in accumulating $PM_{2.5}$ and recapturing particles after rainfall compared to broadleaved species. This difference in efficiency was attributed to the acicular needle shape characteristic of conifers. On the other hand, the foliar shape and venation of broadleaved species did not demonstrate a significant influence on $PM_{2.5}$ accumulation. However, the number of grooves and trichomes on the leaves of broadleaved species exhibited a positive correlation with foliar $PM_{2.5}$ accumulation. This suggests that the presence of grooves and trichomes could serve as indicators for assessing the effectiveness of tree species in capturing $PM_{2.5}$ particles.

In Bermúdez *et al.* (2021), they used three leaves per species to image the adaxial side and three different leaves to image the abaxial side (BERMúDEZ *et al.*, 2021), in a methodology similar to the one used in this research. The study employs 3D optical profilometry and Scanning Electron Microscopy Scanning Electron Microscopy (SEM) imaging (2D) as methodologies to assess leaf roughness and other micromorphological leaf traits of three distinct plant species (*Hedera helix* 'Woerner,' *Thuja occidentalis* 'Smaragd,' and *Phyllostachys nigra*) situated within a mixed-species green barrier in a school surrounding.

In the methodology, the quantification of leaf roughness utilized the Areal average roughness (Sa), a conventional roughness parameter commonly employed in manufacturing. It is recognized that a higher Sa value corresponds to greater roughness. The areal average roughness (in Micrometer (μm)) is defined as follows (HUTCHINGS; SHIPWAY, 2017), where Z_i represents the height of each point, and N denotes the number of measured points (BERMúDEZ *et al.*, 2021):

$$S_a \approx \frac{1}{N} \sum_{i=1}^{N} |Z_i| \tag{2.1}$$

As a result of the research, the values found for the leaves' surface roughness were as the ones observed on 2:

Table 2 – Leaf roughness of plant species measured by 3D optical profilometry.

Specie	Leaf side	Sa (μm)
H. helix	adaxial	2,37
	abaxial	2,57
T. occidentalis	adaxial	4,10
	abaxial	3,06
P. nigra	adaxial	1,39
	abaxial	2,84

Sa = areal average roughness.

Source: (BERMúDEZ *et al.*, 2021)

The author observed A tenuous correlation between PM capture and Sa values on both the adaxial and abaxial surfaces. Despite being situated within the interior portion of the green barrier, *Thuja occidentalis* exhibited the lowest surface roughness yet demonstrated the highest PM density. Conversely, *P. nigra* displayed the most excellent leaf roughness but showed the lowest PM density. Only *Hedera helix* demonstrated a proportional relationship between leaf roughness and PM density among the species examined.

The analysis revealed that utilizing leaf roughness, as quantified by S_a, may not be the most effective approach for estimating PM capture by plant species. Instead, employing 3D optical profiling analysis aids in comprehending the intricacies of PM adherence to leaf surfaces. It is elucidated that the total surface area alone does not directly correlate with PM capture; instead, three specific leaf roughness descriptors—groove width, depth, and frequency—are critical factors influencing PM capture. Different groove types exhibit varying capacities for PM capture, with groove dimensions relative to airborne particle sizes playing a crucial role. Hence, four groove types are defined based on their combined width and depth dimensions, each possessing distinct PM capture potentials. Shallow/narrow grooves are capable of capturing small PM like PM_1 and $PM_{2.5}$, while shallow/wide grooves may trap PM_{10} but are prone to particle remobilization. Deep/narrow grooves can capture small PM effectively, whereas deep/wide grooves are capable of trapping larger PM sizes ranging from $PM_{2.5}$ to PM_{10} (BERMúDEZ *et al.*, 2021).

Speak about the volumetrics Squared micrometer (μm^2) Cubic micrometer (μm^3)

2.3 Methodology

Surface characteristics are crucial in understanding leaf behavior in capturing particles near transportation sources. To initiate this investigation, a thorough examination of the roughness characteristics of leaves was conducted, as they can contribute to the retention of traffic-related PM, depending on their characteristics. At the same time, in the literature, a more profound usage of the volumetric parameters obtained by leaf surface scanning was not observed. Due to that, these variables will be explored in this research and the S*a* to provide a comparison with previous papers' findings.

The volumetric values pose a challenge when attempting qualitative comparisons with other scientific studies, as this technique remains pioneering in its application within this field. Therefore, the volumetric parameters will be compared between the studied plants and those of other scientific works, particularly concerning Sa.

The experimental techniques employed in this study were based on the methodology previously utilized by Dzierzanowski *et al.* (2011) in assessing PM deposition on leaf surfaces and waxes of urban forest species, considering different size fractions of PM.

Furthermore, the methodology applied by Dzierzanowski *et al.* (2011) was followed to evaluate PM deposition on the leaf surfaces. A controlled exposure chamber was utilized, exposing leaves to known concentrations of PM particles generated from transportation-related sources. After a defined exposure duration, the leaves were carefully collected, and techniques such as gravimetric analysis or microscopic imaging were employed to measure the amount of deposited PM on the leaf surfaces, as will be discussed in Chapter 3.

2.3.1 Leaves species

The initial phase of the leaves choice encompassed the meticulous selection of suitable leaves from urban forest species commonly used in French road vicinity. Great care was taken to choose leaves with diverse surface roughness characteristics, ensuring a representative sample. Additionally, to conduct a final comparison between laboratory and real-scale particle exposure, plants disposed of in the surroundings of the Carrousel of Fatigue (Figure 52) were deliberately selected, as will be described in Chapter 4. Table 3 details the chosen plant species for this purpose.

Table 3 – Leaf species selected for the investigation.

ID	Specie	Morphology	Growth form
1	*Vanhouttei de spirala*	Small thin diamond-shaped	Shrub
2	*Euonymus Europaeus*	Large diamond-shaped	Shrub
3	*Cotoneaster aspressus*	Small thick diamond-shaped	Shrub with cascading-trunks
4	*Cupressus leylandii*	Thick elongated needle-shaped	Shrub to tree

Source: Author

Figure 9 – Leaf species selected for the investigation - collected samples.

Source: Author

2.3.2 *Collecting Leaves*

The chosen leaves were carefully collected and handled to minimize any potential damage or alteration of their natural traits, as can be seen in Figure 10.

To ensure minimal interference with the surface roughness, a laboratory clip was utilized to collect each leaf specimen and deposit it into a stable surface container, which was then transported to the laboratory. Immediately after arriving at the laboratory, the leaves were promptly transferred to a refrigerator, where they were stored temporarily while the remaining leaves underwent cleaning and analysis.

The remaining leaf samples were maintained in the refrigerator during the experiment involving a specific species to prevent any potential surface alterations. This precautionary measure aimed to preserve the natural roughness characteristics of the leaves and ensure consistency throughout the experimental process.

To minimize the time interval between collection and execution of the experiment, the duration was always kept under one hour. This time constraint was implemented to mitigate any potential changes or degradation in the surface roughness that could occur over extended periods.

By implementing these measures, the study aimed to maintain the integrity of the leaf surface roughness and ensure accurate analysis of its characteristics without introducing any unnecessary external factors that could influence the results.

Figure 10 – Collect leaves for scanning, microscopical analysis, and experiment procedure.

Source: Author

2.3.3 *Samples cleaning*

Still, according to Dzierzanowski *et al.* (2011), each leaf sample was individually placed in a glass container containing 250 milliliter (mL) of water. The container was then subjected to agitation for 60 seconds with distillate water. The purpose of this process was to effectively wash off any particles present on the surfaces of the leaves. The agitation helped dislodge and remove the particles.

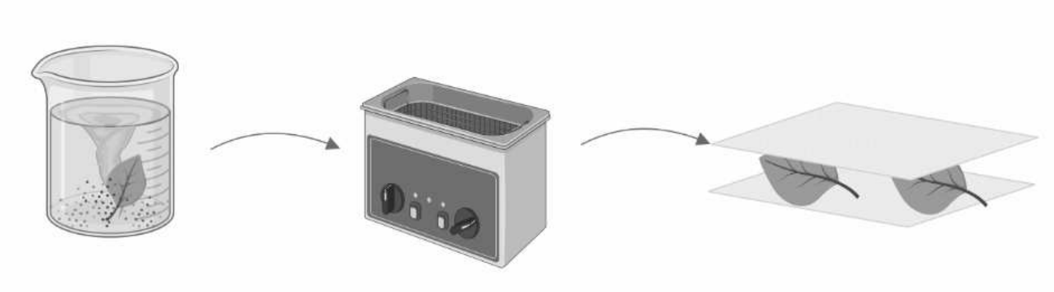
In the following sequence, they were exposed to an additional cleaning step, with an Ultrasonic bath, which, according to Laboratory Instruments (2023), is a highly reliable cleaning method for final cleaning components and tools. This technique utilizes ultrasound and a liquid medium to clean objects effectively. Causality bubbles are generated by subjecting the liquid to high-frequency pressure waves, known as ultrasound.

The cleaning effect of ultrasonic baths is achieved through the cumulative impact of millions of imploding bubbles. The cavitation bubbles collapse near the object's surface, creating high-energy shockwaves and microjets. These intense forces dislodge and remove contaminants from the surface, providing a thorough and efficient cleaning process (LABORATORY INSTRUMENTS, 2023).

In the context of this study, a frequency of 80 kilohertz (kHz) was selected for the ultrasonic bath. This frequency is most effective for cleaning parts with intricate components and complex geometries. Examples include objects with small holes, fine threads, and other intricate features that may pose challenges for traditional cleaning methods. The higher frequency improves cleaning performance and removes contaminants from hard-to-reach areas. This method offers reliable cleaning results and contributes to successfully preparing and analyzing the objects under investigation.(LABORATORY INSTRUMENTS, 2023)

The last cleaning step was the drying of the samples. Absorbent paper was used to proceed with this step until total dryness was achieved. The cleaning scheme is shown in the Figure11.

Figure 11 – Leaf cleaning protocol.



Source: Author

2.3.4 Pre-experiment surface analyse

Several techniques were employed to analyze the characteristics of the selected leaves. First, adapting the strategy used by Zheng *et al.* (2022), the leaves were visually inspected to identify prominent surface features, including grooves, ridges, and irregularities. Microscopy techniques such as binocular microscope and Infinite Focus Instrument were utilized to obtain high-resolution images of the leaf surfaces, enabling a detailed examination of their topographical features.

To quantitatively assess leaf volumetric parameters, specialized software was employed to analyze the Infinite Focus Instrument images, commercially called Alicona, and measure relevant parameters. The software chosen was Mountainsmap®, which allowed for calculating surface parameters and graphical observation of these values. (Bruker Alicona, 2023).

According to Bruker Alicona (2023), the Infinite Focus optical measuring instrument offers precise and efficient 3D measurements with exceptional accuracy, operating within the μm and sub-μm range. It enables area-based measurements of components, regardless of their size, material, geometry, weight, or surface finish, while maintaining high resolution.

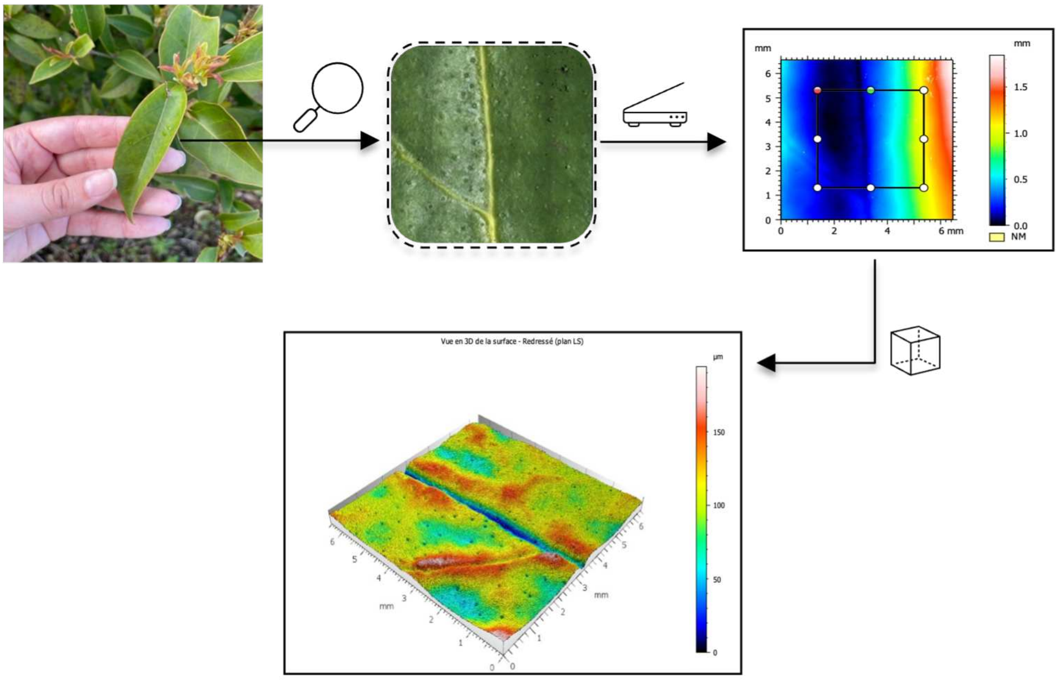
Additionally, Bruker Alicona (2023) mentions that the instrument is equipped with an automation interface, allowing for fully automatic measurements, making it suitable for integration into production processes. The Alicona Infinite Focus is a versatile tool that provides accurate and fast measurements for various applications.

Following the scanning process utilizing the Alicona instrument, the generated file is subsequently exported to the software platform known as Mountainsmap® for further analysis and examination.

Maia *et al.* (2020) mentioned that, MountainsMap® software produces analysis of 2D and 3D surface textures. This software enables users to visualize, correct, and analyze profiles and surfaces accurately and reliably.

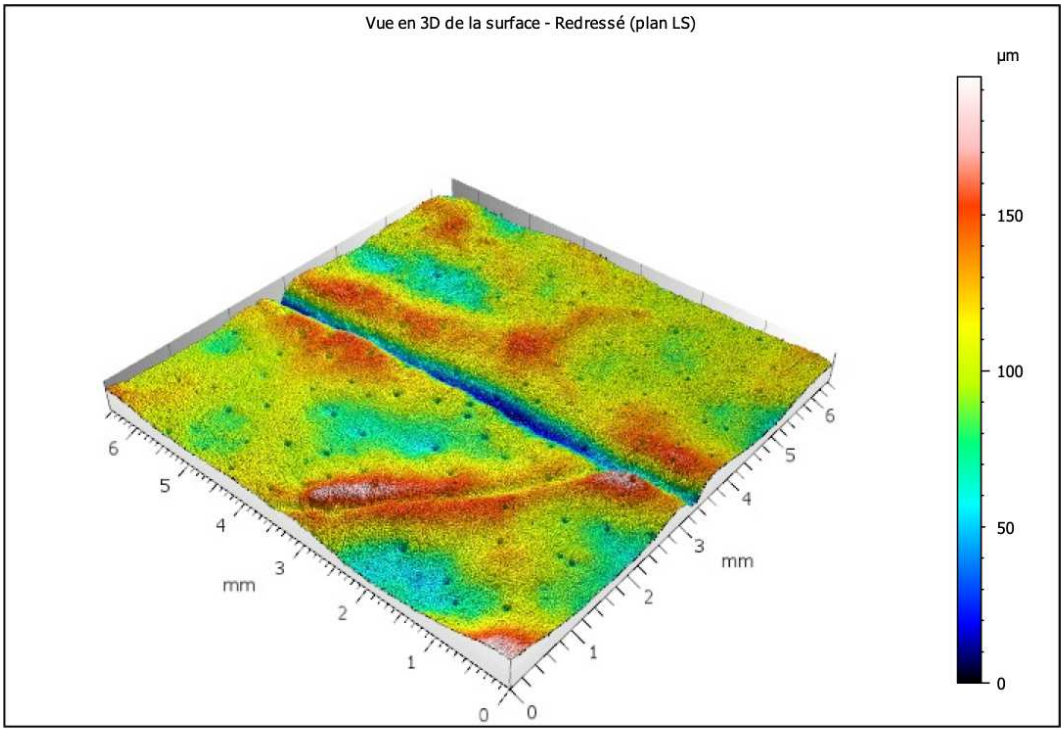
This software allows users to filter roughness and waviness by ISO 16610 standards, facilitating standardized and consistent analysis. The software also offers comprehensive capabilities for calculating ISO profiles and areal parameters. The step-by-step to arrive at this output can be seen in Figure 12. The larger 3D model can also be seen in the Figure 13 (DIGITAL SURF, 2023).

Figure 12 – Step-by-step for the parameters obtention.



Source: Author

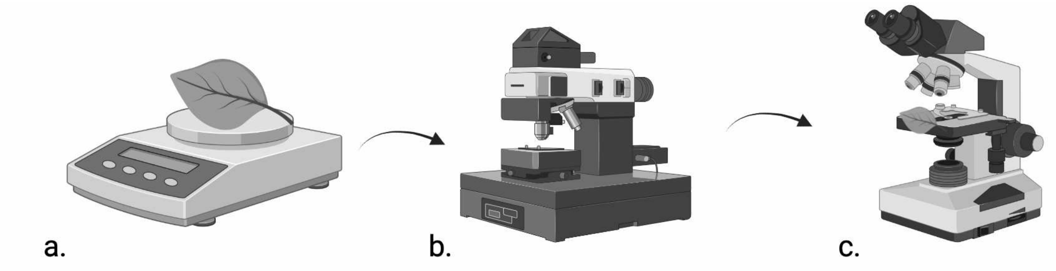
Figure 13 – 3D models of leaf surface processing with Mountainsmaps®.



Source: Author

To facilitate a weight comparison, the five units of cleaned leaves of each leaf species were carefully weighed using a high-precision scale capable of measuring up to four decimal places. This step-by-step procedure is visually depicted in Figure14, illustrating the sequential stages involved in this process. A high-precision scale ensures accurate and precise measurements, enabling a reliable assessment of the weight differences among the leaves before and after each experiment.

Figure 14 – Pre-experiment leaf data storage.



a.sample weight, b. alicona scanning c. binocular observation
Source: Author

2.3.5 Mountains Maps® surface analyse parameters

Throughout this research, various output parameters obtained from the academic research area cluster will undergo statistical analysis to explore their correlations within the study's phenomena. Since not all parameters are directly relevant to the objectives of this research, only a select few will be discussed in this chapter. The units and definitions of these software parameters can be found in Table 5, as specified by Digital Surf Head Office RD Center (2016).

Table 4 – Mountains Maps® output relevant functional volume parameters meaning and units

Parameter	Meaning	Acronym & unit
Functional parameters		
Core material volume	For mr = 100%, the void volume is a maximum. For mr = 0%, the void volume is zero (the cutting plane above the highest point).	Vmc (mm^3/mm^2)
Valley void volume	The Vmp parameter can be used for the same purpose as the Spk parameter, i.e., characterize the volume of material likely to be removed during the running-in of a component.	Vvv (mm^3/mm^2)
Peak material volume	can be used for the same purpose as the parameter, i.e., characterize the volume of material likely to be removed during the running-in of a component.	Vmp (mm^3/mm^2)
Core Void Volume	it represents the volume of void space or empty areas within the core of a material	Vvc (mm^3/mm^2)

mr: material ratio, counted from the highest point on the surface (where the curve equals 0%)to its lowest point

Source: Blateyron (2013) adapted by the author

Table 5 – Mountains Maps® output relevant height parameter meaning and units

Parameter	Meaning	Acronym & unit
area average roughness	standard roughness parameters commonly used to quantify roughness parameters for manufacturing. In here can be used to quantify leaves' roughness	Sa (μm)

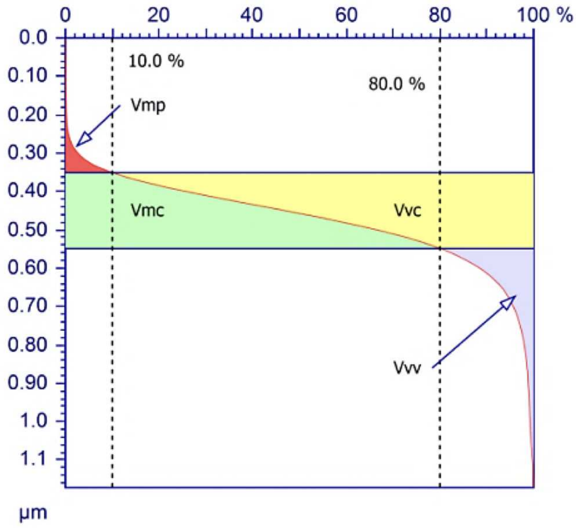
Source: Blateyron (2013) adapted by the author

The Graphical Study of Volume Parameters (Figure15) shows the Abbott-Firestone bearing ratio curve and the ISO 25178 functional volume parameters calculated concerning it.

- The Peak material volume (V_{mp}) (peak material volume) parameter is shown in red.
- The Core material volume (V_{mc}) (core material volume) parameter is shown in green.
- The Core void volume (V_{vc}) (core void volume) parameter is shown in pale yellow.
- The Valley void volume (V_{vv}) (valley void volume) parameter is shown in blue.

The Vmp, Vmc, and Vvv zones are sometimes called the friction, core, and lubrication (or entrapment) zones, respectively.

Figure 15 – Graphical explanation of Mountains Map volumetric parameters.



Source: Digital Surf Head Office RD Center (2016)

2.4 Results

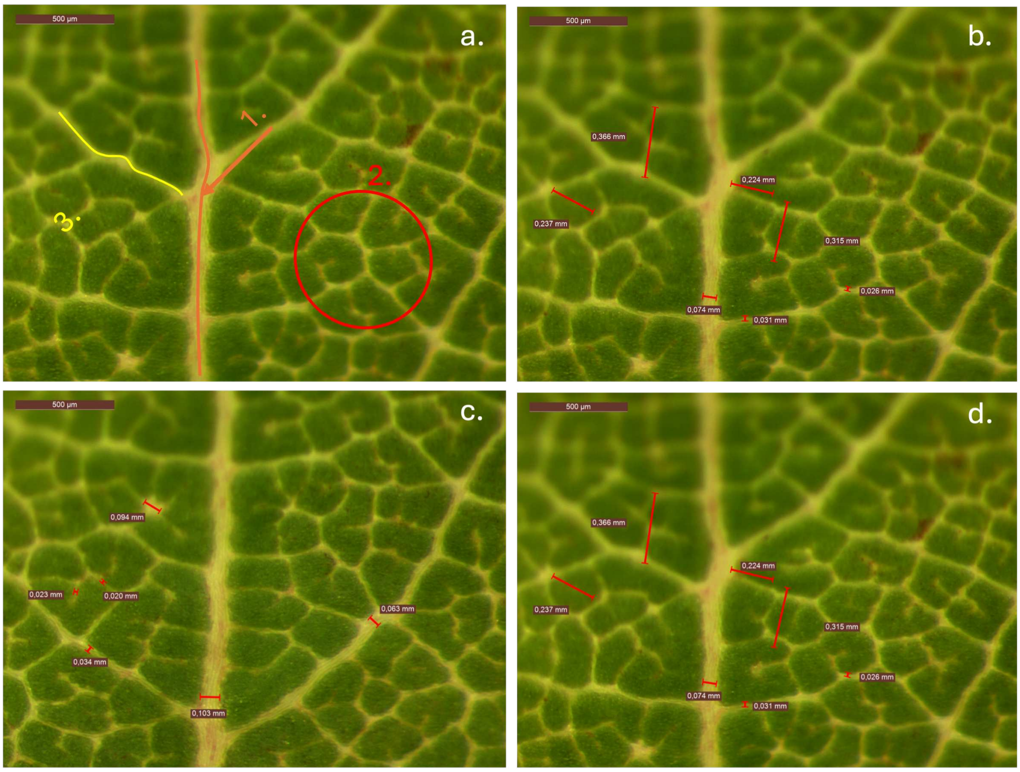
2.4.1 Leaf micromorphology analysis

In the binocular microscopy images, we can identify traces as grooves, presence or absence of trichomes ("hairs"), presence or absence of wax, and surface specifies, as can be seen in Figures 16, 20, 26 for adaxial facets, 18, 22 and 24 for abaxial facets. Lastly, 28 for the needle-shaped Leaf 4. One samples of each leaf type was scanned and another ones exposed to the binocular microscope.

2.4.1.1 Vanhouttei de spirala

The *Vanhouttei de spirala* leaf exhibits a midrib, represented by the number one arrow, with widths between 0.216 mm and 0.074 mm. The veins, represented by the arrow numbered as three, have spaces ranging from 0.063 Millimiter (mm) to 0.034 mm, characterized by a heterogeneous distribution and asymmetric shapes (see Fig. 16(b)). Lastly, number two encompasses the venules, having widths ranging from approximately 0.094 mm to 0.020 mm.

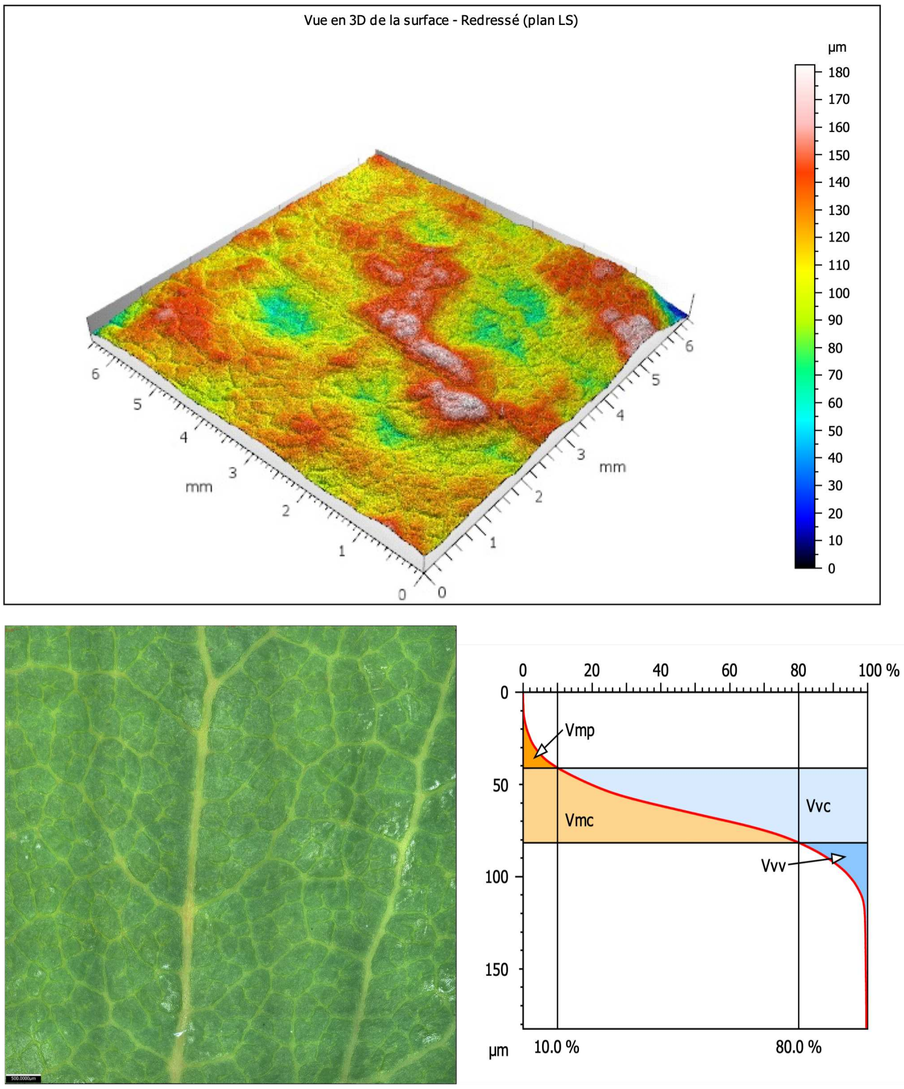
Figure 16 – Adaxial observations of a cleaned Leaf 1.



a. Morphological elements of the leaf surface, b. Grooves cotes c. Midrib, vein and venule cotes d. Additional surface traits cotes. Scale: 500 μm
Source: Author

Upon initial observation of the scanned area (42.33 mm^2) at Figure 17, it becomes evident that the midrib's elevation influences a heightened volumetric slope, particularly in conjunction with inter-venule regions of lesser elevation. This configuration facilitates the formation of deeper flat surfaces conducive to particle deposition. Additionally, the prevalence of grooves of varying widths contributes to establishing multiple paths along veins and venules. Moreover, the veins and venules exhibit varying widths, resulting in a blade characterized by numerous shallow valley void volumes that, in the broader picture, have some void island.

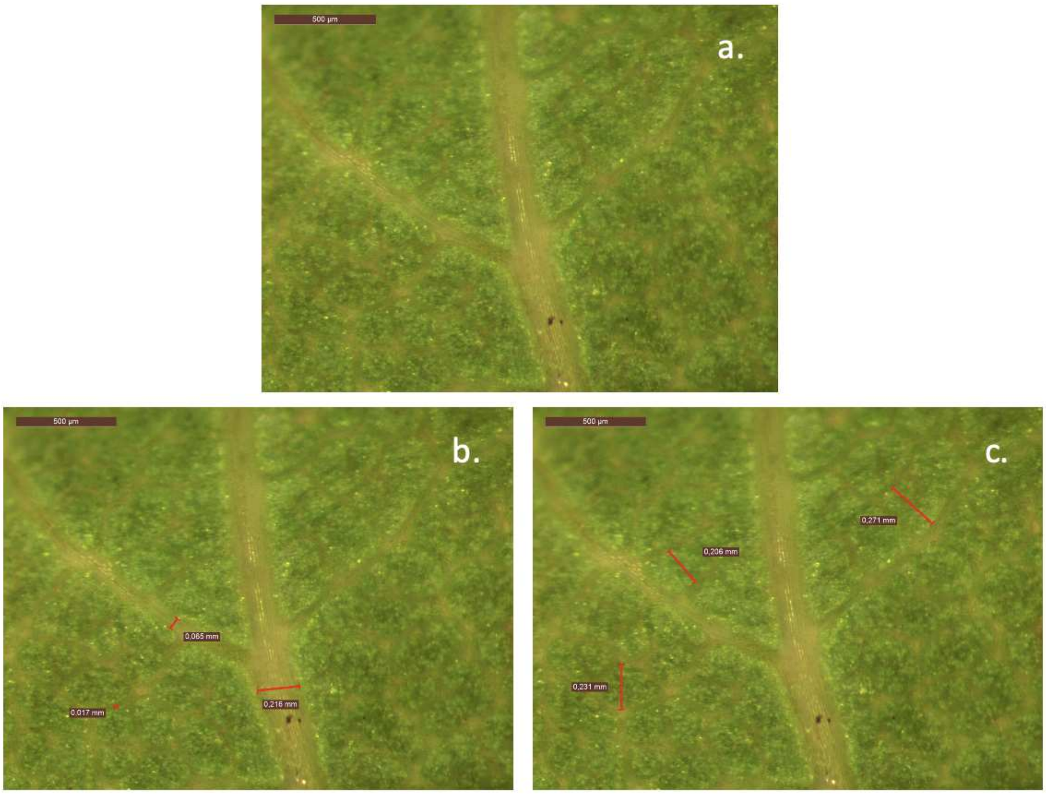
Figure 17 – *Vanhouttei de spirala* 3D image of the scanned surface with its volumetric parameters graphic



Top: Mountainsmap 3D image. Bottom left: Picture of the scanned area scale: 500 μm. Bottom right: Volumetric parameters according to ISO 25178
Source: Author

The abaxial surface (see Figure 18) poses a similar scenario as the one observed at the adaxial facet, with midrib width of 0.216 mm, 0.065 mm for veins and 0.017 mm in venules. This scenario is similar to the one observed on the adaxial side. No wax or trichomes can be observed in either facet. As expected, the grooves have cotes between 0.206 mm and 0.271 mm, within the range observed at the adaxial side.

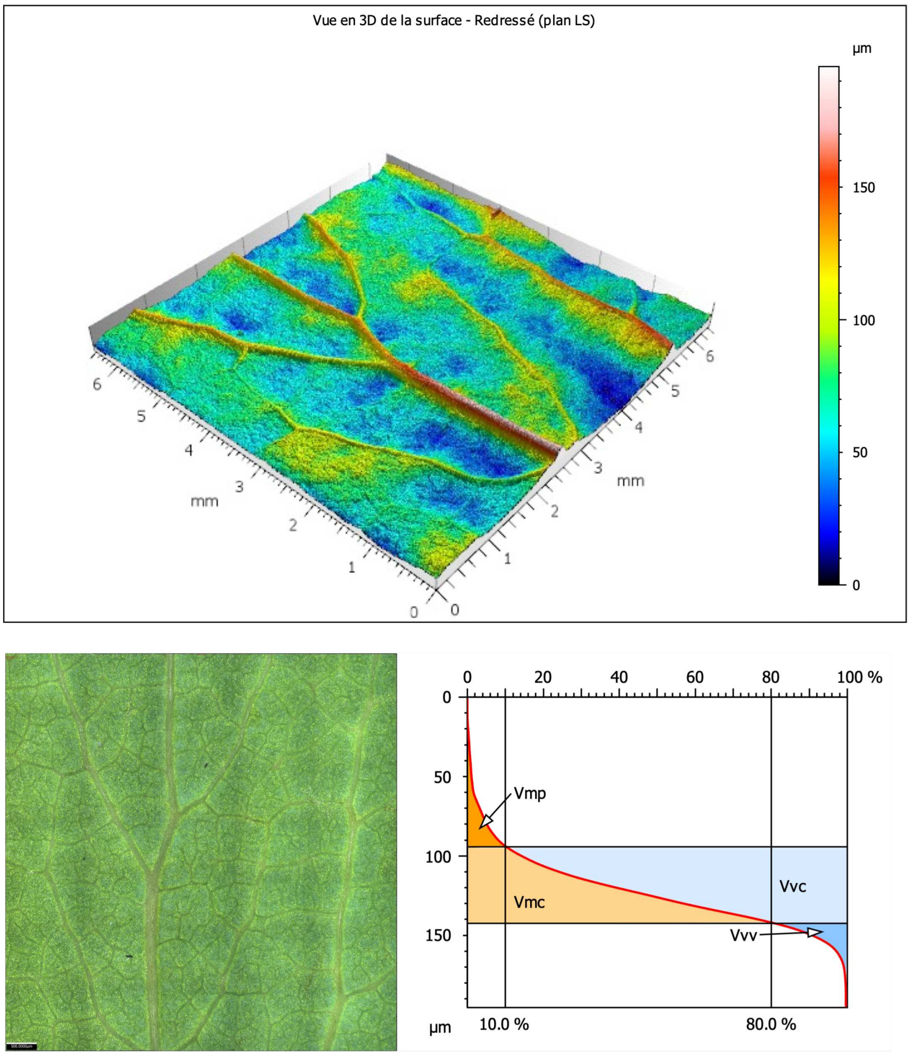
Figure 18 – Abaxial observations of a cleaned Leaf 1



a.Abaxial facet without cotes, b. cotes between grooves c. grooves cote. Scales: 500μm
Source: Author

Examining the 3D image (refer to Figure 19), we can now correlate the deep accumulation island observed here with the elevated regions of the adaxial side. Notably, the midrib and vein stand out compared to the surrounding surface area. It’s crucial to note that if particles fail to adhere sufficiently to the abaxial surface, despite substantial void volumes, gravity may cause them to be dislodged, as this surface is oriented towards the ground.

Figure 19 – *Vanhouttei de spirala* abaxial side parameters



Top: 3D Mountainsmap graphic. Bottom left: Scanned leaf image scaled:500μm. Bottom right: obtained volumetric parameters according to ISO 25178

Source: Author

Comparing the volumetric parameters on the adaxial, we have the Vmc and Vvc with heights between 80-40 μm, representing 60% of the surface. In the abaxial now, the heights are varying between 140 - 94 μm, representing 60% of the surface. It concludes that the Vmc and Vvc on the abaxial side are higher then on the adaxial facet.

Table 6 – Leaf 1 - *Vanhouttei de spirala* surface parameters

Parameter	Adaxial	Abaxial
Vmp (μm^3/μm^2)	0.95	1.99
Vmc (μm^3/μm^2)	16.97	18.77
Vvc (μm^3/μm^2)	23.60	29.41
Vvv (μm^3/μm^2)	2.57	1.83
Scanned area (mm^2)	42.33	42.29
Sa (μm)	15.31	18.04

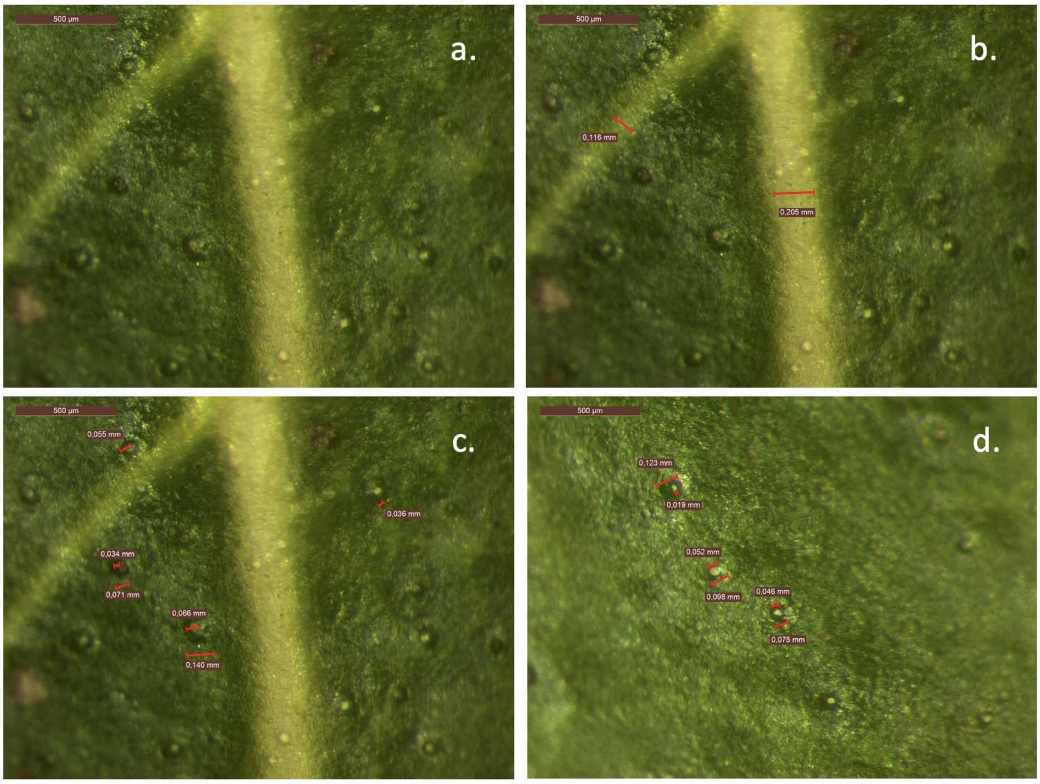
In this scenario, summarized in Table 6, the adaxial surface exhibited a higher valley void volume per surface area for particle deposition, reflecting what was observed on the volumetric graphics. This means that it had an additional gap with a deeper surface than the average surface deepness. However, the abaxial side presented a more expressive core void volume, with a higher available volume per area. The roughness observed on both sides far exceeds that reported in the evaluations conducted by Bermúdez *et al.* (2021), indicating a significantly rougher leaf texture.

2.4.1.2 Euonymus Europaeus

Leaf 2 exhibits a considerably larger size than leaf 1 and 3, in scale of around 5-8 times larger than these plants. Additionally, the scan instrument could not zoom out enough to cover the whole leaf surface. To adequately capture the complexity of this leaf's features, three scans on the adaxial side and four on the abaxial were conducted on each side, culminating in final values obtained through averaging calculations.

This plant does not present wax in its surfaces, nor trichomes (see Figure 20). What was, however, observed were rounded picks, which reminded the beginning of a thorn that does not develop. These shapes are around 0.050 mm in length, as shown in the C. picture below.

Figure 20 – Clean adaxial side of *Euonymus Europaeus* leaf.

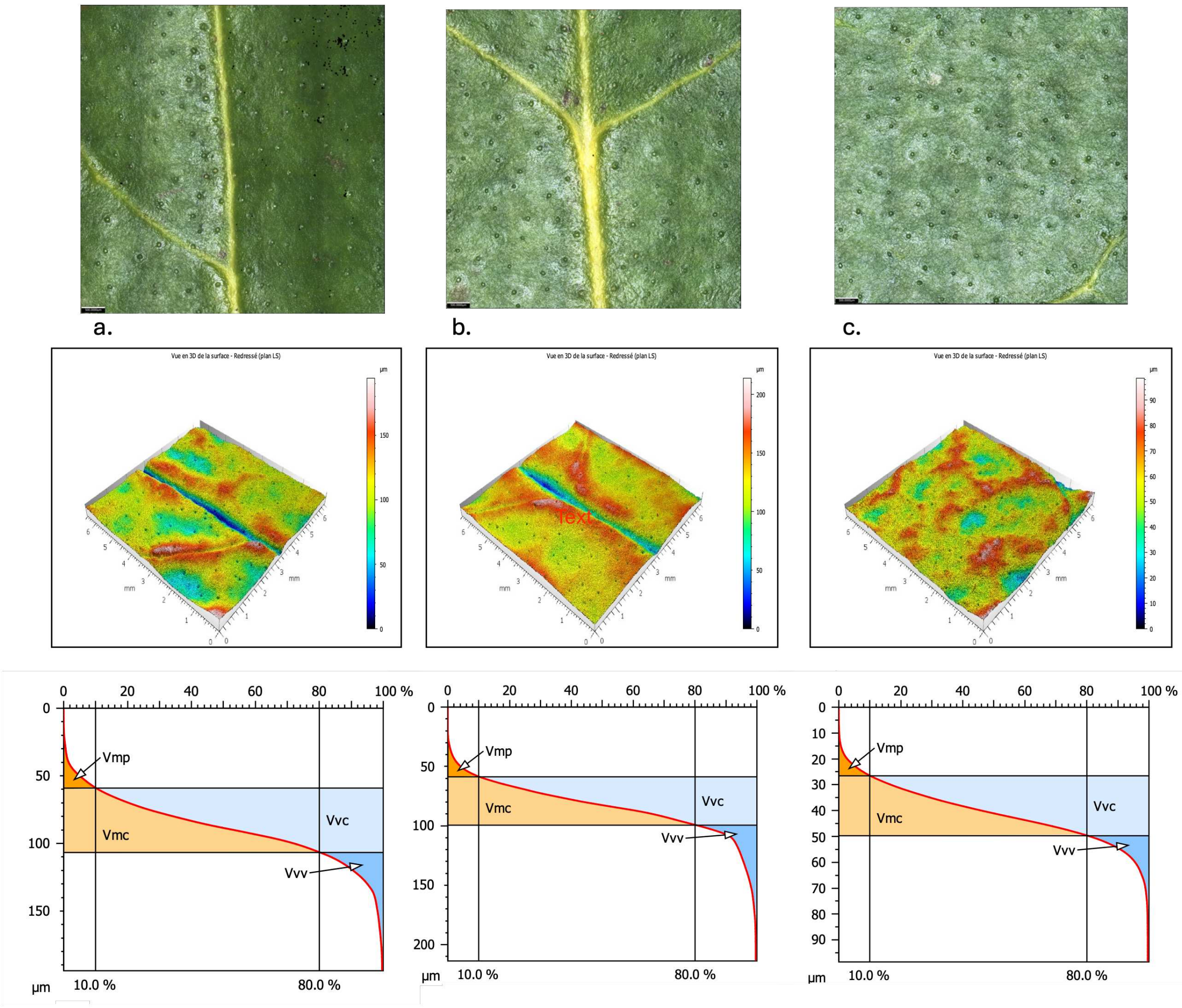


a.Adaxial facet without cotes, b. Midrib and vein's cotes c. Leaf trait additional votes d. The bottom and upper surfaces pick diameter cotes. Scale: 500 μm
Source: Author

In the top three scanned pictures (see Figure 21 a., b., c.), the goal was to observe different, but significant, specific micromorphologically different elements of this plat, where a. and b. cover the midrib length, subdividing in one or two veins, and c. the leaf blade. For Leaf 1 and 2, using the same scanned area, the entire leaf could be covered and its elements are taken into account in the calculation of the parameters; however, this adaptation here was needed to guarantee full leaf observation coverage.

Now observing the Figure 23 second line, the 3D images, the midrib is highlighted as a considerably deeper region on the A. and B. situations. This fact depicted around 80 μm depth. In veins, other than midrib in their lengths, had depth between 60 - 10 μm. The blade had, in general, 20 μm to 30 μm depths. Analyzing the volumetric parameters, slight variations were observed, 25-49 μm height representing 60% of the surface volumetric values. This shows a similarity with the Leaf 1 height observation.

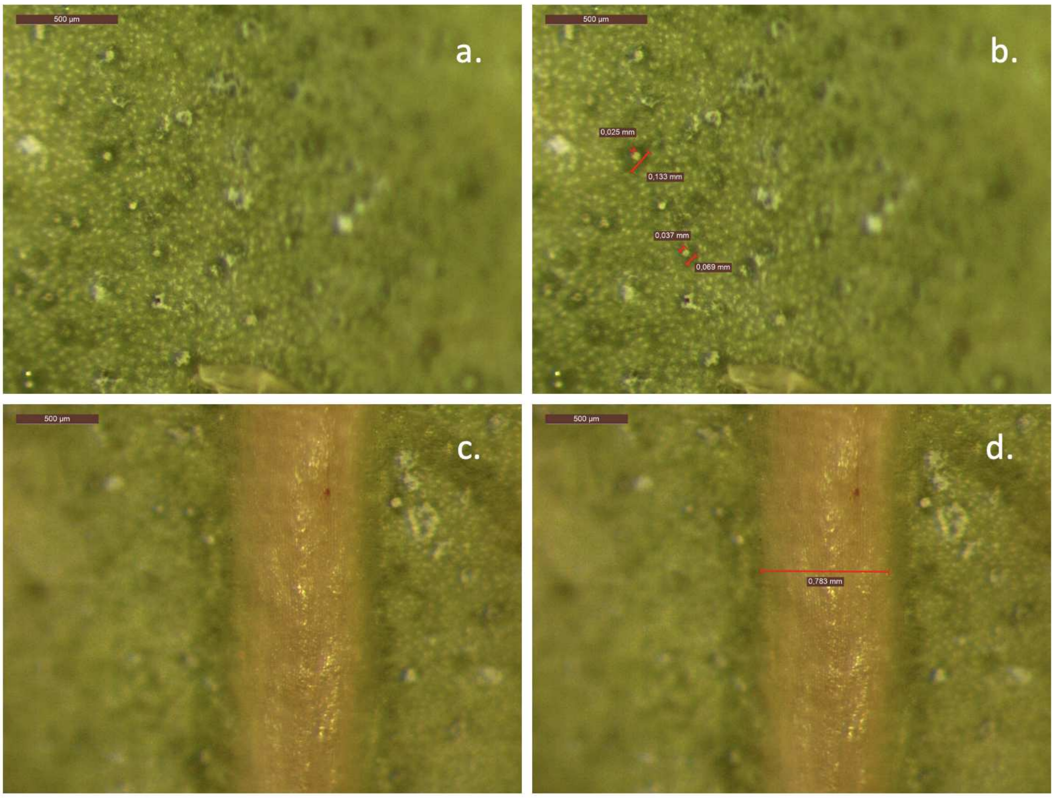
Figure 21 – *Euonymus Europaeus* adaxial side parameters .



a. Area 1: its scanned area image covering midrib, 3D mountainsmap figure, and obtained volumetric parameters b. Area 2: Its scanned area image covers additional veins, a 3D Mountainsmap figure, and obtained volumetric parameters. c. Area 3:its scanned area image covering just the leaf blade, 3D mountainsmap figure, and obtained volumetric parameters. Scale:500 μm
Source: Author

Figure 22 depicts this plant's small abaxial facet details, presenting a midrib of 0.783mm width. No wax or trichomes are observed. This is a homogeneous facet trait from the microscopic 500 μm scale observation.

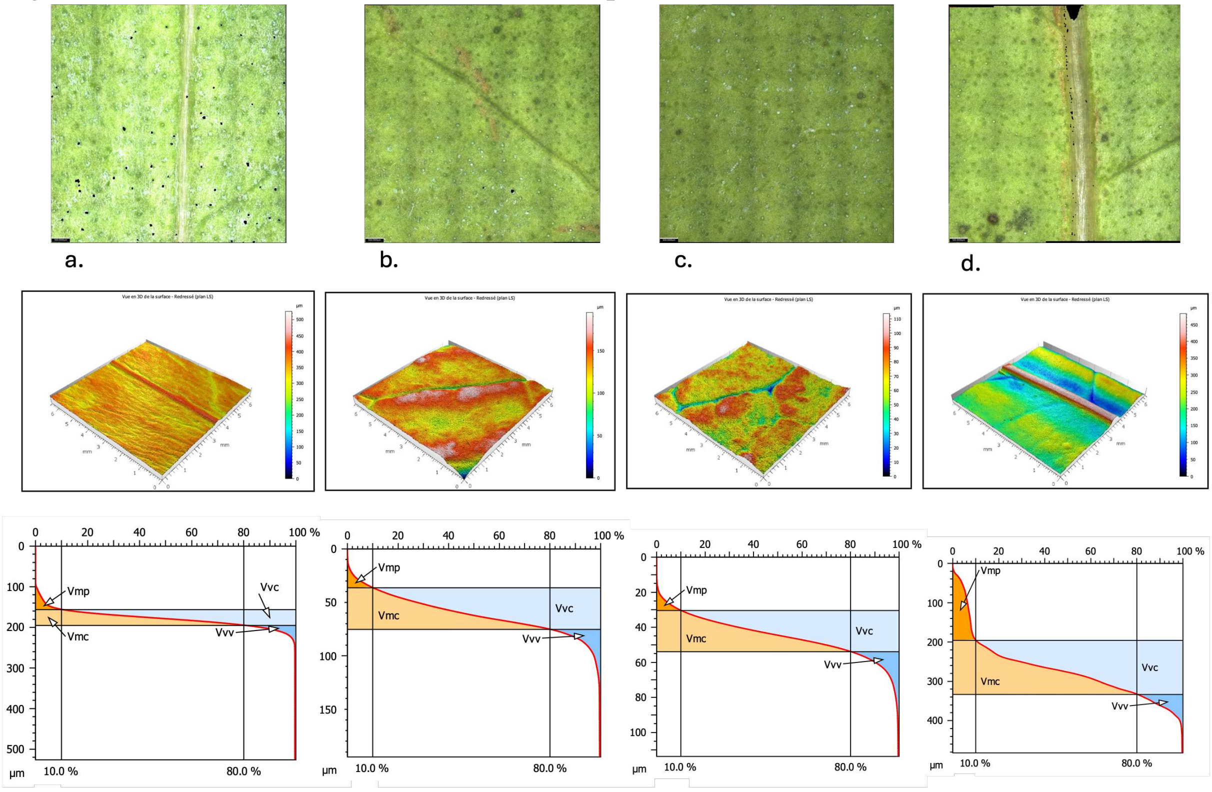
Figure 22 – Clean abaxial side of leaf 2.



a. Abaxial surface observation focused on the leaf blade, without cotes, b. leaf pick area cotes c. Midrib observation without cotes d. Midrib cotes on the abaxial facet. Scale: 500 μm
Source: Author

Moving to the 3D images and their volumetric parameters graphics, the second and third rows on Figure 23 respectively, highly different scenarios can be observed. First, the A., B., and C. figures are similar in their volumetric and 3D images, with between 25 - 40 μm height in their volume areas, not so expressive Vmp and Vvc volumes, and having their deepest points into the veins and venules. However, when looking at the D. figure, all parameters have a significant increase, with a strongly expressive Vmp, that is caused by the vast and high midrib traits and a deep slope from the blade to the midrib area, forming then a possible path to particle accumulation. This highly affects the average volumetric values for this plant.

Figure 23 – *Euonymus Europaeus* abaxial side parameters.



Top: a.Area 1 with its scanned area image focused on a vein, 3D Mountainsmap figure and obtained volumetric parameters b. Area 2 with its scanned area image focused on the blade and small vein, 3D Mountainsmap figure and obtained volumetric parameters c. Area 3 with its scanned area image focused on the blade, 3D Mountainsmap figure, and obtained volumetric parameters d. Area 4, with its scanned area image, focused on the midrib, 3D Mountainsmap figure and obtained volumetric parameters. Scale:500 μm
Source: Author

To summarize the numeric observations of the images previously analyzed, the 7 brings all the average values for the abaxial and adaxial faces. This leaf presented all the abaxial parameters higher than the adaxial side. This can be due to the midrib form Figure D. characteristics, influencing all the parameters.

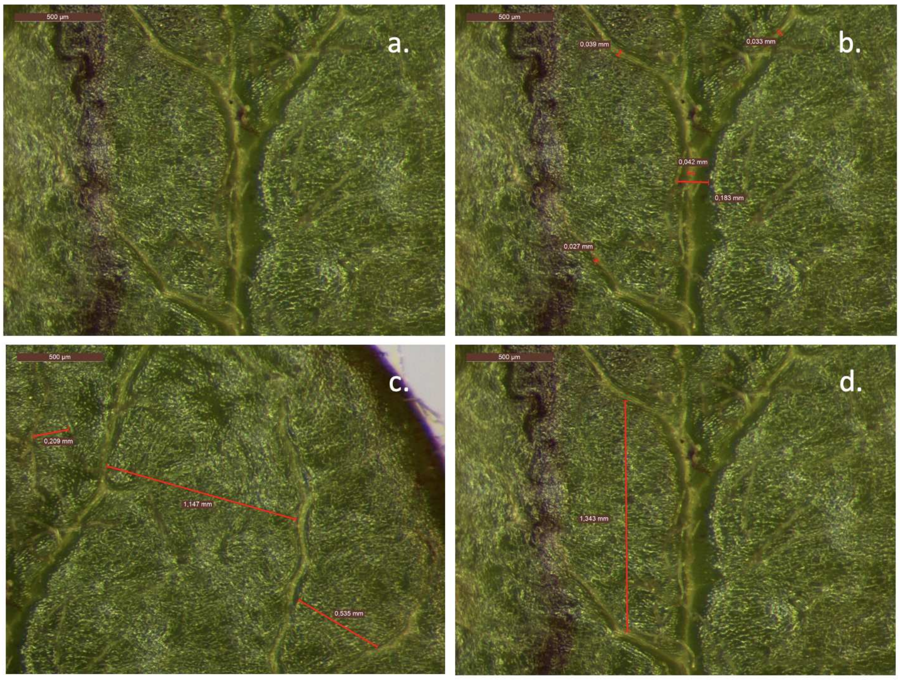
Table 7 – Leaf 2 - *Euonymus Europaeus* surface parameters

Parameter	Adaxial			Avg.	Abaxial				Avg.
	A1	A2	A3		A1	A2	A3	A4	
Vmp ($\mu m^3/\mu m^2$)	1.10	0.92	0.48	**0.83**	1.70	0.79	0.49	10.90	**3.47**
Vmc ($\mu m^3/\mu m^2$)	19.87	17.72	9.62	**15.74**	22.19	15.56	10.01	56.59	**24.74**
Vvc ($\mu m^3/\mu m^2$)	27.76	22.97	13.54	**21.42**	22.19	23.44	13.49	80.98	**35.03**
Vvv ($\mu m^3/\mu m^2$)	3.29	3.36	1.31	**2.65**	2.40	2.28	1.68	6.18	**3.41**
Scanned area (mm^2)	42.32	42.33	42.37	**42.34**	42.31	42.57	42.36	42.30	**42.38**
Sa (μm)	18.23	16.53	8.72	**14.49**	15.70	14.71	9.17	56.60	**24.05**

2.4.1.3 Cotoneaster aspressus

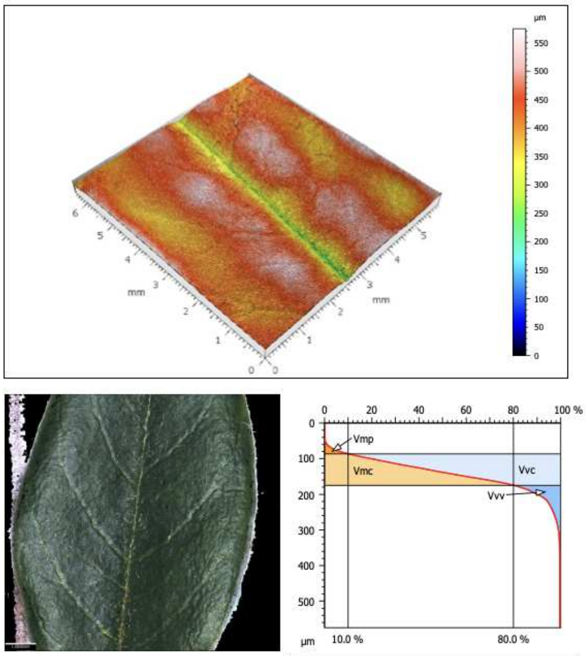
Leaf 3, depicted in Figure 24, is smaller than the leaves 1 and 2. However, the shrub is more dense than these two plants. It was not observed that there was a strong wax layer on the facets; however, there was a strong presence of trichomes, mainly on the abaxial facet and on the borders. Looking at the dimensions, it has a midrib of 0.183mm width (Figure B.) and grooves between 0.209mm and 1.147mm (see Figure C.). It is possible to observe a pretty homogeneous surface in its front, highlighted just by the midrib length.

Figure 24 – Clean adaxial side of leaf 3.



a.Adaxial facet without cotes, b. midrib and vein cotes c. groove cotes, d. additional groove cote. Scales: 500μm
Source: Author

Figure 25 – *Cotoneaster aspressus* adaxial surface paramters

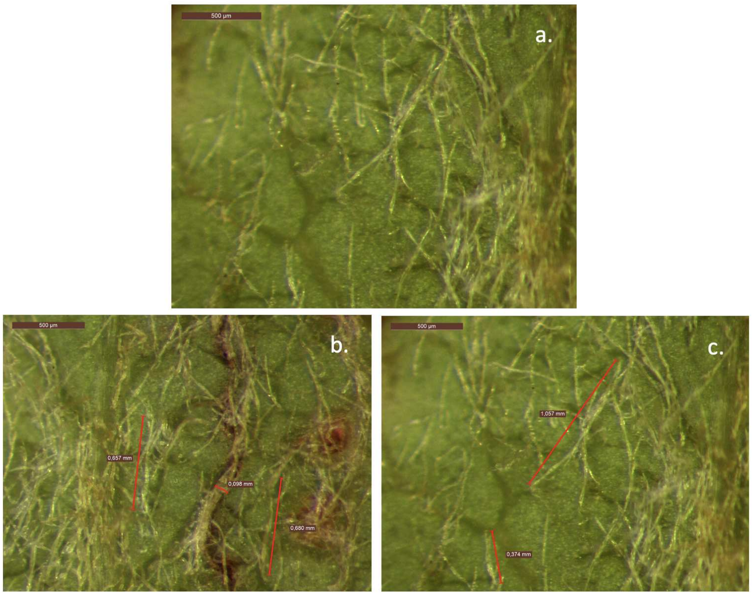


Top: Mountainsmap graphic. Bottom left: Scanned leaf image. Bottom right: obtained parameters. Scale:500 μm
Source: Author

Looking at the 3D image and its volumetric parameters, this plant presents a pretty homogeneous surface, with no strong picks or valleys. Its highlight is, as the previous ones, the midribg depth, that have around 200 μm.

On the abaxial side, the trichomes are highly present on the surface. Additionally, the midrib is high and forms a depth accumulation area within the surface. The trichomes have lengths between 0.374 to 1.007 mm disposed unevenly. Wax was not a treat observed on this facet. This is an element already tested and proved by the scientific community as a key element for particle retention.

Figure 26 – Clean abaxial side of leaf 3.

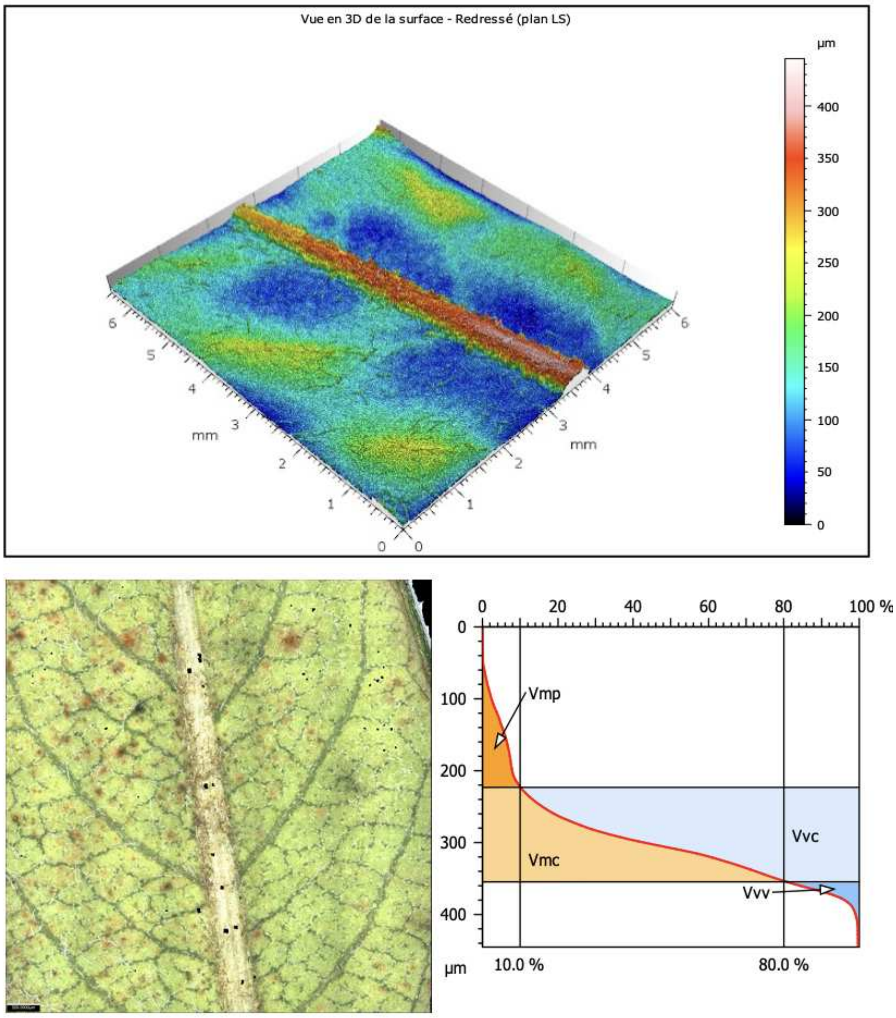


a. no cotes, b. trichomes' cotes, c. additional trichomes' cotes.
Scale: 500 μm
Source: Author

When scanned, the trichomes do not look like they are affecting the volumetric parameters. In fact, the midrib and the blade shapes are the ones to affect its parameters. Once again, the area around the midrib is the one with deeper void areas, having its pick on the midrib pick. This leaf's 3D configuration is highly similar to Leaf 2. Both of them have a harder blade surface, while the Leaf 1 is malleable and not so thick. The blade malleability can be an influencing factor on these leaves observed topography.

In this situation, the Vmp had a strong presence, as in previous situations, due to the midrib volume. Additionally, the Vmc and Vvc had a larger height amplitude compared to the previously studied leaves.

Figure 27 – *Cotoneaster aspressus* abaxial surface paramters



Top: 3D Mountainsmap graphic. Bottom left: Scanned leaf image. Bottom right: obtained parameters according to IS0 25178. Scale:500μm
Source: Author

Transferring all values to Table 8, we can point out that the Vvc has its pick on the abaxial facet, having the possibility to be influenced by the leaf's curvature. Vmp, Vmc, and Vvc had greater values on the abaxial facet, again, with bigger void volumes on the surface facing the ground. Regarding roughness, the result is similar to the preview plan: the abaxial results are more significant.

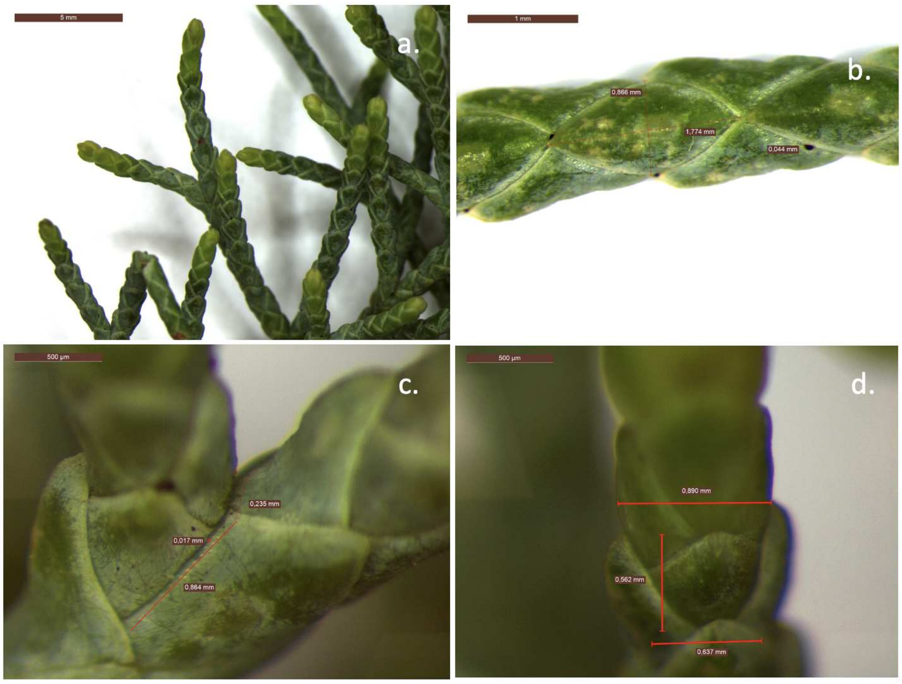
Table 8 – Leaf 3 - *Cotoneaster aspressus* surface parameters

Parameter	Adaxial	Abaxial
Vmp ($\mu m^3/\mu m^2$)	1.28	8.21
Vmc ($\mu m^3/\mu m^2$)	39.06	50.89
Vvc ($\mu m^3/\mu m^2$)	49.27	80.39
Vvv ($\mu m^3/\mu m^2$)	7.15	3.41
Scanned area (mm^2)	38.41	39.23
Sa (μm)	36.23	48.38

2.4.1.4 Cupressus leylandii

Leaf 4, which is not symmetric and can not have an abaxial and adaxial classification. The needle shape adds to this plant the ability to capture particles falling from different angles, with the sub pieces of the shrubs between 0,888mm-0,637mm width and between 1,774mm - 0,562mm height, as observed in Figure 28 C. and D. On top of that, the joints between the leaves propitiate even deeper and larger particles possibly retaining corners. During the observation, a fluid wax was found bending between shrubs. Sometimes it was leaking on the plant surface, but not always. An example of that will be seen in the next chapter. Trichomes were not observed at any moment.

Figure 28 – Clean leaf 4.



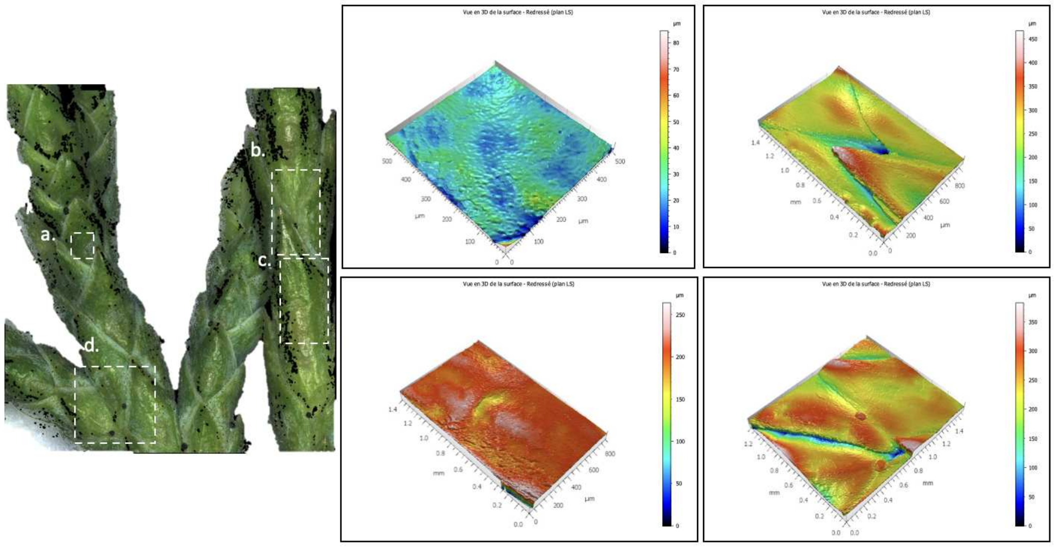
a. no cotes, b. cotes in the leaf shrub, c. shrubs joint cotes, d. additional surface cotes. Scale: 500 μm
Source: Author

During the scanning methodology step, there were several challenges faced for this leaf. First, that capture the complexity of these samples in 2D was a step still taken as not entirely covered. Several trials were done to pick the best approach to cover the maximum possible of this sample. In order to compare it with the other plants, a deeper zoom was taken to picture four key characteristics seen as determining for this plant.

The selected scanning areas were intended to encompass various aspects of this plant; however, they were still insufficient to depict this plant's complexity fully. When transforming the 3D complexity into 2D, some deeper spaces could not be covered, leaving room for future improvements in this methodology. As a result, the surface analyzed areas are different from the other three leaves.

Looking into Figure 29, the depictured surfaces can be compared with the leaves blades, which have several small joints instead of midrib, veins, and venules. The surfaces are generally homogeneous with the presence of small rounded external structures, as observed in the area C.

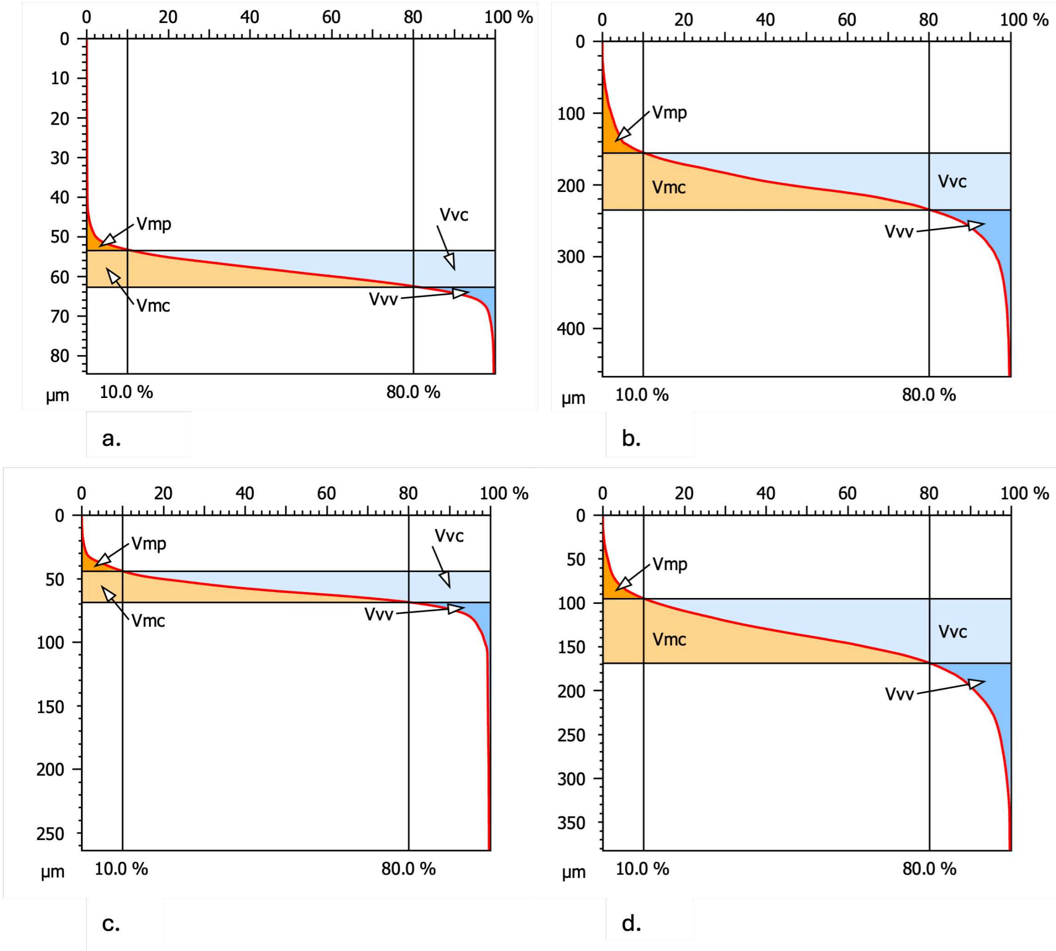
Figure 29 – Surface 3D Leaf 4



a. area A rendering, b. area B rendering, c. area C rendering, d. area D rendering, e. surface picture. Scale: 500 μm
Source: Author

Moving to the volumetric observations, grouped in Figure 30, the highlight is on the void volumetric volumes (Vvv), that had a more expressive presence in this scenario. This can be justified by the shrub joints.

Figure 30 – Volumetric parameters of Leaf 4



Volumetric graphics: a. area A, b. area B, c. area C, d. area D. Scale: 500μm
Source: Author

Finally, all the volumetric parameters of this leaf are summarized in Table 9. As mentioned previously, it was a challenge to cover all this leaf complexity, due to that, the values observed for Vvc, for example, are lower than the expected.

Table 9 – Leaf 4 - *Cupressus leylandii* surface parameters

Parameter	A1	A2	A3	A4	Average
Vmp ($\mu m^3/\mu m^2$)	0.26	3.06	0.74	1.88	**1.49**
Vmc ($\mu m^3/\mu m^2$)	3.95	34.01	9.69	32.18	**19.96**
Vvc ($\mu m^3/\mu m^2$)	5.29	45.36	14.85	41.34	**26,71**
Vvv ($\mu m^3/\mu m^2$)	0.48	7.21	1.95	7.54	**4.30**
Scanned area (mm^2)	0.28	1.39	1.19	2.10	**4.96**
Sa (μm)	3.55	33.57	9.73	31.57	**19.61**

A compilation of all the previous findings is shown in Tables 10 and 11. The strongest Vvc comes from Leaf 3, both on the abaxial and adaxial facets. Vvv had its highlight on Leaf 3 and 4. Leaves 1 and 2 had similar results. These results can suggest that Leaf 3 had more volumetric void able to receive particles, however, this efficiency has to be exposed to environmental variables, such as the wind, humidity, particle topographic and chemical characteristics, rain accuracy, etc.

Table 10 – Adaxial result

Parameters	Leaf 1	Leaf 2	Leaf 3	Leaf 4
Vmp ($\mu m^3/\mu m^2$)	0.95	0.83	1.28	1.49
Vmc ($\mu m^3/\mu m^2$)	16.97	15.74	39.06	19.96
Vvc ($\mu m^3/\mu m^2$)	23.60	21.42	49.27	26.71
Vvv ($\mu m^3/\mu m^2$)	2.57	2.65	7.15	4.30
Sa (μm)	15.31	14.49	36.23	19.61

Source: Author

Table 11 – Abaxial result

Parameters	Leaf 1	Leaf 2	Leaf 3	Leaf 4
Vmp ($\mu m^3/\mu m^2$)	1.99	3.47	8.21	1.49
Vmc ($\mu m^3/\mu m^2$)	18.77	24.74	50.89	19.96
Vvc ($\mu m^3/\mu m^2$)	29.41	35.05	80.39	26.71
Vvv ($\mu m^3/\mu m^2$)	1.83	3.41	3.41	4.30
Sa (μm)	18.04	24.05	48.38	19.61

Source: Author

2.4.2 Statistical analyses

The software used to develop the statistical study is the R. To start with, an Analysis of variance (ANOVA) calculation was performed to ascertain whether significant differences existed in the volumetric parameters of leaves. The parameter used to evaluate the leaf roughness (Sa) will not be assessed statistically due to the restricted database; combined with the fact that this is not a rate but a singular value, it was impossible to proceed with a statistical study. The central question addressed was whether these four studied leaves could be grouped together or if they should be observed separately. The test assumptions included:

- Random sampling.
- Independent sampling (no leaf repeats).
- Normal phenomenon distribution (derived from nature, likely normal).
- Distribution of parameters follows Poisson distribution.

ANOVA is a statistical method used to analyze differences among group means in a sample, determining whether these differences are statistically significant. As Leaf 4 has its own topographic specificities, it tests the values with and without this plant data. It was assumed significance at $p < 0{,}05$. Given the assumptions above, the hypotheses considered were:

H0: There is no statistically significant difference between the means (lambdas).

H1: There is a statistically significant difference between the means (lambdas).

Table 12 – P-values test results

Facet	p-value with L4	p-value without L4
	Vmc	
Adaxial	0.0618806^R	0.0254384^R
Abaxial	0.0145768^R	0.0145768^R
	Vvc	
Adaxial	0.0554138	0.0224638^R
Abaxial	0.0038162^R	0.0038162^R
	Vvv	
Adaxial	0.3691112	0.2662541
Abaxial	0.7825789	0.7825789
	Vmp	
Adaxial	0.9418533	0.9500522
Abaxial	0.1789873	0.1789873

R: Values that had the null hypothesis rejected as the calculated p-value is less than 0.05
Source: Author

Looking at the core material value on the adaxial side of p-values, including the Leaf 4 data, we have insufficient evidence to reject the null hypothesis ($p = 0{,}0618806 > 0{,}05$). In contrast, for the abaxial side, the null hypothesis is rejected ($p<0{,}05$), implying that there is enough evidence to support the alternative hypothesis that there is a statistically significant difference between the lambdas. However, when we remove leaf 4 (due to its shape difference), both for the adaxial and abaxial facets, we have p-values$< 0{,}05$. It means that the null hypothesis (that there is no statistically significant difference between the Vmp means) is rejected. It is essential to mention that in situations where the null hypothesis is not rejected, it implies that there is enough evidence to support the alternative hypothesis that there is a statistically significant difference between the leaf's means.

For the core void value, similarities with Vmc were observed. For p-values including leaf 4, on the adaxial side, the null hypothesis is rejected ($p = 0{,}554138 > 0{,}05$), implying enough evidence to support the alternative hypothesis that there is a statistically significant difference between the lambdas. For the abaxial surface, together with both leaf facets for the analysis excluding leaf 4 data, we have p-values$< 0{,}05$. It means that the null hypothesis (that there is no statistically significant difference between the Vvc means) is rejected.

Unlike the preview parameters, the valley void volume and the peak material value bring all its p-values of the adaxial and abaxial side, with or without leaf 4, more significant than 0,05, so there is insufficient evidence to reject the null hypothesis. It is essential to highlight that if the null hypothesis (that there is no statistically significant difference between the Vmp means) is not rejected, it does not necessarily mean that the alternative hypothesis is true; instead, it suggests that there is insufficient evidence to conclude otherwise.

This predominant result can be associated with the fact that the database for this research was composed of a restricted number of observations divided into four groups, which could e reflected the p-value.

Principal Component Analysis (PCA) is a statistical technique utilized for dimensionality reduction in extensive datasets, condensing the information into principal components while retaining most of the original information. It accomplishes this by transforming potentially correlated variables into a smaller set of uncorrelated principal components. Initially developed by Karl Pearson in 1901, PCA gained widespread popularity with the advent of computers, particularly for multivariate statistical computations. It proves highly effective in visualizing and exploring high-dimensional datasets or those with numerous features, facilitating the identification of trends, patterns, or outliers (IBM, 2024).

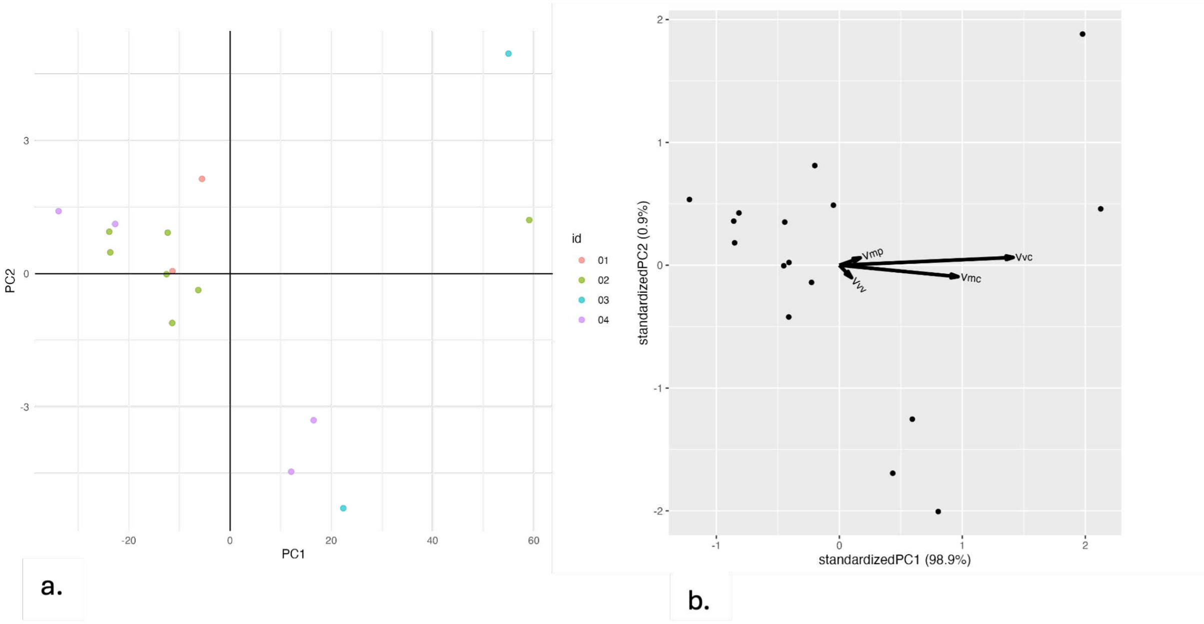
In this database, this statistical technique was chosen as a tool to find out which of the available variables would be the principal and able to be used in the practical application. According to DATAtab Team (2024), in PCA, each vector represents a principal component, and the size of each vector (i.e., its magnitude or length) indicates the importance or contribution of that component to the overall variance in the data. Here's a short explanation of how to interpret the size of the vectors in PCA analysis:

– Magnitude: The length of the vector represents the amount of variance explained by that particular principal component. Longer vectors indicate components that capture more variance in the data.
– Direction: The direction of the vector in the feature space indicates the correlation between the original variables (features) and the principal component. Variables that have a strong correlation with a principal component will have larger loadings and will contribute more to that component.
– Component Importance: The importance of each principal component is usually de-

termined by the proportion of variance it explains. Components with larger variances (represented by longer vectors) are considered more important in describing the underlying structure of the data.

The values taken to plot the PCA were the Vmp, Vvv, Vvc, and Vmc of each plant. After the Poison evaluation, the results of this analysis can be seen in Figure 31 a. and b. below:

Figure 31 – Principal Component Analyses (PCA) for volumetric parameters



a.Color-coded PCA biplot graphic b. Vectorial PCA representation
Source: Author

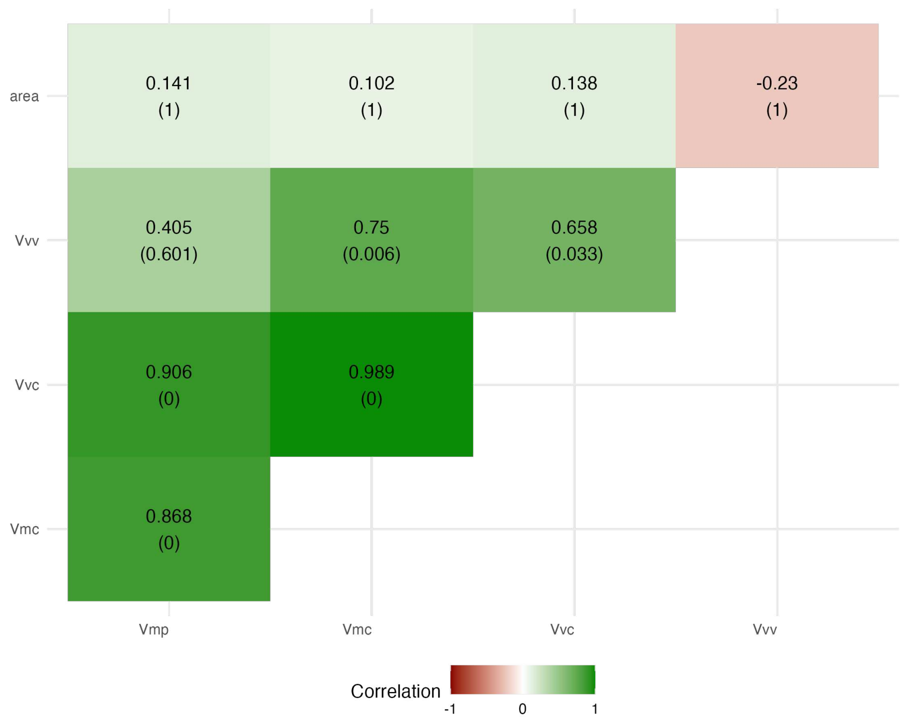
PC1 can be interpreted as capturing the dataset's most significant proportion of variance. It represents the primary source of variability among the variables. Positive values of PC1 indicate higher values of the original variables that contribute most to the variance, while negative values represent lower values of these variables. In terms of interpretation, PC1 may reflect the overarching trend or pattern present in the data. It often corresponds to the most significant factor influencing the observed variability. Looking at Figure 31 b, the Vvc and Vmc, respectively, are the first and second larger vectors, representing the most significant factor influencing the observed variability. In practice, this means that the core void volume is variable with more substantial influence in the observation variation; it has the more considerable variability compared to the other parameters, explaining 98,9% of the variance coming from Vvc and Vmc.

On the other hand, PC2 captures the second-largest proportion of variance in the dataset, orthogonal to PC1. It represents additional variability not explained by PC1. Positive values of PC2 represent variations in the dataset that PC1 does not capture, and negative values represent variations orthogonal to PC1. In this study, the Vmp and Vvv contribute to its variability. It often reveals secondary trends or structures in the dataset that PC1 does not explain. It means that, Vmp and Vvv explains 0,9% of the variance.

Figure 31 aims to show how the data is distributed, propitiating the possibility of observing group distributions. In this figure, this group observation is not clear using PCA, with no clear grouping.

To observe the correlation between the variables and determine which ones would be more representative of leaves' surface characterization, Figure 32 correlation matrix based on the correlation and p-values were plotted:

Figure 32 – Correlation matrix (Pearson) p-value



Source: Author

Taking as a reference the result from the PCA analysis, that the Vvc is a variable with higher variance and that better represents the leaf characterization between the volumetric parameters, the interpretation of Figure 32 has its foundation.

As a starting point, as these four variables are complementary and total 100% of the functional parameters, the correlation matrix is expected to present a high correlation between the parameters. We typically select variables with lower correlation values for inclusion in the analysis. This is because PCA aims to identify uncorrelated (or minimally correlated) components that explain the maximum amount of variance in the dataset.

By including variables with lower correlation values, we ensure that the components derived from PCA are more orthogonal (uncorrelated) to each other. This is important because PCA assumes that the components are orthogonal, meaning they capture distinct sources of variance in the data.

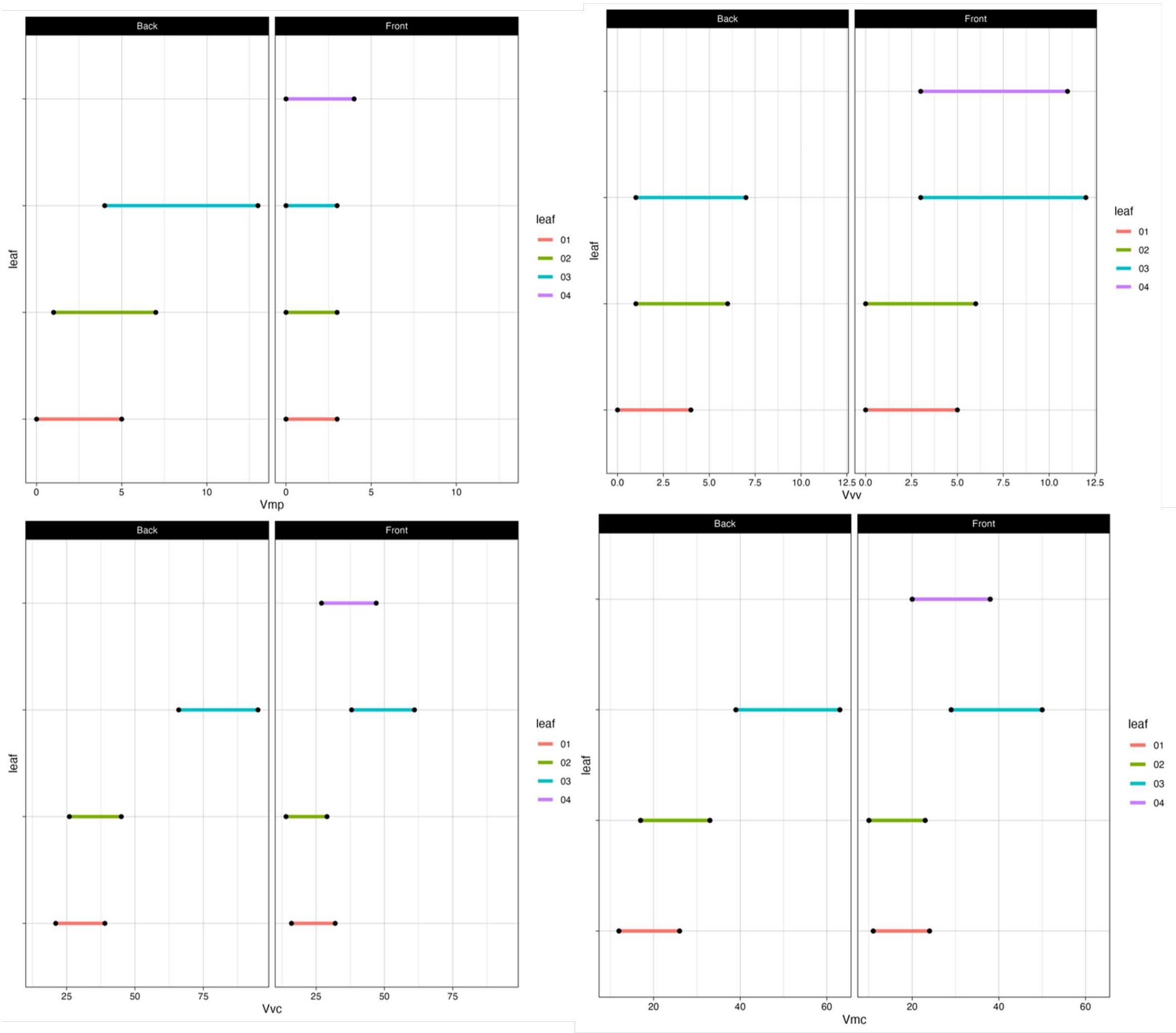
Including highly correlated variables in PCA can lead to multicollinearity issues, where the components become highly correlated, making it difficult to interpret their contributions to the overall variance. Additionally, including variables with high correlation values may result in redundancy, where similar information is captured by multiple components, reducing the effectiveness of PCA in dimensionality reduction. Therefore, selecting variables with lower correlation values helps ensure that the derived components are more independent and provide a more accurate representation of the underlying structure of the data.

The area variable cannot be considered because the samples had different scanning sizes due to the other leaf sizes and individual characteristics. The Vvv related to Vmp, for example, presents a low correlation, however, a high p-value, meaning that there is insufficient evidence to reject the null hypothesis that the populational correlation is equal to 0, so there is insufficient evidence to conclude otherwise.

The other correlated variables have high correlation values, bringing to the termination that, assuming that Vvc is the parameter with higher variance and better representing the data, as Vvc has a high correlation with the other variables when used as a parameter for decision makers, it should be used alone, to avoid multicollinearity issues.

Lastly, a graphic representation of interval estimation is presented in Fig 33. As leaf four has a different 3D distribution, without an adaxial and abaxial clear surface, the values for this plant were disposed on the "front" analyses, colored purple. Leaves one, two and three have red, green and blue as color.

Figure 33 – Graphic representation of interval estimates



Source: Author

Leaves 1 and 2 consistently yielded similar confidence intervals, as depicted in the Vvc and Vmp graphics. In contrast, leaf 3 exhibited a distinct outcome in adaxial and abaxial analyses compared to the other plants, as evidenced by variations in Vmp, Vvv, Vvc, and Vmc. Finally, leaf 4 exhibited markedly different results from the preceding plants, as evidenced by observations in Vvc and Vmc.

This means that with the confidence interval of leaves 1 and 2 overlappings, there is no evidence that these two are different; conversely, it is appeasing proof to reject the null hypothesis that they are equal. Additionally, the Leaf 3 intervals are, in all representations, on the right-hand side of the Leaf 1 and 2 intervals. This means that Leaf 3 has no significant values but is not random. Once more, this can happen due the small database used in this analyse.

2.5 Conclusion

A leaf surface scanning can be a challenging task, mainly to ensure the whole leaf complexity coverage. For plants with needle shapes, an appropriate methodology can be developed, and larger data to be compared with Leaf 4 can be the next step. On top of that, the scanned areas difference can be taken into consideration as a second challenge to be sorted. Lastly, an increase in the entire scanned database is advised as a future step after this research.

Looking into the qualitative aspects leaves 1 and 2 are highly similar in their leaf size. On the other hand, leaves 2 and 3 are thicker and not so malleable. Additionally, the only one with trichomes was the leaf 3. This can be seen as key important characteristics that can be an add on to a green corridor planning, the different treats.

From the statistical perspective, leaves 1 and 2 can be considered simillar regarding microscopic parameters. Leaf 4 does not present significant volumetric differences from the two previous leaves; however, its geometry is known to be the most distinct. Leaf 3 has parameters distinct from leaves 1 and 2. Hence, it is suggested a division into three different groups according to their parameters' similarity and specificity:

Groups:

A. Leaves 1 and 2
B. Leaf 3
C. Leaf 4

The parameter Vvc stands out as the most suitable choice for leaf characterization among volumetric parameters. Therefore, it is advisable, particularly in green corridor planning, to exclusively utilize Vvc as a parameter to represent plant preferences.

From the preview starting point, the leaves that presented higher Vvc, which means higher volume per area of leaf to accumulate pollutants, are leaves 3, 4, 1, and 2, respectively, as summarized in Table 10 and 11.

With that said, in green corridor planning, leaves similar to leaves 3 and 4 could be listed as a highly probable choice to mitigate pollutants by retention in the core void volumes. These findings should be exposed to particles to observe if this chapter's finding is applied in practice. If looking strictly at this result, the criteria to conclude which plants are similar to the picked choices would be the Vvc.

3 IMPACT OF LEAF SURFACE VOLUMETRIC PARAMETERS ASSESSMENT ON NON-EXHAUST TRANSPORTATION PARTICLE RETENTION

3.1 Introduction

According to Knight *et al.* (2020), tire road wear particles (TRWPs) substantially contribute to the overall environmental burden of plastic debris. Yet, their representation in assessments of plastic pollution remains significantly inadequate. Jan *et al.* (2017) mention that TRWPs are generated through the mechanical abrasion of vehicle tires on road surfaces during driving, acceleration, and braking. They consist of a mixture of natural and synthetic rubber. It has been estimated that tires can release up to 12% of their mass into the environment throughout their lifespan. The annual tire wear emissions vary between countries, ranging from 0.2 to 5.5 kg per capita per year(BAENSCH-BALTRUSCHAT *et al.*, 2020).

The presence of TRWPs in the environment poses an airborne risk to human health through inhalation. Additionally, concerns arise regarding the chemicals incorporated into tire materials, which have the potential to leach into the surrounding environment. These chemicals encompass a variety of metals and organic additives utilized in tire production(BAENSCH-BALTRUSCHAT *et al.*, 2020).

Implementing regulatory standards has significantly reduced PM exhaust emissions from road traffic in developed countries. However, non-exhaust particle emissions from brake and tire wear and road surface abrasion, combined with road dust resuspension, remain unregulated and often surpass exhaust emissions in numerous jurisdictions. Although there is a reasonable understanding of the sources of non-exhaust particles, there are limited measurements of airborne concentrations specific to each source(FUSSELL *et al.*, 2022).

The predominant emphasis is on leaf characteristics in the literature on transport infrastructure and its association with vegetation's PM capture properties. Bermúdez *et al.* (2021) noted that investigating foliar surface roughness and other micromorphological features aids in understanding the nuanced variations among plants regarding their efficacy in air purification. This knowledge can guide the selection of optimal plant combinations to mitigate air pollution and enhance public health. However, directing appropriate attention to the specific types of particles captured by vegetation can represent a significant advancement in the quest for more effective air pollution reduction strategies.

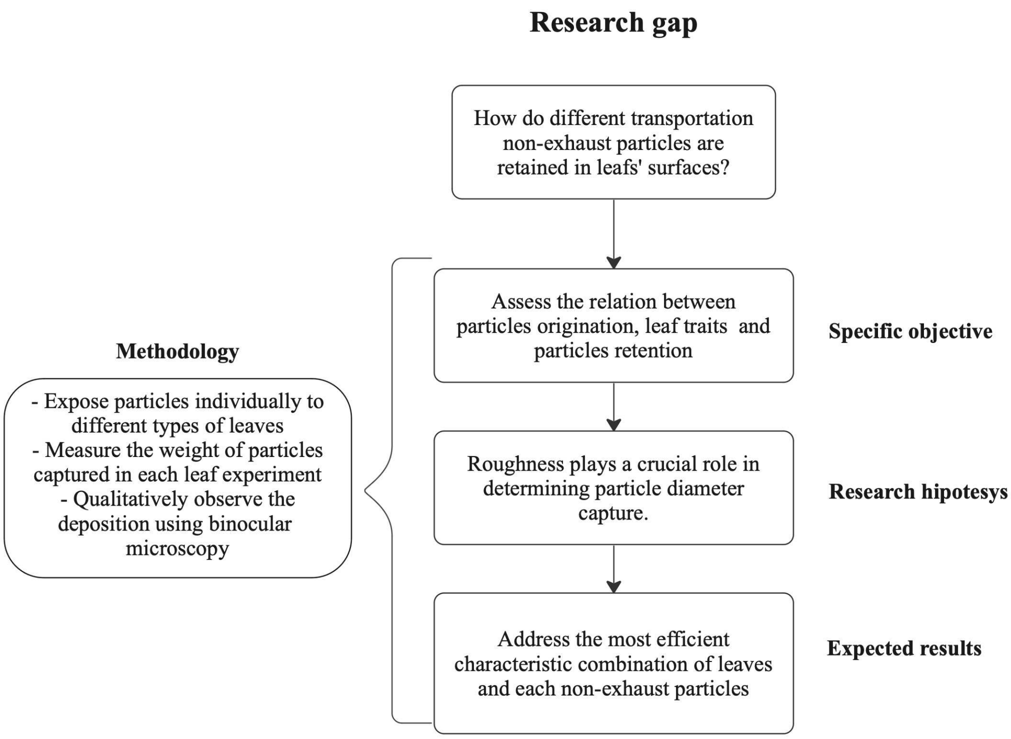
3.1.1 Chapter objective

In the context of investigating a range of non-exhaust particles generated by diverse modes of transportation characterized by varying shapes and sizes, it is feasible to mitigate extraneous factors by subjecting individual plant samples exclusively to particular transportation particles.

The primary focus of this chapter will be on particles emitted through the tire-road wear mechanism. This approach enables a targeted analysis of specific leaf traits' importance for each particle's physical trait. The specific objective of this study is to assess the correlation between the origin and properties of particles, their association with leaf traits, and the extent to which the leaves retain these particles.

The expected outcome of this chapter's investigation is to shed light on the direct correlation between the quantity of particle retention and visual disposition on the leaf surface and evaluate the leaf properties in the previous chapter. To facilitate this assessment, tire-road wear particles produced at earlier laboratory experiments will be the reference material on a laboratory scale, representing the real-size PM generated by the mechanical friction mechanism. This choice is particularly relevant considering the steep growing prevalence of electric vehicles worldwide, which do not emit exhaust particles during road usage and contribute significantly to PM emissions from road traffic sources. The visual representation of the strategic approach adopted in this chapter can be observed in Figure 34.

Figure 34 – Research gap 2.



Source: Author

3.2 State of the art

3.2.1 Systematic literature review

As an initial step in the methodology employed in the previous chapters, evaluating already published articles was the primary strategy to establish a comprehensive understanding of the physical traits of non-exhaust transportation particles that contribute to their retention in leaf surfaces.

The databases selected for the review were Scopus, Web of Science, and Science Direct. Initial exclusion criteria were established and applied as filters provided by the platforms, aiming to refine the search results and import the most pertinent data into Vosviewer. Initially, 3,033 studies were obtained based on the defined search strings. Applying the first filter, which focused on studies published within the last five years, 1,503 surveys were excluded. Additionally, with the implementation of the second filter to remain only review and research articles, excluding encyclopedias and book chapters, 98 studies were eliminated. Lastly, a third criterion of "open access papers" was used to restrict even more the database, resulting in 615 studies for further analysis. Table 13 summarizes the studies obtained after each filter application.

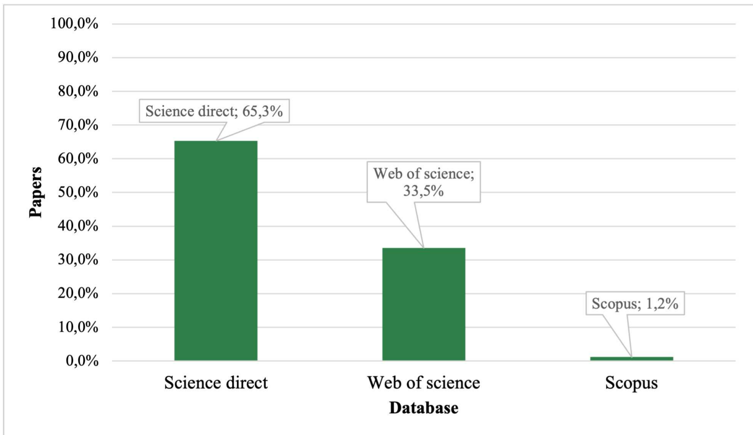
Table 13 – Summary of criteria used in the systematic review for non-exhaust transportation PM characterization.

Keywords	Database	Total papers	Criteria 1	Criteria 2	Criteria 3	Final papers
"non-exhaust" OR "unex-hausted" AND "road traffic" OR "traffic road" AND "Wear debris" OR "Tire wear" AND "particulate matter" or "PM" AND "Tire road"	Scopus	35	19	0	0	19
"non-exhaust" OR "unex-hausted" AND "road traffic" OR "traffic road" AND "Wear debris" OR "Tire wear" AND "particulate matter" or "PM" AND "Tire road"	Science direct	1,982	1,051	69	582	280
"non-exhaust" OR "unex-hausted" AND "road traffic" OR "traffic road" AND "Wear debris" OR "Tire wear" AND "particulate matter" or "PM" AND "Tire road"	Web of Science	1,016	433	29	238	316
					Total	615

Source: Author

Figure 35 depicts the number of papers scanned in each scientific database, revealing that Science Direct yielded the highest quantity of relevant documents for the applied keywords, as the methodology used by Pereira (2021).

Figure 35 – Papers scanned in each scientific database for the non-exhaust transportation particles characterization.



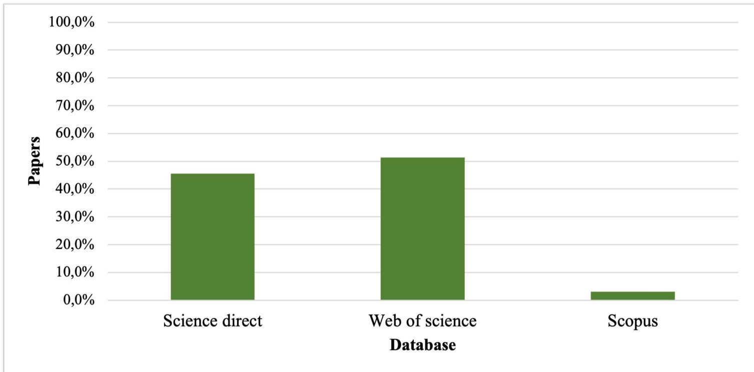
Source: Author

The initial searches yielded 615 studies, which were exported to .BibTeX format. In the subsequent analysis using Zoreto, the following criteria were applied:

- Exclusion of duplicated/repeated articles.
- Exclusion of articles whose title and abstract did not align with the research focus.

After applying these criteria, it was determined that 105 articles were duplicates, and 427 articles did not meet the requirements based on their title and abstracts. Consequently, 83 articles were left for the next stage of analysis. The percentage can be seen in the following image:

Figure 36 – Database and author's papers search for the non-exhaust transportation particles.



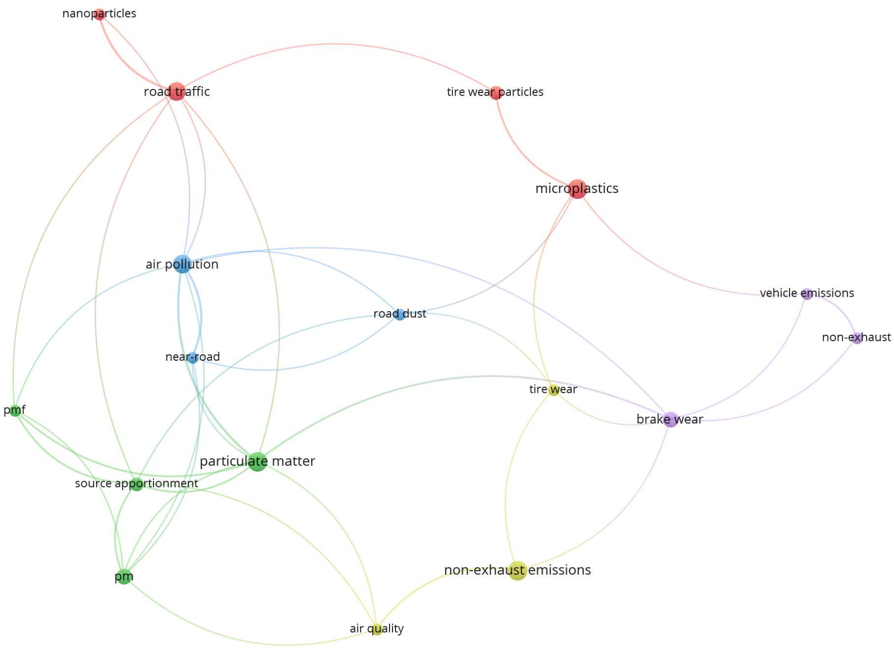
Source: Author

The data from these 83 articles were then imported into the Vosviewer program for further analysis and summarizing. During the extraction phase, a set of three questions were defined:

- What are the main physical characteristics of the non-exhaust transportation particles?
- Do these traits directly connect with the PM retention in leaves?
- What is the adequate methodology, from the leaf collection until the surface scanning?

These questions were a guideline for extracting relevant information from the selected articles. The next step was to upload the data to the software Vosviwer. As a thesis that bridges various significant study areas, it is intriguing to observe how the convergence of these distinct clusters manifests itself. This convergence can be visually represented in Figure 37.

Figure 37 – VOSViewer keywords clusters network visualization for the non-exhaust transportation particles.

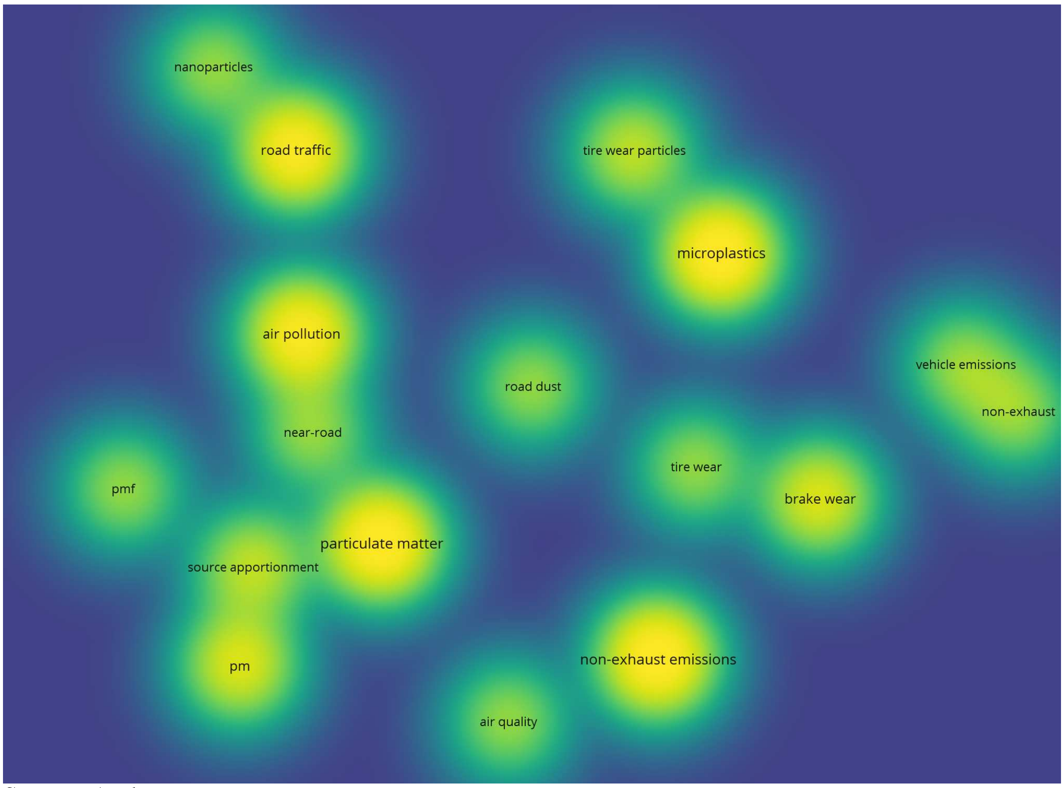


Source: Author

The first prominent cluster revolves around air pollution, road traffic, microplastics, and non-exhaust emissions. This indicates the main words used in those papers and which topics have been connected to this study area. When looking at the keyword cloud, in Figure 38, it is observed that microplastics, road traffic, PM, and non-exhaust emissions have taken significant highlight compared to other keywords.

Additionally, two new keywords were observed: Source apportionment and pmf. Digging into its meaning, Source Apportionment (SA) involves determining the origins of pollution and quantifying their respective contributions to overall ambient air pollution levels. This analytical task is typically achieved through the utilization of emission inventories, source-oriented models, and receptor-oriented models, also known as receptor models (Joint Research Centre (JRC), European Commission, n.d.). On the other hand, researchers have employed Positive Matrix Factorization (PMF) as a powerful multivariate factor analysis method for chemometric assessment and modeling of environmental datasets, notably by institutions such as the US Environmental Protection Agency (COMERO; GAWLIK, 2009). These terms should be added to the research keyword list and observed if they could be an additional method or idea to bring gains to the research.

Figure 38 – VOSViewer keywords clusters network visualization for the non-exhaust transportation particles.



Source: Author

The significant decline observed in the number of papers included in the databases and subjected to content analysis can be attributed to a substantial volume of research papers centered explicitly around the characterization of chemical and mineralogical particles. Furthermore, a considerable portion of these articles primarily focused on investigating the health-related toxicological impacts of these particles rather than delving into their inherent characteristics. However, mechanical properties play a crucial role in examining the retention aspect. Another prominent area of research generating a substantial number of papers pertained to modeling and simulation.

As part of this systematic review, a summarized table will be compiled to present the key findings from each selected article. The table will provide a concise overview of the main results and conclusions obtained from the individual studies. This compilation allows for a comprehensive comparison and analysis of the findings, highlighting the similarities, differences, and essential insights derived from the collective body of research. By synthesizing the main findings in a structured format, this table will serve as a valuable resource for researchers, policymakers, and other stakeholders interested in understanding the current state of knowledge on the topic.

3.2.2 Bibliographic review

During their study, Lewis *et al.* (2013) observed that the size and shape of small particles in the ultra-fine region - aerosols with an aerodynamic diameter of 0.1 µm (100 nm) or smaller - are exciting when considering contact temperatures. These particles exhibit an almost spherical shape. It was noted that the concentration of these particles tends to be higher in scenarios where the sliding velocity during the test run is increased, indicating a correlation with higher speeds on the road.

Alves *et al.* (2019) concluded that the emission factor resulting from the wear between pavements and tires amounted to approximately 2 mg/km^{-1} x $vehicle^{-1}$. It was observed that trace and significant elements constituted approximately 5% of the mass of the tire fragments. However, these elements accounted for 15-18% of the PM_{10} generated from wear, indicating the significant contribution of mineral elements originating from the pavement.

Castan *et al.* (2022) mentioned that Tire Wear Particles (TWP)-derived compounds are readily taken up by plants like lettuce, used in salads, with measured maximum leaf particle concentrations between similar to 0.75 (N-phenyl-N'-(1,3-dimethylbutyl)-p-phenylenediamine (6PPD)) and 20 $\mu mg.g^{-1}$ (hexamethoxymethylmelamine (HMMM)). This research investigation revealed that despite the metabolism of certain compounds within the plant, numerous transformation products were detected, many of which exhibited greater stability within lettuce leaves compared to their parent compounds. Moreover, ongoing leaching from TWP contributed to the continual presence of these metabolized compounds within the lettuce leaves. The persistence of these metabolized TWP-derived compounds, characterized by largely unspecified toxicities, raises significant concerns and introduces a novel consideration for evaluating the environmental impact of TWP.

In contrast to the predominant focus on the chemical composition of particles in existing research, our study aims to explore the connection between physical particle characteristics and physical leaf traits. While the chemical composition of particles is crucial in understanding their toxicological effects, investigating the physical aspects of particles and their interaction with leaf surfaces can provide valuable insights into the mechanisms of particle capture and retention by plants.

By examining physical particle properties such as size, shape, surface roughness, and aerodynamic behavior, we can assess their influence on the leaf surface morphology, surface area, and other physical leaf traits. This approach allows for a comprehensive understanding of the physical processes involved in particle deposition and adhesion to plant leaves.

By delving deeper into the physical aspects of particle-leaf interactions, this research aims to provide a more holistic understanding of how the particles are captured and retained by leaves, complementing the existing knowledge of their chemical composition. This can contribute to developing targeted strategies for selecting plant species and optimizing urban green spaces to mitigate air pollution and improve overall air quality effectively.

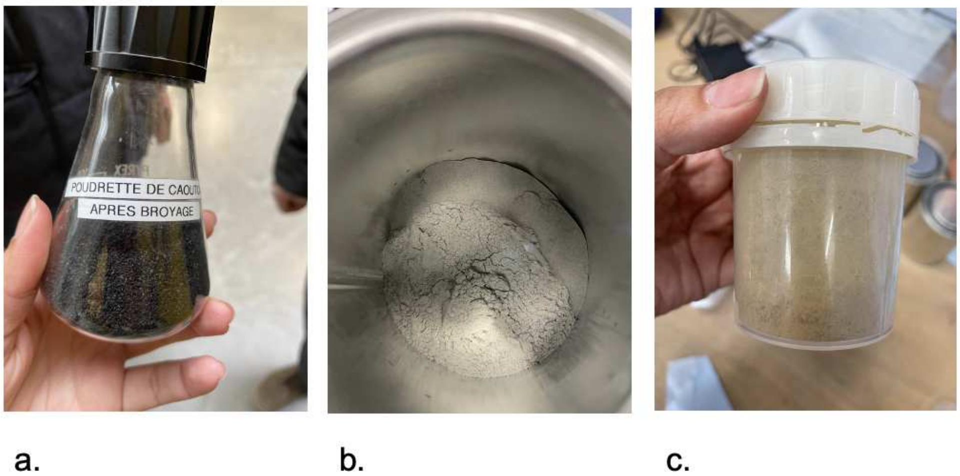
These questions served as a guideline for extracting relevant information from the selected articles, as chosen by Pereira (2021) in her work field. Those results will be compiled in a summarized table in the following research step.

3.3 Methodology

For an appropriate simulation of tire road wear particles, three materials (Figure 39) were obtained from the road construction laboratory at the University Gustave Eiffel Research center:

- A fine tire rubber;
- An aggregate fine particles;
- A soil particles.

Figure 39 – Non-exhaust transportation particles samples.



a.fine tire rubber, b.aggregates fine particles, c.soil particle
Source: Author

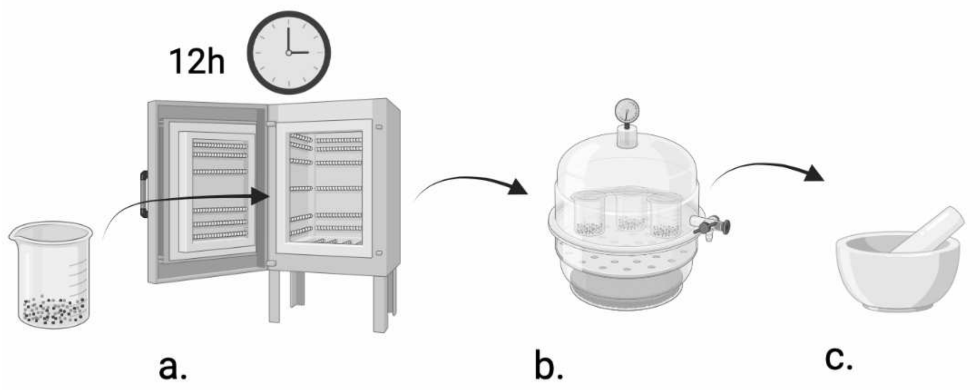
3.3.1 Materials preparation

A total of 5 leaves of each species were taken and efficiently cleaned and dried, as detailed in Chapter 2. The day before, the non-exhaust transportation particle samples started to be prepared. To uniform the particle samples, all materials passed through the sieve of 0.075mm before being taken to the experimental laboratory.

After sieving, the aggregate and soil samples from the road construction laboratory were left to dry for 12 hours in an oven at 90°C. This sample was not exposed to a drying process to avoid chemical interference and physical properties damage to the rubber, as they are not subject to high humidity absorption as the fine soil and aggregate particles. However, this last material was kept in the vacuum desiccator until weight stabilization.

On the following day, the particles from the oven were transferred to the vacuum desiccator until we achieved weight stabilization, concluding the material preparation. The two powders were macerated in a ceramic mortar (gral) as a last step. A summary of this methodology can be seen in Figure 40.

Figure 40 – Drying experimental particles in the oven, vacuum dessicator



a.12h mineral particles drying, b.vacuum desiccator until weigh stabilization, and c.mortar
Source: Author

3.3.2 Experiment preparation

The simulation exposure system consisted of 2 glass laboratory clean and dry bottles, one tube connecting the entrance to the first bottle, one tube connecting both bottles and one last silicone tube as an exit to the pressure air and expelled particles. The laboratory experiment planning was based in Bermúdez *et al.* (2021) and Zheng *et al.* (2022) as methodology references, where its exposure system was designed as shown in Figure **??** and in the scheme below.

Figure 41 – Bottles polluted air experiment preparation

a. methodology scheme designed for this experiment b. laboratory set of the designed methodology
Source: Author

With this scheme, pressure air will be used to simulate the outdoor and cars' resulting wind. To ensure uniform wind speed in the experiment, an anemometer set a speed of around 3m/s while the particles were suspended inside the first bottles of polluted air. This speed assured the suspension of leaves and particles, transferring a suspended air particle from the first bottle to the second bottle.

3.3.3 Particles exposure

After passing both bottles, the air pressure exit was left free to let the air with suspended particles go out. After the leaf's exposure, the second bottle was carefully opened, and each leaf was collected and stored correctly for the following experiment stages. The practical illustration of this methodological step can be observed in Figure 42.

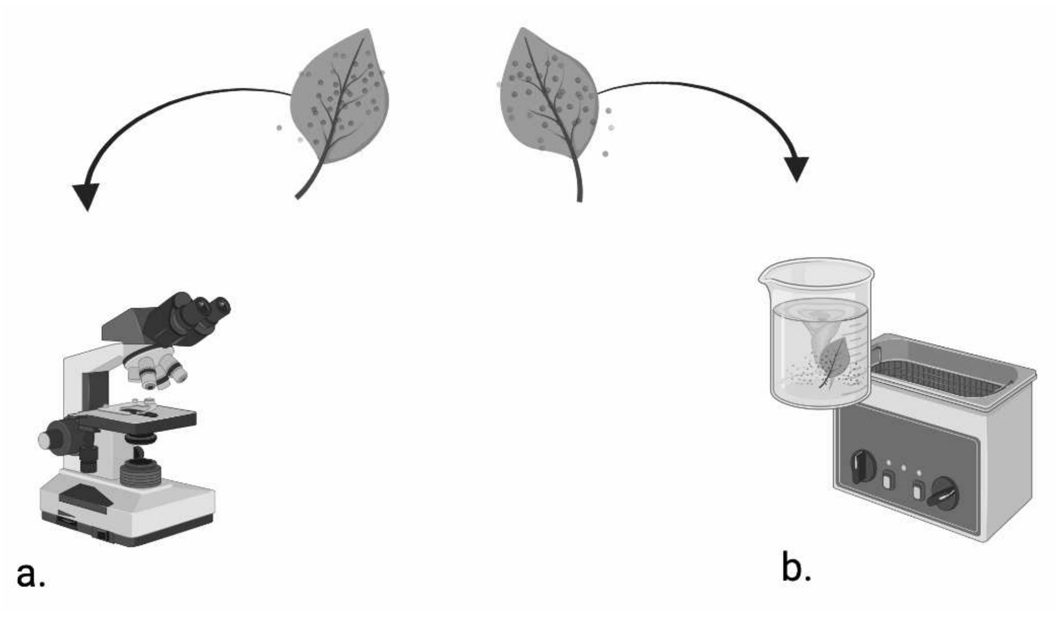
Figure 42 – Exposure of particles to leaves at a laboratory scale

Source: Author

3.3.4 Particle separation and analysis

Following the particle exposure phase, one leaf sample was carefully weighed and subsequently subjected to observation under a binocular microscope. Simultaneously, the remaining leaf samples were immersed in distilled water and subjected to ultrasonic bath treatment, as drawn in Figure 43.

Figure 43 – Particle separation after laboratory experiment and analysis



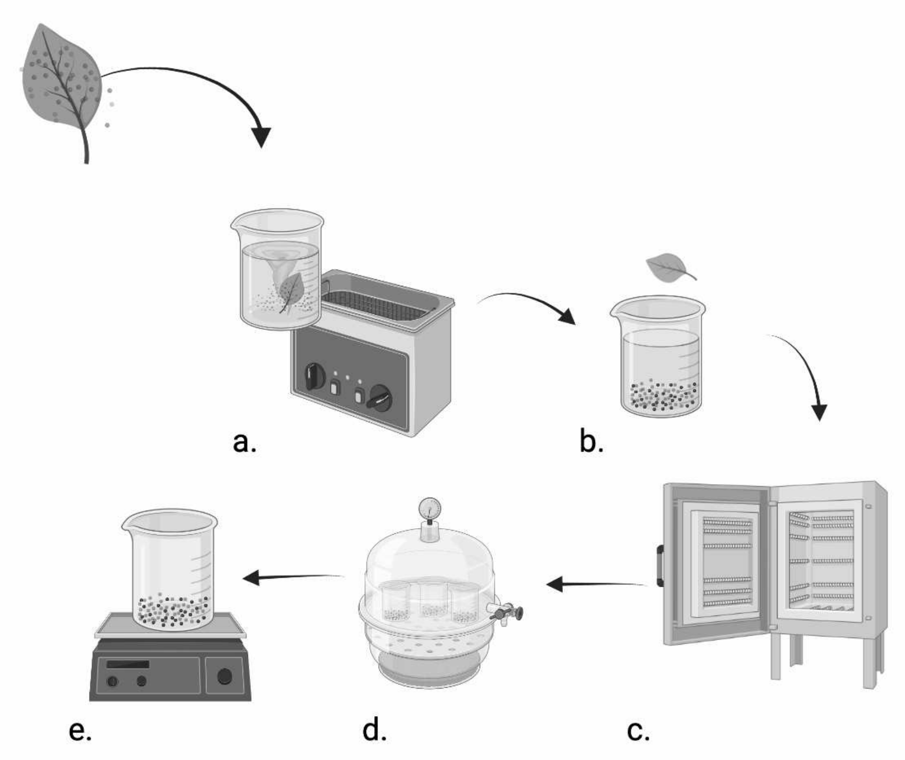
a. one leaf sample was taken to observations b. the remaining leaves samples were taken to the ultrasonic bath
Source: Author

3.3.4.0.1 Measurement of particle weight removed from leaves surfaces

Lastly, upon completion of the ultrasonic bath treatment, the leaves were delicately detached from the backing material, and the remaining mixture of distilled water and collected particles was transferred to a laboratory oven overnight to facilitate evaporation of the liquid. The temperature for aggregate and soil samples was set at 95°C, while for the rubber collection, the oven temperature was set to 40°C, necessitating more than two days for complete water evaporation.

Subsequently, all dried samples were placed in a vacuum desiccator for at least 12 hours or until weight stabilization was achieved. The weight of the collected particles was then determined.

Figure 44 – Procedure to retained laboratory experiment particles weigh determination



a. leaves cleaning with distillate water on the ultrasonic baths, b.leaves removal, c.evaporation of distillate water, d. stabilization of weight in the vacuum e.retained particle weight measurement
Source: Author

The entire methodology scheme can be seen in Annex A at the end of the thesis.

3.4 Results

The data produced in this methodologic step will start with each leaf surface observation after exposure to pollutants, with further continuous data analysis. To facilitate this undertanding, the observations will be done for each kind of leaf and facet separetly.

3.4.1 Vanhouttei de spirala

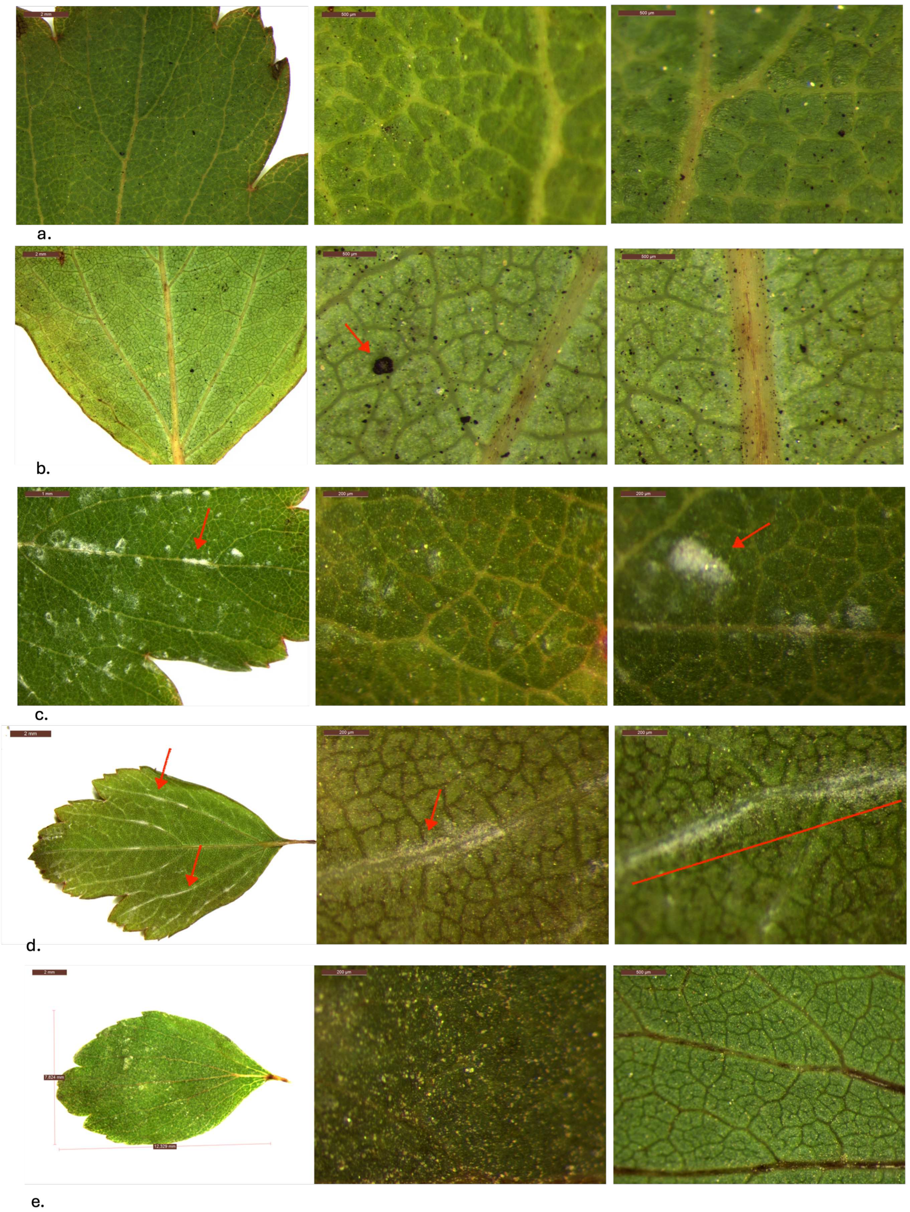
This investigation describes how the leaf's surface physical properties visually influence particle capture and retention. Some examples of each leaf species collection can be seen in Figures 45, 46, 47 and 48.

The rubber retention in this leaf (Figure45 a, b) was broader in particle size retention, covering from 0,199mm - 0,007mm, according to the binocular microscope capability observation. The distribution along both facets looked like a homogeneous particle distribution. There was a relatively homogeneous retention pattern on the midrib and the blade, without clearly observing a more robust retention pattern in veins, micro veins, or midrib.

A more substantial accumulation of particles on the midrib, vein, and venules is apparent when looking at the aggregate particle retention (Figure45 c, d). A thicker layer comes around these physical structures and enters some of them. The particles are heterogeneously distributed on the blade, with a few accumulation picks at specific points.

Lastly, the sand particles (Figure 45 e) are more uniformly spread on the surface than the aggregates, with fewer accumulation picks in specific areas

Figure 45 – Leaf 1 exposed to three kinds of pollutants



a.adaxial facet rubber particles retention b.abaxial facet rubber particles retention c.adaxial facet aggregate particles retention d.abaxial facet aggregate particles retention e.adaxial and abaxial facet soil particles retention
Source: Author

3.4.2 Euonymus Europaeus

The rubber retention phenomenon on leaf 2 (Figure 46 a, b) is less effective than the first plant observation on both the adaxial and abaxial sides. There is no precise observation of the influence of midrib topography on retention, neither in veins nor micro veins.

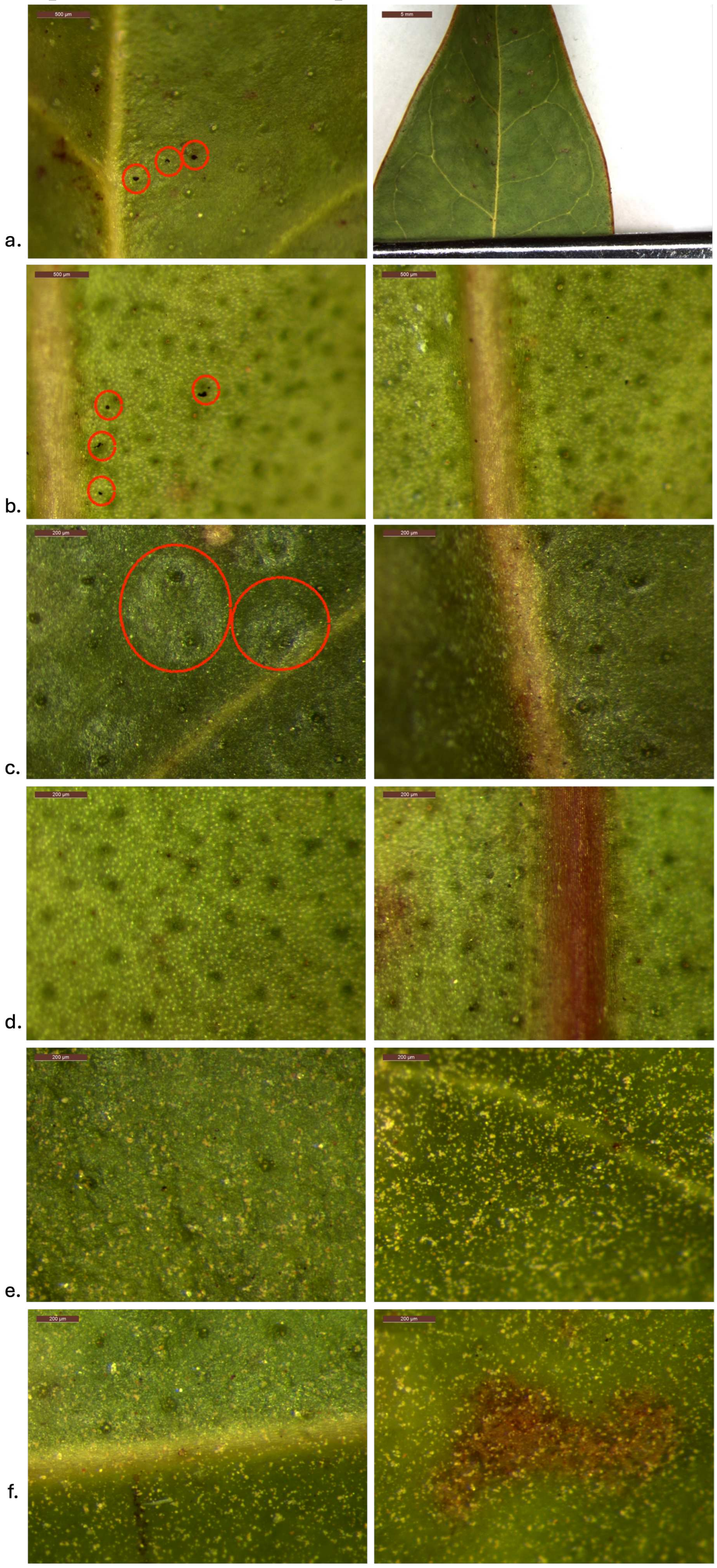
On the other hand, the aggregate (Figure 46 c, d) and soil (Figure 46 e, f) retention phenomenon have similar behavior, with an eye-level homogeneity, with no more robust accumulation in veins, micro veins or midrib, with no pick accumulation points.

3.4.3 Cotoneaster aspressus

This plant shares the phenomenon with superficial trichomes on both leaf facets. For the rubber retention (Figure 47 a, b), particles from 0,096mm - 0,016mm were observed. On the adaxial facet, the rubber presence is not as strong as on the abaxial side. More substantial trichomes on the abaxial surface could improve the capture of this pollutant.

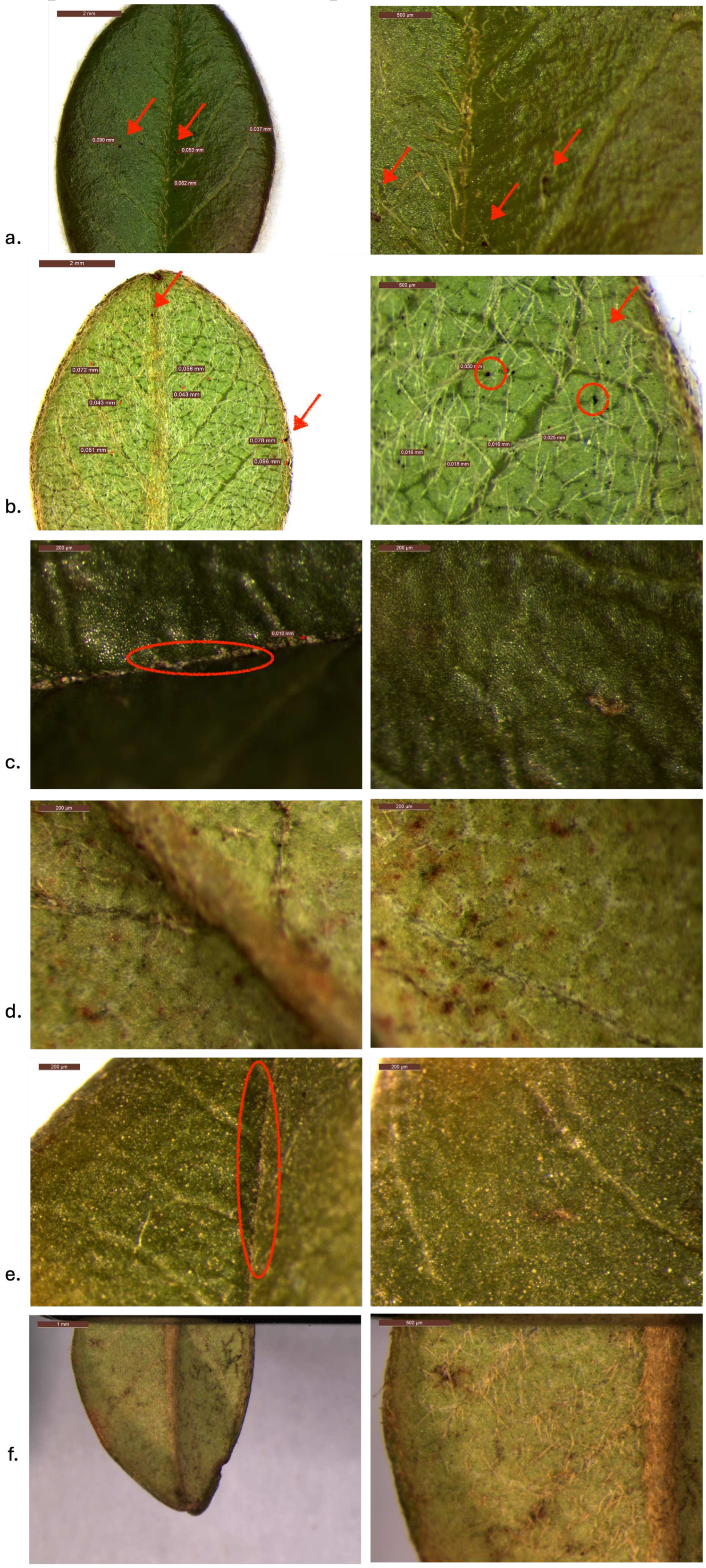
When looking at the distribution around the leaf blade, a homogeneous pattern is observed, with no more robust accumulation in veins, micro veins, and midribs but with stronger attachment to trichomes.

Figure 46 – Leaf 2 exposed to three kinds of pollutants



a.adaxial facet rubber particles retention b.abaxial facet rubber particles retention c.adaxial facet aggregate particles retention d.abaxial facet aggregate particles retention e.adaxial facet soil particles retention f.abaxial facet soil particles retention
Source: Author

Figure 47 – Leaf 3 exposed to three kinds of pollutants



a.adaxial facet rubber particles retention b.abaxial facet rubber particles retention c.adaxial facet aggregate particles retention d.abaxial facet aggregate particles retention e.adaxial facet soil particles retention f.abaxial facet soil particles retention
Source: Author

3.4.4 Cupressus leylandii

In a qualitative analysis, the *Cupressus leylandii* demonstrated highly effective retention capabilities. Here, the analysis should be considered as a three-dimensional topography. One notable observation from the rubber experiment, shown on the first two lines in Figure 48 (a) is the diverse range of particle size retention, spanning from 0.246mm to smaller than 0.017mm.

A second observation pertains to the distribution of particles around the branches. Larger particles, the ones possible to be observed on the microscopy on 500 μm scale - were found on the blade surfaces and branches' junctions. Conversely, smaller particles were uniformly distributed around the leaves, with some accumulation peaks observed at the branch joints and adhering to the naturally occurring surface moisture observed sporadically in these samples.

When observing the aggregate experiment result, the third and fourth lines of Figure 48 (b), the particles are uniformly distributed, with no eye-level accumulation pattern. This can happen due to a higher precision near the branch observation, as the aggregate particles are smaller than the rubber and soil ones. Lastly, in the soil experiment result (Figure **??** c), larger soil particles were retained on the branch joints and smaller ones on the blade surface.

Figure 48 – Leaf 4 exposed to three kinds of pollutants

a.tire particles retention b.aggregate particles retention c.Soil particles retention
Source: Author

3.4.5 Statistical analyse

After the complete water evaporation, each sample was carefully weighed, and each particle retention data was numerically determined. The preliminary results are in the Table 1. The "rubber," "Aggregate," and "Soil" columns display the weight of particles retained in the experiment made for each leaf type (Leaf ID columns). These values were obtained through the Figure 43 methodology. The clean leaf weight was also received before pollutants in the exposition experiment procedure. The graphical representation of these numbers can be observed in the Figure 49.

This graphic pictures *how much weight of singles pollutants were retained by weight of leaf?*, in a columns distributions. This calculation is the Dirt Index (DI), or particles retention index, computed using the equation 3.1:

$$DI = \frac{rp}{clw} \tag{3.1}$$

where *rp* represents retained particles and *clw* denotes the weight of clean leaves.

Table 14 – Particles retained by leaves

Leaf ID	Rubber (g)	DI	Aggregate (g)	DI	Soil (g)	DI
1	0.001	0,0035	0.0071	0,0227	0.0037	0,0150
2	0.0013	0,0003	0.0266	0,0047	0.0201	0,0044
3	0.0006	0,0090	0.0007	0,0049	0.0007	0,0096
4	0.0033	0,0010	0.0120	0,0022	0.0257	0,0079

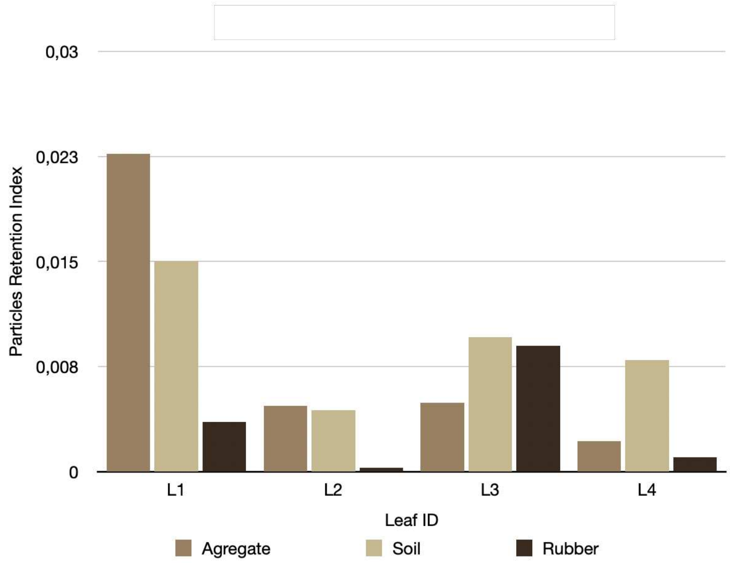
Source: Author

This graphic allows us to perceive Leaf 1 as the most significant aggregate retained per leaf weight between all the tested leaves, colored brown. Followed by the *Vanhouttei de spirala*, leaves 3, 2, and 4, respectively, were the ones to retain more aggregate. This material generally hadn't strong accumulation points in veins, micro veins, and blades. As Leaf 4 still showed space to keep particles in the branch joints, with more extensive sample data, this accumulation capability can be analyzed. In agreement with the microscope observations, aggregate, and soil had uniform particle distribution around the samples and similar results.

When looking at soil retention, leaves 1, 3, 4, and 2 (see Figure 49) had their retention results, as shown in the beige columns picture on the graphic. In this experiment, the retention around the midrib was present, with thick visible layers, having a surface topographical influence on the result.

Finally, in rubber retention, colored dark brown in the figure below had the DI order: leaf 3 was the most considerable retainer, followed by Leaf 1, 4, and 3. On the other hand, leaf 4 was the one with larger particles observed. At the same time, due to the branch joints, the volumetric void possible of particle retention still had empty spaces. In Leaf 2, the trichome's presence can have played an essential function in larger particle retention.

Figure 49 – Particles retention per leaf weight unit

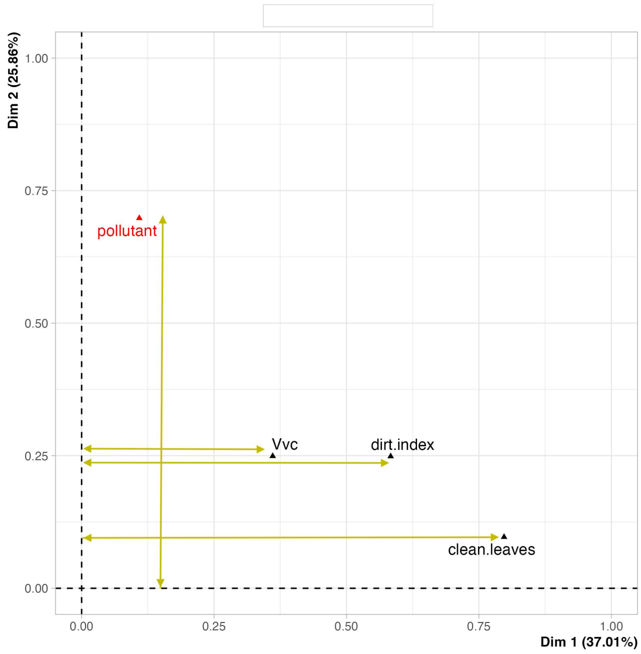


Source: Author

To observe which parameter would have a higher influence on the phenomena covariance, it means, that would explain mostly the results, the PCA graphic shown in Figure 50.

In Principal Component Analysis (PCA), each vector represents a principal component, and the size of each vector (i.e., its magnitude or length) indicates the importance or contribution of that component to the overall variance in the data. In this situation, the distance of the variable to the axis origem would be similar to the vector representation. To facilitate the understanding of the position meanings of each variable on the graphic area, yellow arrows were added.

Figure 50 – Variables displayed on a multi-factor principal component analysis graphic



Source: Author

From the figure above can be taken that, from the continuous variables, Vvc followed by dirt index and then clean leaves weight, together, explain 37.01% of the phenomenon covariance, where the clean leaves weight is the prominent one. Looking into the Y-axis, the pollutant-type domains the covariance explanation at dimension 2 (the dimension that explains 25.88% of covariance). As the clean leaves' weight had an expressive result in this analysis, this will be the variable taken from this experiment to support the next chapter's data construction.

After that, a linear regression was performed to numerically determine how these variables work together to obtain the dirt index output value. The basic equation is the one Equation 3.2 below:

$$DI = \beta_0 + \beta_1 Soil + \beta_2 Rubber + \beta_3 Clean\ leaves + \beta_4 Vvc \quad (3.2)$$

The coefficients regression values can be seen in Table 15 and its resulting Equation 3.3 below:

Table 15 – Multi-factor Linear Regression results for dirt index values

Coefficients	Estimate	P-value
Intercept (β_0)	0.0215247	0.00562
Soil (β_1)	-0.0014414	0.67079
Rubber (β_2)	-0.0074308	0.05684
Clean leaves (β_3)	-0.0024131	0.01200
Vvc (β_3)	-0.0001609	0.13760
Adjusted R-squared:	0.507	

Source: Author

$$DI = 0.021 - 0.001Soil - 0.007Rubber - 0.002Clean\ leaves - 0.0001Vvc \tag{3.3}$$

In a multiple linear regression equation like the above, each coefficient represents the change in the dependent variable (dirt index) associated with a one-unit change in the corresponding independent variable, holding all other variables constant. The following interpretations can be done:

- The intercept (0.021) represents the estimated value of DI when all independent variables (Soil, Rubber, Clean leaves, V vc) are zero.
- A one-unit increase in the Soil variable weight value is associated with a decrease of 0.001 units in DI, holding all other variables constant.
- A one-unit increase in the retained rubber weight variable is associated with a decrease of 0.007 units in DI, holding all other variables constant.
- A one-unit increase in the Clean leaves weight variable is associated with a decrease of 0.002 units in DI, holding all other variables constant.
- A one-unit increase in the Vvc variable is associated with a decrease of 0.0001 units in DI, holding all other variables constant.

The coefficient of determination (R-squared) value of 0.507 indicates that approximately 50.7% of the variability in the dependent variable (DI) can be explained by the independent variables included in the model, taken as a good representation percentage. From all the variables, the rubber is the one that has a stronger influence in this equation, and the soil is the weakest. The aggregate didn't appear on the equation because the model removed it from the coefficients list.

3.5 Conclusion

From the qualitative perspective, leaf 1 is the more considerable pollutant retainer per leaf weight, followed by leaves 3, 4, and 2. In simultaneous, leaf 1 showed a high retaining potential scenario, while leaf 4 could still have space for higher results. This can happen due to several factors, such as the wind direction and speed in which the pollutants are, the plant's leaf density, and the surrounding location on the road. On the other hand, as leaf 4 has a higher leaf density, a total potential of the leaf capture should be expected.

Lastly, the trichomes present on leaf 3 can be a crucial factor for its plant results, agreeing with the literature. Leaf 2 had an apparent higher retention affinity with soil and aggregate particles. This can be explained by the particle and leaf chemical composition interaction and by the particle's different shapes and sizes.

From the statistical analysis, the clean leaf weight was taken as the continuous variable that has explained more of the phenomenon covariance. This will be taken as a reference for the next chapter's methodology.

4 ANALYZING THE CORRELATION BETWEEN LEAF VOLUMETRIC TRAITS AND POLLUTANT RETENTION ACROSS THE ENTIRE VEGETATIVE SYSTEM

4.1 Introduction

According to European Environment Agency (EEA) (2014), green infrastructure comprises strategically planned natural and semi-natural areas, alongside other environmental features, intended to provide various ecosystem services. These services encompass water purification, air quality improvement, recreational space, and climate mitigation and adaptation. By incorporating green (land) and blue (water) spaces, this network enhances environmental conditions, enhancing citizens' health and overall quality of life.

When assessing population and environmental health, proactive consideration of such plants becomes crucial in mitigating the adverse effects of air pollution. Tomson *et al.* (2021) added that a critical strategy to improve air quality involves increasing the density of plants per unit of land surface area through urban greening initiatives. In addition to photosynthesis, which reduces harmful gas emissions, incorporating high-density street vegetation, green walls, or green façades is a barrier against atmospheric aerosol particles in densely populated areas. Tomson *et al.* (2021) adds that design strategies tailored to local plant availability can minimize air pollution and maximize air quality. The same writer found that in her research in Australia, the plant materials were highly efficient in filtering coarse particles ($\geq 2.5\mu$m), with efficiencies ranging from 50.1% to 99.9%.

The importance of selecting appropriate plants suited to the local climate, capable of improving air quality and atmospheric depollution, is often underestimated. Evaluating a plant's adaptability to the local environment and its potential to thrive under such conditions is a fundamental consideration. To accomplish this, researchers employ the Air Pollution Tolerance Index (APTI), which assesses factors including ascorbic acid levels, total chlorophyll content, pH, and relative water content. This comprehensive evaluation provides a reliable method for categorizing plants as either tolerant or sensitive to air pollution, as elucidated by Joshi *et al.* (2023).

In addition to these considerations, Ribeiro *et al.* (2019) underscores the importance of integrating environmental factors into transportation system planning and development. They emphasize the intricate relationship between local traffic patterns, land use, building density, and the specific concentrations of NO_2. To evaluate the efficacy of such measures, (TOMSON *et al.*,

2021) devised a dynamic aerosol chamber measuring 280 mm in length and 45 mm in diameter (0.4 L), densely packed with Australian vegetation as a filtering material. While this experimental setup presents a higher leaf density than observed in natural settings, it is a targeted laboratory assessment of filtration efficiency. Offering insights for future research, the authors recommend focusing on developing and evaluating full-scale green barrier systems for PM filtration in urban environments. It is this gap in research that the current chapter seeks to address.

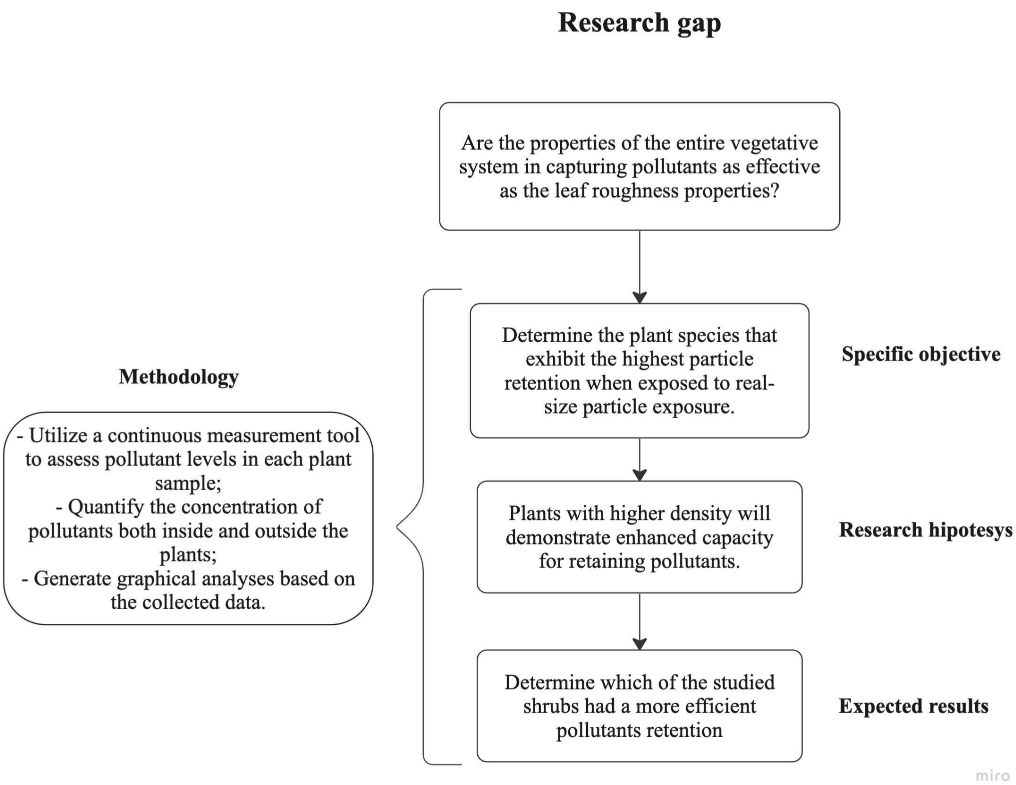
4.1.1 Chapter objective

In identifying optimal plant choices for strategic urban locations with enhanced pollutant retention capabilities, this chapter presents a methodology to design and evaluate the effectiveness of the entire vegetative system in pollutant retention. The specific objective is to identify plant species exhibiting the highest particle retention under real-scale particle exposure conditions.

By assessing particle retention capacities across different plant species, this research aims to identify those demonstrating superior performance in capturing and retaining pollutants under real-world exposure scenarios. The chapter integrates findings from previous chapters as premises to evaluate correlations between laboratory-studied parameters and real exposure conditions.

Ultimately, the conclusions, suggestions, and valuable insights provided herein will assist urban planners, environmental agencies, and researchers optimize plant selection and placement in urban environments for effective pollution mitigation strategies. The visual representation of the strategic approach adopted in this chapter can be observed in Figure 51:

Figure 51 – Research gap 3

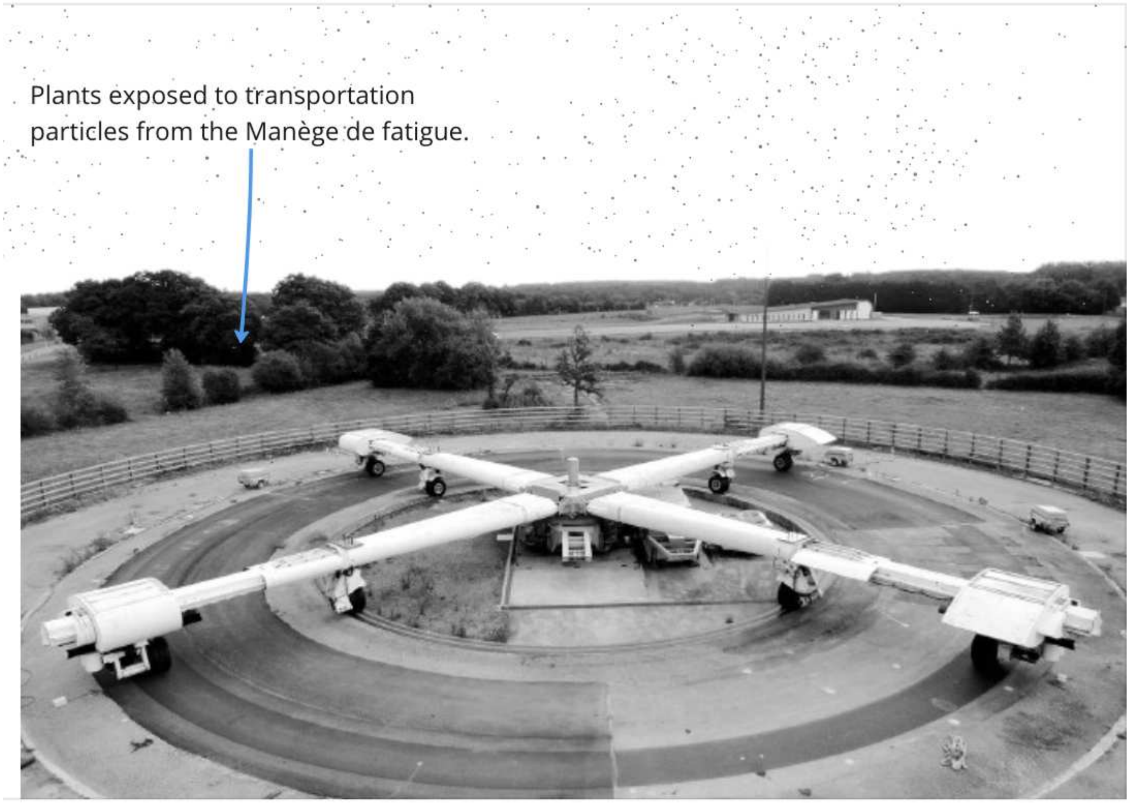


Source: Author

4.1.2 Experiment location

The experiment was developed in the transportation and infrastructure laboratory at the Université Gustave Eiffel campus in Nantes, France. Due to an incoming experiment with a fatigue carrousel during days, which continuously exposes the surrounding vegetation to its emitted particles, shrubs equidistant from the emission source were assessed continuously while exposed to the pollution, as seen in Figure 52.

Figure 52 – Carrousel of fatigue in the NEMO project, Nantes - France

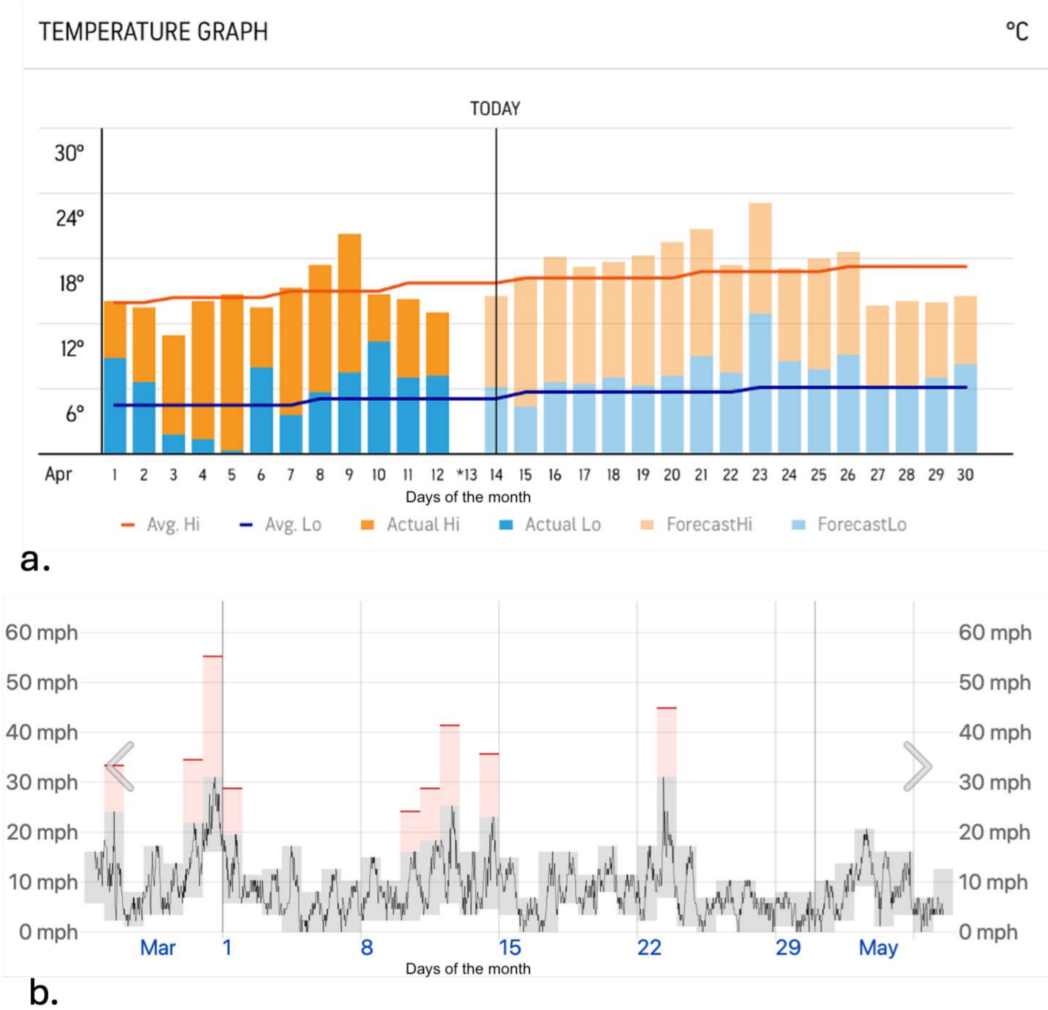


Source: Author

4.1.3 Weather

The procedure was conducted during the third week of April 2023, coinciding with the spring season. The local weather conditions have temperatures between 5°C and 24°C, with sunny and cloudy moments. During the experiment days, the winds variated between 10 mph and 20 mph, characterizing these as gentle to fresh, breezy days, according to National Weather Service (2024), and no rain occurred. Some of their information is detailed and illustrated in Figure 53.

Figure 53 – April 2023 Nantes, France weather caracterization



a. Nantes, France temperature (ACCUWEATHER, 2023), b. Nantes, France wind speed (WeatherSpark, 2024)
Source: Author

4.2 State of the art

4.2.1 Systematic literature review

As an initial step in the methodology employed in the previous chapter, the evaluation of already published articles served as the primary strategy to establish a comprehensive understanding of the green corridors' task in pollution reduction. The databases selected for the review were Scopus, Web of Science, and Science Direct.

Initial exclusion criteria were established and applied as filters provided by the platforms, aiming to refine the search results and import the most pertinent data into Vosviewer. Initially, 180 studies were obtained based on the defined search strings. Applying the first filter, which focused on studies published within the last five years, 71 surveys were excluded. Additionally, with the implementation of the second filter to remain only review and research articles, excluding encyclopedias and book chapters, 12 studies were eliminated, resulting in 85 studies for further analysis. Table 16 summarizes the number of studies obtained after each filter application. Science Direct yielded the highest quantity of relevant documents for the applied keywords, as the methodology used by Pereira (2021).

Table 16 – Summary of criteria used in the systematic review for green corridors and transportation air pollution.

Keywords	Database	Total papers	Criteria 1	Criteria 2	Final papers
"air pollution" AND "transportation" AND "green corridor"	Scopus	8	8	6	6
"air pollution" AND "transportation" AND "green corridor"	Science Direct	142	89	77	77
"pollution" AND "transportation" AND "green corridor"	Web of Science	30	18	18	18
				Total	103

Source: Author

The initial searches yielded 103 studies, which were exported in .csv format. In the subsequent analysis using Excel, the following criteria were applied:

- Exclusion of duplicated/repeated articles.
- Exclusion of articles whose title and abstract did not align with the research focus.

After applying these criteria, it was determined that four articles were duplicates, and 70 articles did not meet the requirements based on their title and abstracts. Consequently, 33 articles were left for the next stage of analysis.

In addition, to ensure the inclusion of relevant papers not selected by the database, the author manually added six additional documents to the system. The data from these 39 articles were then imported into the Vosviewer program for further analysis and summarizing. During the extraction phase, a set of four questions was defined:

- Does plant density play a significant role in particulate retention?
- Was an experiment conducted to evaluate the effectiveness of plants in retaining particles? If yes, which?
- Which plant species demonstrated higher levels of particle retention?

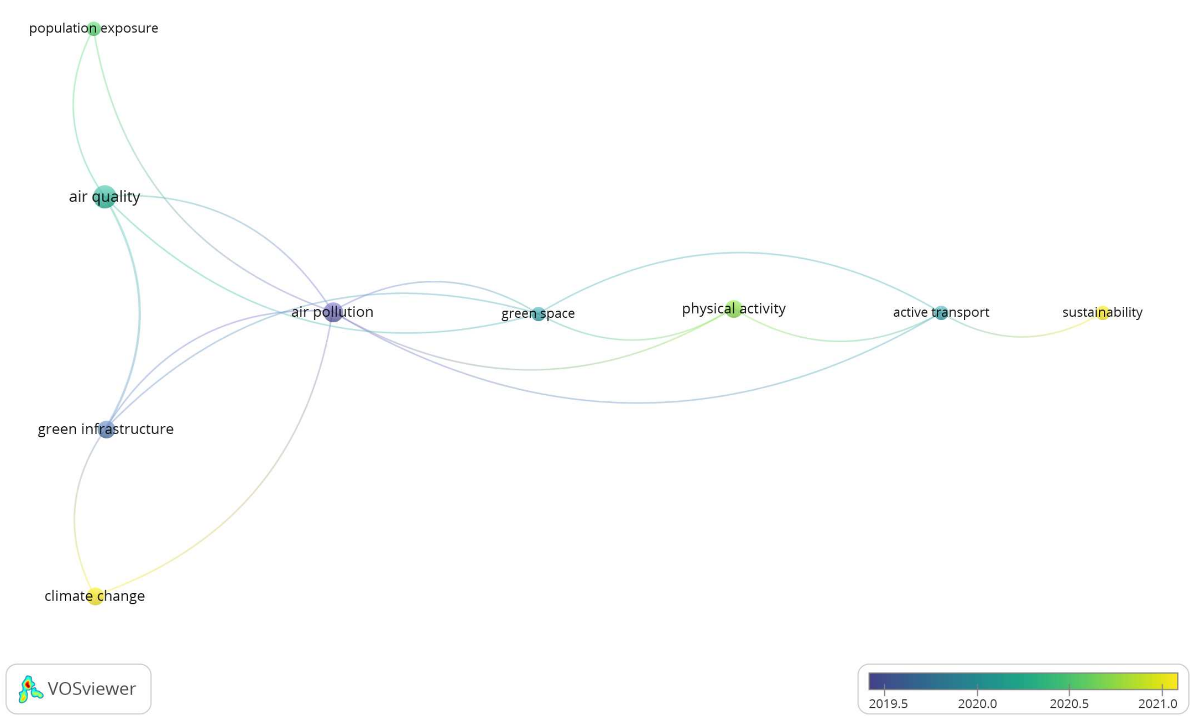
– Does plant density play a significant role in particulate retention?
– Which plant species are recommended for integrating green corridors? Why?

These questions served as a guideline for extracting relevant information from the selected articles, as chosen by Pereira (2021) in her work in the field.

The next step was to upload the data to the software VosViwer. As a thesis that bridges various significant study areas, it is intriguing to observe how the convergence of these distinct clusters manifests itself. This convergence can be visually represented in Figure 54. The first prominent cluster revolves around air quality, with a notable surge in paper releases observed around 2020. This indicates a significant emphasis on studying and understanding various aspects related to air quality during that period, according to Figure 55.

The second significant cluster focuses on green infrastructure, closely intertwined with "green spaces." According to Figure 54, this cluster experienced a considerable influx of research papers around 2019. This suggests a heightened interest and scholarly exploration of the connections between green infrastructure and its impact on the environment, urban planning, and sustainability.

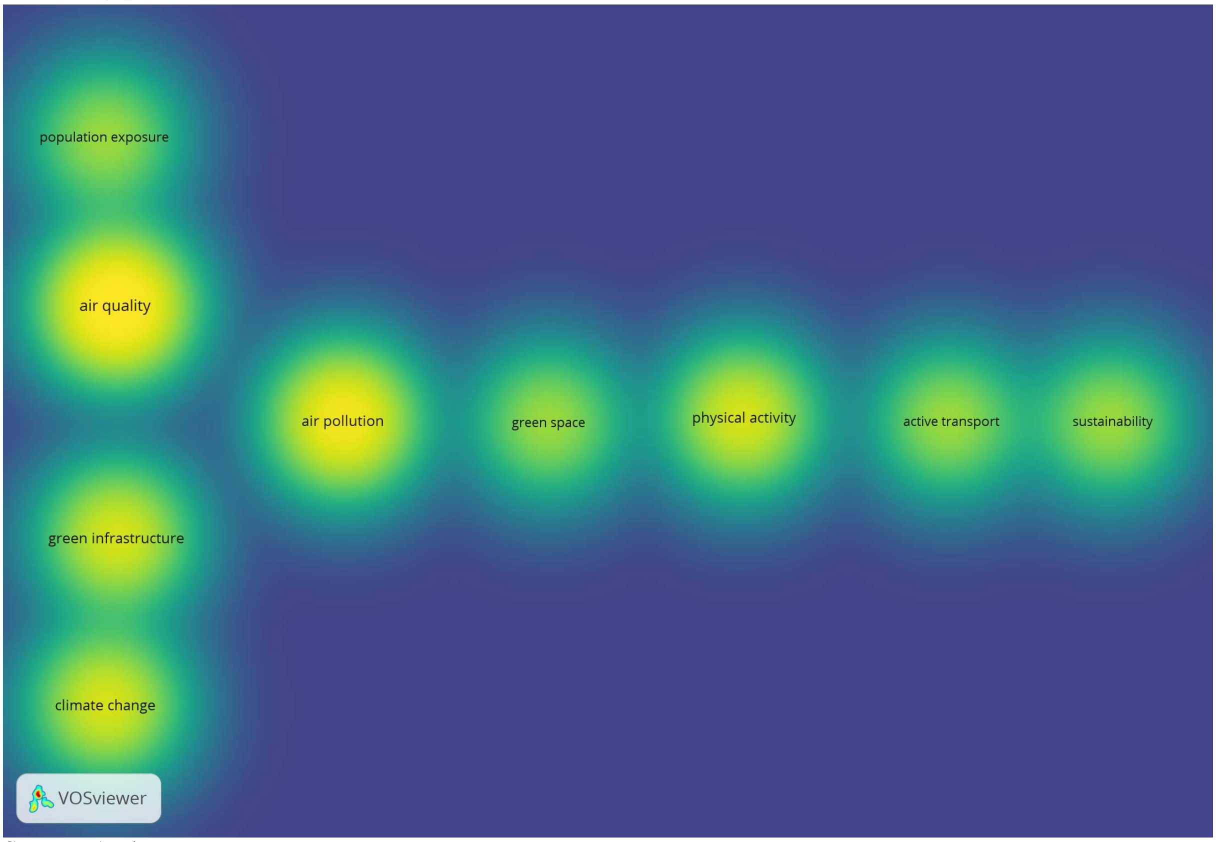
Figure 54 – Clusters network visualization for the effectiveness of the entire vegetative system in retaining pollutants



Source: Author

In contrast, there is a noticeable disparity in the density of published papers across each research area. Figure 55 highlights the prominence of the "air quality" cluster, signifying a substantial volume of content created within this domain.

Figure 55 – Clusters density visualization for the effectiveness of the entire vegetative system in retaining pollutants



Source: Author

These questions were a guideline for extracting relevant information from the selected articles. Those results will be compiled in a summarized table in the following research step. As the next research stage, a portion of the information extracted from the selected articles, highlighting the primary plants used in green corridors, as well as the main factors observed as essential to the green corridors plants when aiming to reduce PM in the local environment will be evaluated in those articles and posteriorly presented.

4.2.2 Bibliographic review

The deposition of particles has been extensively investigated in various scenarios. For instance, Xie *et al.* (2017) conducted a study on this phenomenon under different wind conditions. The research revealed that the retention of particulate matter (PM) by plant leaves exhibited complex and dynamic processes, with maximum values exceeding minimum values by over ten times. The average PM measurement obtained from multiple periods and situations proved to be a reliable indicator of a plant's ability to retain PM. The findings demonstrated that the use of plants with intricate crowns in urban greening initiatives and the reduction of wind speed within plant communities have a positive impact on reducing PM pollution.

Simultaneously, Baldacchini *et al.* (2017) examined leaf traits of the same plant species, *Platanus acerifolia*, in different geographical locations where they were situated. The study revealed satisfactory PM capture on the leaves in all the examined locations, thus bringing up the possibility of using similar plant traits in different places when solving similar air quality issues.

Another researcher observed that combining trees, shrubs, and herbs in vegetation can effectively reduce the concentration of particulate matter (PM) concentration. Vegetation barriers demonstrated the ability to reduce total suspended particles (TSP) and PM10 concentrations by approximately 5% to 23% in areas situated behind the vegetation barriers, compared to control areas in oblique wind canyons. However, the effect of vegetation barriers on $PM_{2.5}$ concentrations varied and could be either positive or negative, showing inconsistency (CHEN *et al.*, 2021). To enhance roadside air quality, Chen *et al.* (2021) recommended to encourage the use of shrubs or hedges with heights lower than 2 meters.

In their study, Khomenko *et al.* (2020) utilized the Urban and Transport Planning Health Impact Assessment (UTOPHIA) methodology to evaluate the annual mortality, Life Expectancy (LE), and economic consequences associated with non-compliance with exposure guidelines in the adult population of Vienna. Their findings revealed that a significant proportion (76%) of the premature mortality was attributable to exposure to PM2.5 and insufficient physical activity.

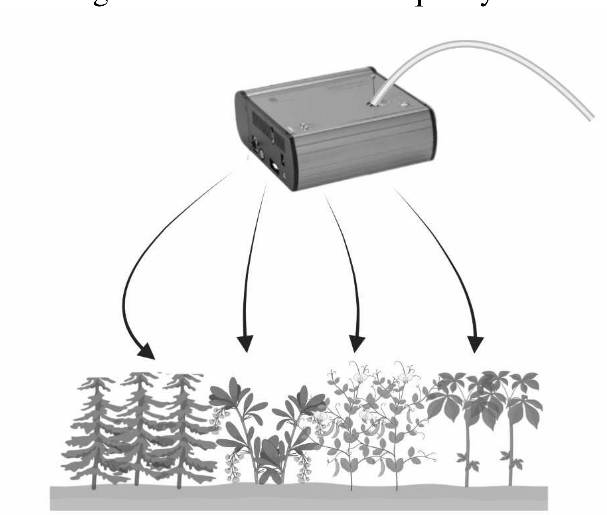
Based on these results, Khomenko *et al.* (2020) recommends implementing policies to reduce motorized traffic and promote active and public transportation. Additionally, they emphasize the importance of urban greening initiatives. These measures are aligned with the objectives of enhancing the livability of metropolitan areas, improving environmental health, and promoting social equity and justice. By adopting such policies, cities can effectively address the negative health impacts associated with air pollution and physical inactivity, benefiting their populations' well-being and longevity precisely as this thesis research aims.

4.3 Methodology

In this last step of the phenomenon study, different from the the laboratory experiment (simulated in the previous chapter) that simulated the real particle deposition, an in-situ experiment will be performed. The method involves a 20-minute continuous measurement of external air quality at various positions inside and outside the perimeter of each plant.The instrument used for this outdoor measurements is the Mini-Wras, a portable wide-range aerosol spectrometer for ultrafine particles and PM measurements, with the precision of particle sizing and counting from 10 nm to 35 μm. This instrument was placed in different shrub locations, including within a 20-meter distance from all the plants, to obtain a representative local air quality value. This evaluation was done on two different days, - 17th and 18th April 2023 - for each sample.

Figure 56 depicts the experiment scheme, where the Mini-Wras instrument was placed on a stable base surface during the entire experiment. Following the initial setup, the instrument is activated, and the program is initiated. The software immediately begins collecting measurements upon activation. A 5-minute buffer period was implemented each time the instrument needed to be repositioned to ensure a high level of data confidence. This buffer time allowed for stabilization before continuing with data collection.

Figure 56 – Experiment setting scheme for outside air quality



Source: Author

Figure 57 – Experiment execution for outside air quality

Source: Author

The experiments were performed in four different positions: (0) outside the plant, (1) within 0.25m inside the plant, (2) 0.5m inside the plant, and (3) 1 meter inside the plant, as shown in the scheme of Figure 56 and the in situ experiment picture, shown in Figure 57. These experiments were conducted sequentially, as specified in Table 17. Afterward, the data was transferred to a computer and went under treatment and evaluation. The Mini-wras collected values each one minute, totalizing more than 700 minutes of measurement and values obtained for the entire experiment.

Table 17 – Timetable for the air quality external measurement.

Measurement/plant	Plant 1	Plant 2	Plant 3	Plant 4	Duration
Outside the plant	11h-11:25	12:40-13:05	14:20-14:45	16:00-16:25	5 min + 20 min x4 = 1h40
0,25m	11:25-11:50	13:05-13:30	14:45-15:10	16:25-16:50	5 min + 20 min x4 = 1h40
0,50m	11:50-12:15	13:30-13:55	15:10-15:35	16:50-17:15	5 min + 20 min x4 = 1h40
1 m	12:15-12:40	13:55-14:20	15:35-16:00	17:15-17:40	5 min + 20 min x4 = 1h40
Total	1h40	1h40	1h40	1h40	1h40

Source: Author

4.4 Results

To observe how effective was the particle retention inside each shrub, it was calculated the ratio between the number of particles counted by the instrument inside the shrub ($\text{Inside}_{\text{conc}0,25}$, $\text{Inside}_{\text{conc}0,50}$, $\text{Inside}_{\text{conc}1,00}$) and the number of particles measured by the instrument outside the shrubs ($\text{Outside}_{\text{conc}0}$). The Equation 4.1 depicts the three different positions measured inside the plant.

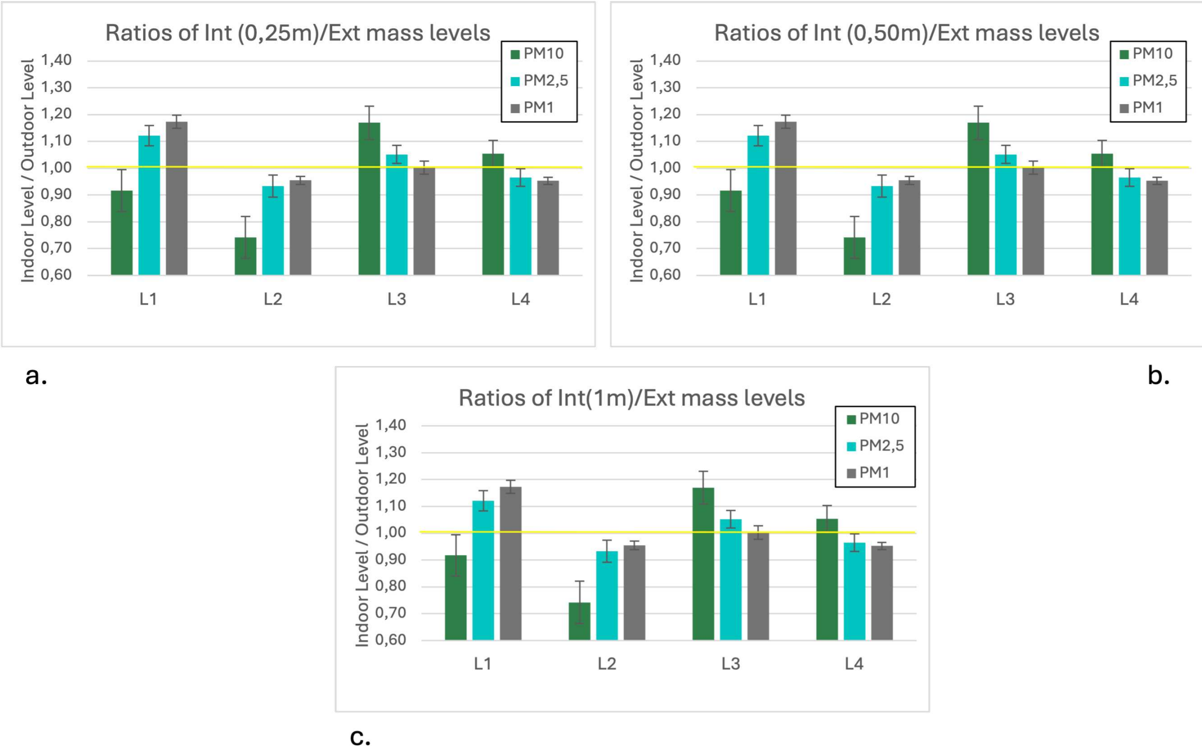
$$Remaining\ particle_{\ i} = \frac{Inside_{conc\ i}}{Outside_{conc0}} \tag{4.1}$$

- Remaining particle$_i$ smaller than 0 means that there were fewer particles inside the plant than in the outside air. The smaller this value, it can means higher the retention efficiency;
- Particle retention$_i$ greater or equal to 0 means that the number of particles inside the plant was higher than outside, meaning a not effectiveness on the retention.

The values were plotted on bar graphics according to each day's data. Figure 59 brings values calculated for each leaf and each pollutant on 17th April, as well as Figure 59 for the 18th April. The axis X represents the four plant types, and the axis Y brings the ratio values calculated based on Equation 4.1. A yellow line was added on the breaking point between retention and no retention results. For the 17$_{th}$ the Leaf 2 bars shows that all pollutants had better concentration in its internal space than in the outside air, mainly PM_{10} followed by $PM_{2,5}$ and PM_1 in all positions.

Following the same order of pollutants results was Leaf 1, but the only one with a positive retention effect was on PM_{10}. The other pollutants had even higher values in the shrub inside than outside. Leaves 3 and 4 had a mirrored result in their particle retention values; Leaf 4 was the only one that presented an effective retention scenario, with better values for smaller particle retention. On the other hand, Leaf 3 didnt look like having effectiveness in this methodology.

Figure 58 – Data comparation from the 17th April 2023 measurements.



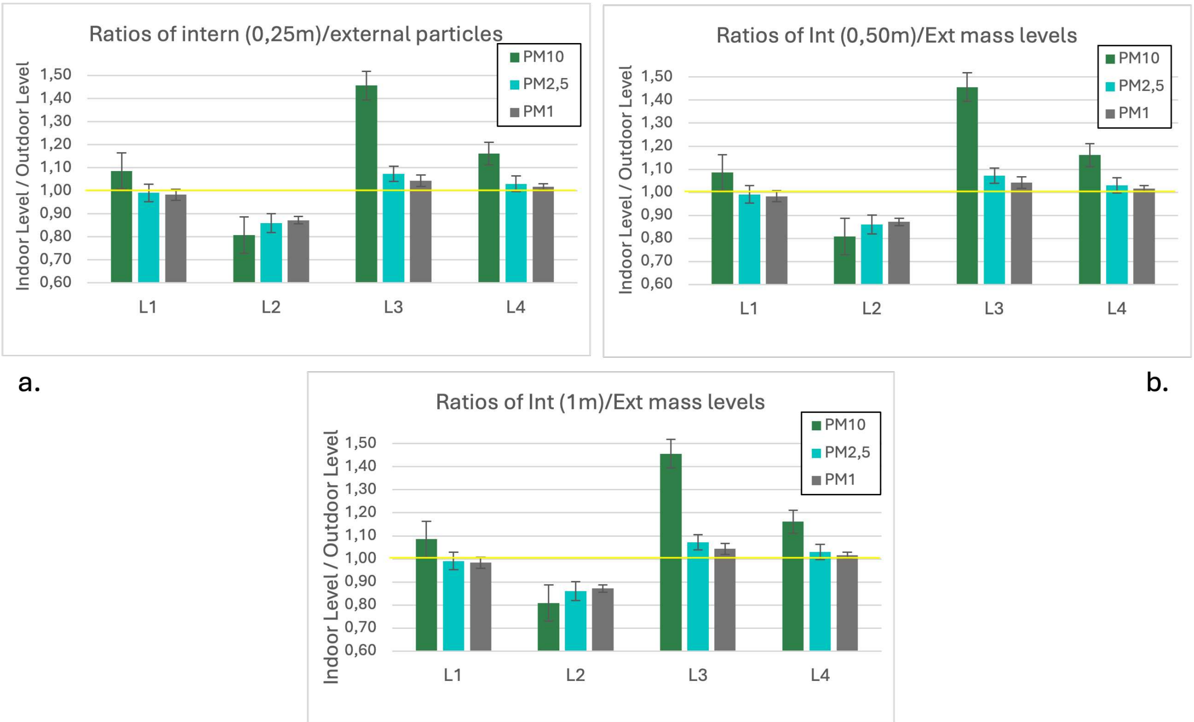
a. Observation on 0,25m shrub depth b. Observation on 0,50m shrub depth c. Observation on 1m shrub depth.
Source: Author

Following the 18th April observations, the scenario depicted by the numbers had some changes. To beginning with, Leaf 2 had its behaviour exactly as the 17th observations, with highly positive particles retention values, mainly for larger particles.

Leaf 1 had its retention with similar behavior as Leaf 3 and 4 in the previous scenario and in this day's observation, where the retention was more efficient for larger particles, however, going in opposition to the previous day's measures, only $PM_{2,5}$ and PM_1 presented effective retention.

Leaves 3 and 4 had no retention efficiency graphically shown. This can be associated with the resuspension phenomenon when the wind speed acting on the branches causes a resuspension of the already collected particles in the plant as a whole. This is an additional factor that, in a study where all environmental aspects are involved, the resuspension phenomenon could be added. As the focus of this research is to isolate just one variable, the particle deposition, the resuspension was not taken into consideration since the research's first steps. Additionally, the values observed here should take into consideration not just the leaf's filtration role but the brunches, the side of the plant, density, and the whole plant structure.

Figure 59 – Data comparation from the 18th April 2023 measurements.



a. b. c.

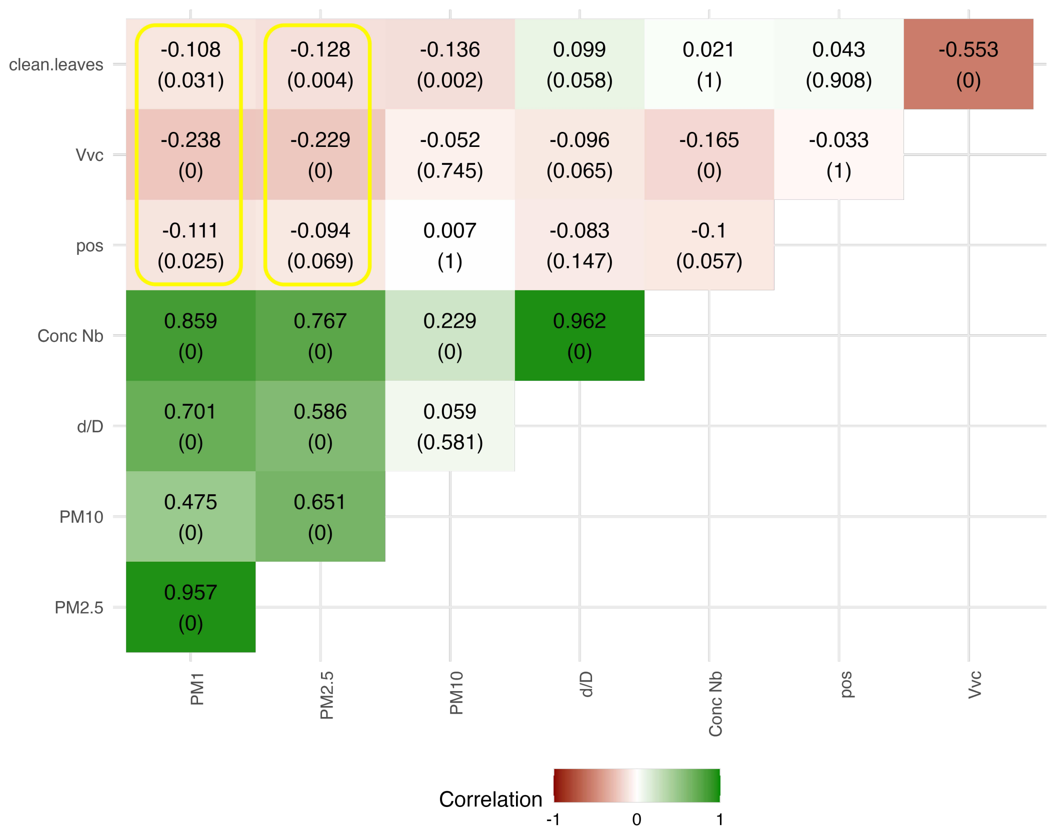
a. Observation on 0,25m shrub depth b. Observation on 0,50m shrub depth c. Observation on 1m shrub depth.
Source: Author

4.4.1 Statistical analyse

To start with, in this step, it is aimed to explain the total pollutants detected by the equipment as a function of the variables of the plants we have from the previous chapters. To achieve that, three statistical techniques were applied. The first one, a correlation matrix was plotted to check how the resulting variable from 2 - the Vvc - and from the 3 - clean leaves value - with the main measured pollutants concentration collected in this experiment and its collecting position. It was depicted, from all the values measured by the mini-was, the most relevant to the scientific community, that is, the PM1, 2.5, 10, d/D and conc Nb, in Figure 60.

Represented as a table, each cell in the matrix contains a correlation coefficient. If there is a value less than zero, there is a negative linear correlation; 0 suggests that there is no relationship, and for values greater than 0, there is a positive linear relationship (DATAtab Team, 2024).

Figure 60 – Pearson correlation matrix - Correlation (p-value)



Source: Author

As mentioned earlier, the closer the correlation value - value outside the brackets- is to 1 or -1, the stronger the correlation between the variables under analysis. Simultaneously, it's crucial to consider this correlation when the p-value, which is inside the brackets, is smaller than 0.05. Consequently, correlations with values below or near 0.05 are highlighted in yellow. These include (1) the correlation between PM_1 measured by the Mini-wras and the continuous variables "Vvc," "clean leaves," and the instrument position on the shrub, and (2) the correlation between the quantity of $PM_{2.5}$ measured by the instrument and the same continuous variables from the previous scenario. This analysis follows to determine how these three continuous variables explain the quantity of particulate inside the plants, as it will be formulated next through linear regression.

In this study, multiple linear regression is employed to examine the influence of several independent variables (Position distance, VVC value, Clean leaves weight) on a single dependent variable (PM_1 and PM_1). Known as a widely used method in both empirical social research and market research, multiple linear regression aims to elucidate the impact of various factors on a given variable. To assess the predictive and explanatory power of the regression model, researchers commonly rely on two key metrics: the coefficient of determination (R^2) and the standard estimation error (DATAtab Team, 2024).

R^2, also referred to as the variance explanation, quantifies the proportion of variance in the dependent variable that can be accounted for by the independent variables. These values can vary between 0 and 1. A higher R^2 value (near to one) suggests a better-fitting regression model. On the other hand, the standard estimation error, representing the standard deviation of the estimation error, provides insight into the accuracy of predictions. Visually, the standard estimation error reflects the spread of observed values around the regression line (DATAtab Team, 2024).

Initially, the multiple linear regression was done for all possible combinations, but as expected, the best values were for the above two scenarios. The general equations that would be generated consist of:

$$PM_1 = \beta_0 + \beta_1 Position + \beta_2 VVC + \beta_3 Clean\ leaves \tag{4.2}$$

Table 18 – Multiple Linear Regression results for PM_1 measured value

Coefficients	Estimated	P-value
Intercept (β_0)	31.916716	<2e-16
Position (β_1)	-0.032465	0.000897
Vvc (β_2)	-0.287264	<2e-16
Clean leaves (β_3)	-1.731791	<2e-16
Adjusted R-squared:	0.1484	

Source: Author

Applying the coefficient values, we obtain the Equation 4.3:

$$PM_1 = 31.91 - 0.03 Position - 0.28 VVC - 1.73 Clean\ leaves \tag{4.3}$$

The Equation 4.3 means that the quantity of PM_1 counted inside the shrub is negatively proportional to the position that the hose was displaced. This means that for a one-unit increase in the hose position, the predicted value of PM decreases by 0.03 units, holding all other predictors constant. In practice, we would have a smaller PM value and fewer pollutants when the hose is placed deeper in the shrub.

The coefficient for Vvc, -0.28, means that for a one-unit increase in Vvc, the predicted value of PM decreased by 0.28 units, holding all other predictors contact. In practise, higher the volume of core voids in the plant surface, less pollutants will be observed inside the plant.

Finally, for the clean leaf weight, for a one-unit increase on it, the predicted value of PM decreases by 1.73 units, holding all other predictors constant. In practice, heavier the leaf would have a slight improvement in particle retention. This is the parameter with a higher coefficient, meaning that is the one that has a higher influence on the PM_1 retention according to this model.

The R-squared value, also known as the coefficient of determination, measures the proportion of the variance in the dependent variable (in this case, PM) that is explained by the independent variables (predictors) included in the regression model.

In this case, an R-squared value of 0.1484 means that approximately 14.84% of the variance in PM is explained by the independent variables included in the model. In other words, the predictors (variables position, Vvc, and Clean leaves weight) collectively account for about 14.84% of the variability observed in the PM values. The remaining variability (85.16%) is not explained by the predictors included in the model and may be due to other factors or random variation.

So, while the model provides some insight into the relationship between the predictors and PM_1, there are other factors not accounted for by the model that also influence PM levels. Looking into the second scenario, now to predict the $PM_{2.5}$ quantity of particles inside the shrub we have the general Equation 4.4

$$PM_{2.5} = \beta_0 + \beta_1 VVC + \beta_2 Clean\ leaves \tag{4.4}$$

Table 19 – Multiple Linear Regression results for $PM_{2.5}$ measured value

Coefficients	Estimated	P-value
Intercept (β_0)	35.83595	<2e-16
Position (β_1)	-0.02900	0.0053
Vvc (β_2)	-0.30825	<2e-16
Clean leaves (β_3)	-1.97136	<2e-16
Adjusted R-squared:	0.1513	

Source: Author

Applying the coefficient values from the multiple linear regression analysis, the Equation 4.5 is generated:

$$PM_1 = 35.83 - 0.03 Position - 0.30 VVC - 1.97 Clean\ leaves \quad (4.5)$$

The Equation 4.5 means that the quantity of $PM_{2.5}$ counted inside the shrub is negatively proportional to the position in which the tube was displaced. This means that for a one-unit increase in the hose position, the predicted value of $PM_{2.5}$ decreases by 0.03 units, holding all other predictors constant. In practice, we would have a smaller $PM_{2.5}$ value, less pollutant when the hose is placed deeper in the shrub.

The coefficient for Vvc, -0.29, means that for a one-unit increase in Vvc, the predicted value of $PM_{2.5}$ decreased by 0.29 units, holding all other predictors contact. In practise, higher the volume of core voids in the plant surface, less pollutants will be observed inside the plant.

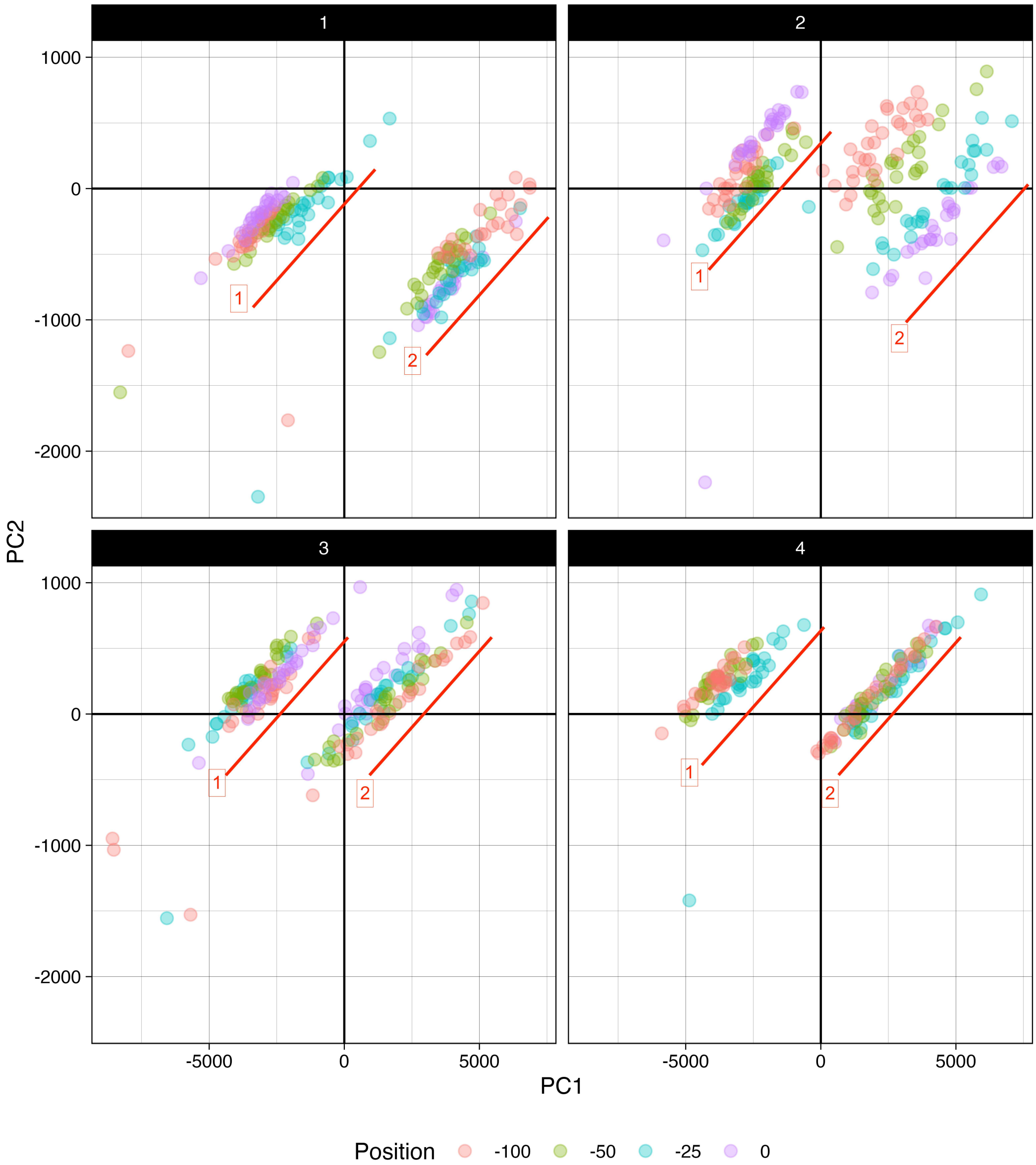
Finally, for the clean leaf weight, for a one-unit increase on it, the predicted value of PM decreases by 1.97 units, holding all other predictors constant. In practice, heavier the leaf would have a slight improvement in particle retention. This is the parameter with a higher coefficient, meaning that is the one that has a higher influence on the $PM_{2.5}$ retention according to this model.

The R-squared value, also known as the coefficient of determination, measures the proportion of the variance in the dependent variable (in this case, $PM_{2.5}$) that is explained by the independent variables (predictors) included in the regression model.

In this case, an R-squared value of 0.1513 means that approximately 15.13% of the variance in $PM_{2.5}$ is explained by the independent variables included in the model. In other words, the predictors (variables position, Vvc, and Clean leaves weight) collectively account for about 15.13% of the variability observed in the PM values. The remaining variability (84.37%) is not explained by the predictors included in the model and may be due to other factors or random variation. So, while the model provides some insight into the relationship between the predictors and $PM_{2.5}$, there are other factors not accounted for by the model that also influence $PM_{2.5}$ levels.

The second method used was the PCA, which aimed to observe if there was grouping formation within the database of PM_1, $PM_{2.5}$ PM_{10}, and d/D values, where d/D means the number of particles with a diameter smaller than one micrometer divided by the number of particles greater than one micrometer. Each leaf data distribution can be seen in Figure 61 below:

Figure 61 – PCA groups distribution according to leaf type and Mini-wras position inside the plant



Source: Author

The first observation in this graphic is the formation of two groups (highlighted in red), for each type of plant. This is connected with the two different days' measurements. When observing each grouping disposition, the values representing the number of pollutants inside the shrub in different positions are highly merged, with no general clear separation, except for Leaf 2.

In this plant observation, on the figure's right side, there is one clear position grouping separation, with values of 1m depth followed by 50 cm, 25 cm, and the outside air quality values. This observation open space to, in future works, a deeper study of how numerical values as umidity, wind speed, and the variables here studied, could have influenced in this singular result.

4.5 Conclusion

The retention pattern observed by Leaf 2 is highly consistent within different days of weather conditions and particle sizes, presenting in all measures a positive retention scenario, with the potential to be a good choice to be placed in the surrounding road infrastructure. A slight difference showed that larger particles were more retained.

The leaves 1, 3 and 4 haven't shown strong influence in the particles retention, with some values that can suggest particles resuspension inside the own plant, with more particles counting inside than outside the plant.

When bringing together the findings of all chapters' equations to understand the variable's influence on the phenomenon, both equations were obtained. They could explain between 14.84% and 15.13% of the PM_1 and $PM_{2.5}$ variance. This is not such a high value, giving space for improvements with the addition of new variables or adjustment of the already existing ones, or an increase in the dataset, for example, in future works. Still, in both scenarios, the hose position in the plant and the Vvc value presented similar coefficient values, while the clean weight of the plant showed higher influence on the $PM_{2.5}$ equation, suggesting the heavier leaves would be able to retain larger particles.

5 CONCLUSION AND SUGGESTIONS

In the initial phase of exploratory research, a key finding emerged: the core volumetric value measured on leaf surfaces could serve as a viable variable for characterizing leaf surfaces. This discovery diverged from previous literature, which had not yielded conclusive results regarding leaf surface roughness as a KPI for particle retention. This suggests that leaves with higher superficial volumetric voids may indeed exhibit greater pollutant retention capabilities.

Moreover, considering not only the Core Void Volume (Vvc) but all volumetric parameters, the four studied plants exhibited a distinct pattern in covariance results. Leaves 1 and 2 showed highly similar outcomes, while Leaf 3 displayed a different behavior. Leaf 4 could not be grouped with either of the plants, resulting in a proposition of three groups of plants based on these parameters: (1) Leaves 1 and 2, (2) Leaf 3, and (3) Leaf 4.

Subsequently, when examining particles from transportation infrastructure present in roadside air pollution, it was noted that soil and aggregate particles were retained by leaves in a manner more similar to each other than to rubber particles. This observation suggests various factors at play, including differences in chemical composition, particle size, shape, humidity, and wind speed.

Bringing the laboratory experiment into the field, it was observed that both PM_1 and $PM_{2.5}$ retention was most strongly influenced by the weight of clean leaves. This implies lower particle concentration in the air when leaf weight is greater. Furthermore, consistent with the findings of the second chapter, a higher Vvc value corresponds to fewer particles inside the plant, indicating that the plant retained more pollutants, thereby preventing them from passing through the green barrier. Additionally, wider barriers resulted in greater particle retention.

Overall, both qualitative and quantitative observations revealed each plant's unique behavior and advantages concerning different factors, suggesting that a combination of different plant species could be advantageous for pollutant retention. Additionally, besides the retention objective, the use of the Air Pollution Tolerance Index (APTI) to ensure that leaves are resistant to the pollutant environment and do not harm the plants is a crucial consideration.

5.0.1 Future works

For future research, the following measures can be taken:

- Increase in the plants' data collection, incorporating additional plant species;
- Padronize the scanned surfaces, able to cover all studied leaves specificities;
- Amplify the laboratory experiment structure to collect weather data, such as room humidity and temperature.
- Obtention of the laboratory particles characterization, both chemical and shape treats, that can be used as input to study the phenomenon.
- In the open-air experiment, a simultaneous air quality assessment of the outside air quality and the different plant positions' tube placement could bring a more accurate database.

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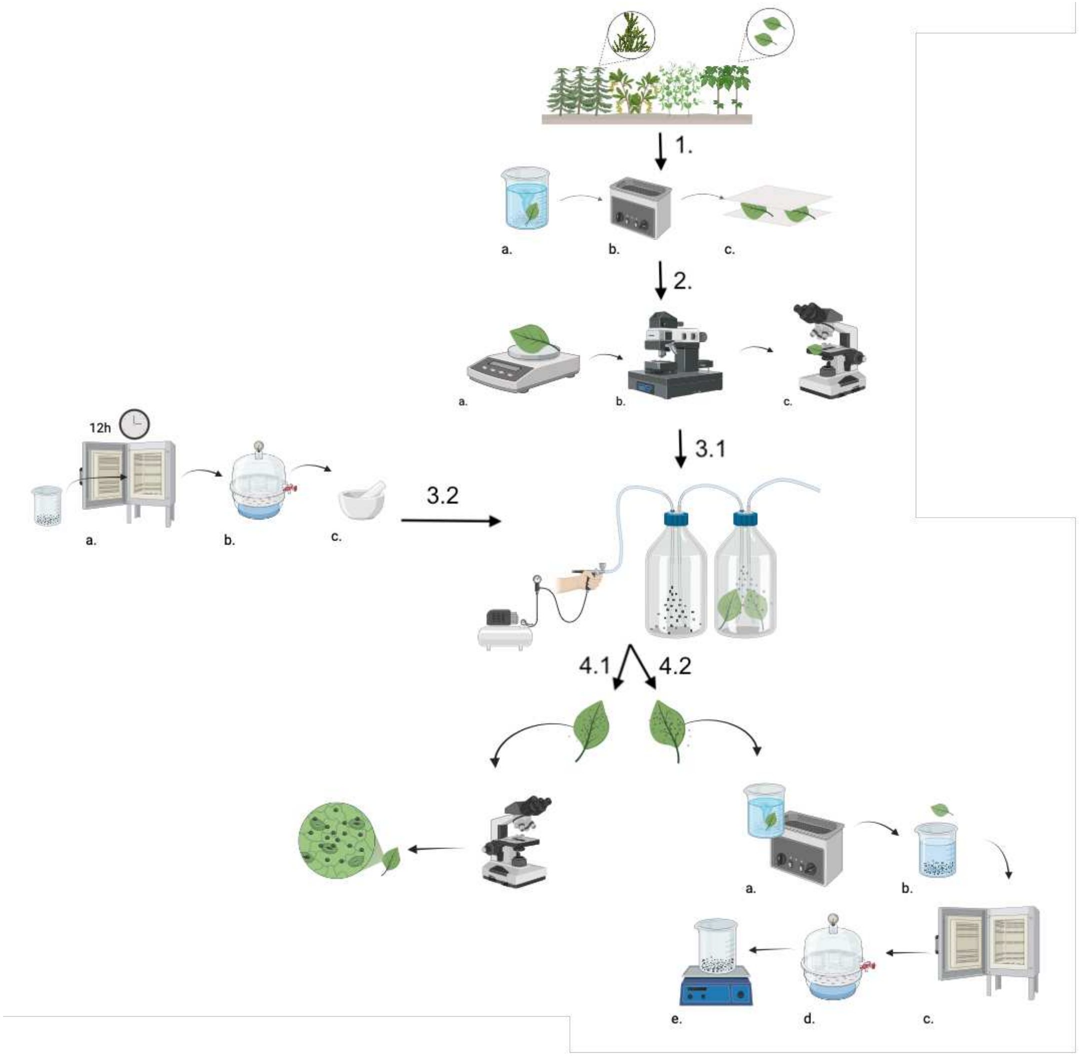
ANNEX A

Figure~62 –~Bottles polluted air entire experiment preparation



Source:~Author