Evaluating the potential of vegetation to capture pollutants in urban environment

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Abstract. Urban environments are subject to a concentration of air pollutants that may cause several health problems and discomfort to their inhabitants. Pollutant emissions are related with several anthropogenic sources, such as biomass heating systems in buildings, the vicinity of industries and especially the intense road traffic. Improvements in air quality and consequent mitigation of climate changes are essential to achieve a more sustainable urban environment. The presence of vegetation sprawled in urban areas is important to achieve this goal. This paper analysis the capacity of several plant species to capture atmospheric pollutants, and specifically Particulate Matter (PM) in urban environment. The adopted methodology focuses on measuring and calculating the ability to absorb PM by three plant species - Parthenocissus quinquefólia, Hedera Helix and Quercus palustris Muenchh - in periods of exposure to pollutants from 3 to 14 days. The specific removal of air pollutants by plants is a parameter influenced by several factors, such as the type of associated green infrastructure, leaf area, leaf density, plant species, location, exposure time and the type of the polluting source. From this research it can be concluded that the type of plant and its morphological characteristics are more influential than the size of its leaves.

Keywords: Green areas, Urban pollution, PM capture

1 Introduction

In 2018, 55 % of the world's population was living in urban areas and forecasts suggest that this percentage will increase to 68 % by 2050 [1]. The growth of the urban population has created impacts on the environment, whether directly or indirectly. If we compare the growth of human population and the CO_2 emissions in the world since 1900, we verify that these two indicators are correlated, as it can be seen on Figures 1 and 2. It means that it is not possible to keep increasing world population without increasing pollutant emissions till reaching unsustainable levels. The increase of temperature in cities; the higher concentration of air pollutants; and the increase in noise, mainly from road traffic, are the most significant impacts [2]. The presence of vegetation is fundamental for reducing the levels of pollutants in urban areas [3] [4].

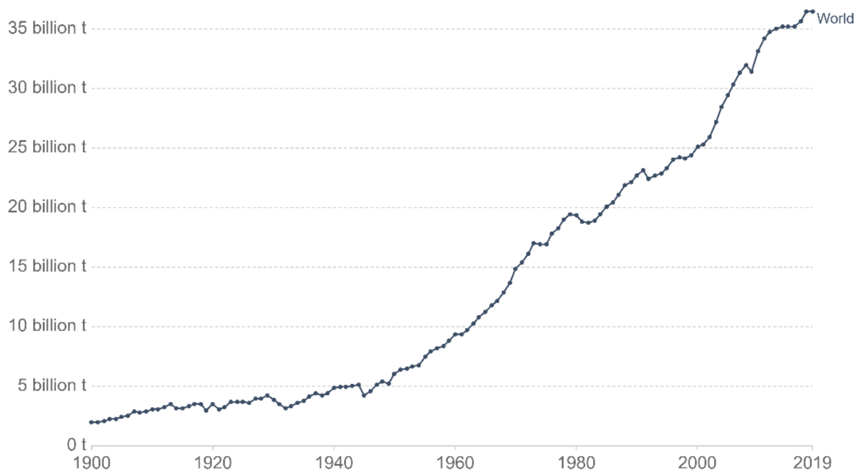


Fig. 1. World CO_2 emissions growth since 1900 (adapted from [5])

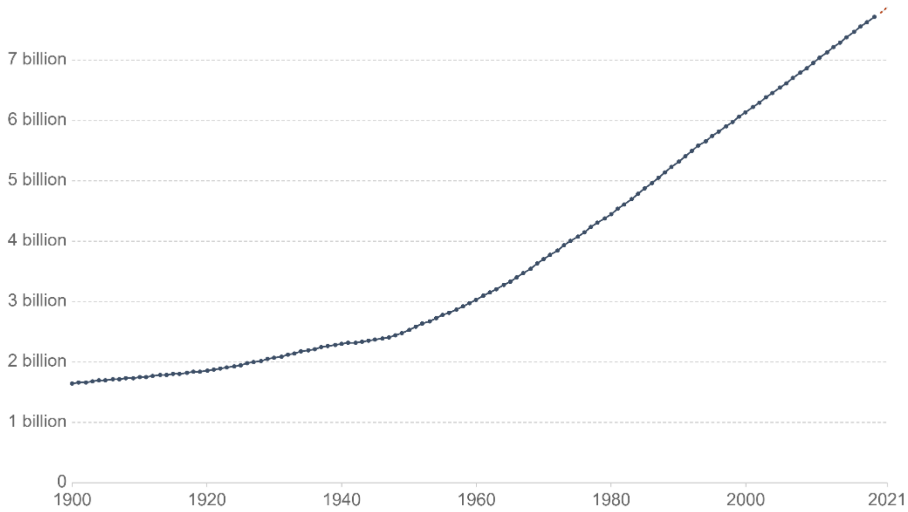


Fig. 2. World population growth since 1900 (adapted from [6])

Vegetation acts as porous bodies that influence the dispersion patterns of air pollutants, creating a barrier between polluting sources and receptors, as well as helping to reduce toxins in the air [7]. Apart from enhancing air quality, vegetation may provide protection against solar radiation, reduce the heat island effect felt in centers and increase thermal comfort in cities [8].

Urban planning should be able to combine social, economic and environmental values [9]. It needs to contemplate the increase of green areas in urban environments to gain recognition. Despite the commonly accepted benefits of vegetation, the impact generated using different species in urban areas needs to be quantified and qualified. This research aims to study the deposition and capture process of atmospheric pollutants of two plant species in urban areas, namely in the vicinity of roads with traffic concentration.

2 Urban Air Pollution and Green Infrastructure

Polluting emissions are mostly related with activities of anthropogenic origin, such as the burning of fossil fuels used in electricity generation, transport, industry and household equipment.

According to Silva et al. [10] [11], the main atmospheric pollutants in urban areas are nitrogen oxides (NO_x), carbon monoxide (CO), ozone (O_3), PM10 and PM2.5.

PM is the term used for particles present in the air, including ash, dust, smoke and small liquid droplets. PM can be classified according to their size, considering the average aerodynamic diameter of the particles. The coarse inhalable particles (PM10) have diameters that vary between 2.5 µm and 10 µm, and the fine particles (PM2.5) have diameters below 2.5 µm. PM can remain in the air for long periods of time, others, however, due to their weight, fall because of gravity and only stay in the air for a few seconds. Some particles are emitted directly into the atmosphere, and are thus considered to be of primary origin. Kumar et al. [12] state that transport is the main source of air pollution in urban environments. Transport is now subject of environmental pressure in the European Union due to its contribution to climate change.

2.1 Atmospheric Deposition

Atmospheric deposition allows to remove air pollutants by gravity sedimentation. There are two types of atmospheric deposition:

Dry deposition - settling of gases and particles from the atmosphere to different surfaces that occurs in the absence of precipitation. It is characterized as a sequence of three main processes: first, there is the turbulent transport of gases and particles from the atmosphere to the thin layer of static air immediately above the surface, on which there will be deposition; second, there is transport by diffusion to the organic surface in that thin layer of air; third, the pollutants are captured through the organic surface by adsorption, absorption or intercepting [13].

Wet deposition - gases and particles are intercepted and removed from the atmosphere by drops of water such as clouds, rain, snow or fog. The amount of pollutants removed by wet deposition depends on the amount of precipitation [13]. It is estimated that around 70 % of the particles present in the external photosynthetic surface of the plants are completely removed after continuous precipitation with an average duration of 5 days [14]. The fall of precipitation is more effective in eliminating the coarse fraction from the atmosphere than the fine fraction [10].

According to Chen et al. [14], humidity and low temperatures have the greatest impact on the removal of PM10, which indicates the importance of relative humidity in local analyses to capture pollutants. Litschke et al. [15] reports that the fundamental effect of moisture on atmospheric deposition is related to the hygroscopicity of the particles, and that their size varies due to their absorption and discharge of water. Therefore, the local relative humidity generates a change in the deposition characteristics of the particles as it increases the size and weight of the particles, which influences the speed of deposition. In addition to the physical characteristics of the particles, i.e., size and shape, atmospheric deposition is subject to the influence of other factors, such as wind speed and direction, pressure and temperature, atmospheric conditions, relative humidity, and the chemical characteristics of particles and gases, in addition to the characteristics of the surfaces on which they will be deposited. The morphological characteristics of the plants, i.e., species and leaf type, are also relevant issues [15].

2.2 Selection of Plant Species

Kumar et al. [7] suggest some measures when selecting plant species for PM capture. When choosing the species is fundamental to know its tolerance to air pollution in Urban environment, remaining healthy and efficient in their mitigation. It is also important to know their characteristics, such as leaf area index, total leaf area and height are considered fundamental for determining the total capacity for removing air pollutants [16]. Persistent leaf plants are preferable as their filtering action is more continuous over the time. Invasive species should not be used, as well as species that are poisonous or that may cause allergic reactions. The introduction of non-indigenous species into the ecosystem can lead to predation, competition with native species, and the transmission of pathogens or parasites, seriously affecting biological diversity, economic activities and public health. It is also essential to pay attention to road safety, as dense vegetation can cause loss of visibility or create obstacles to the circulation of drivers, cyclists and pedestrians.

In facades and green roofs, herbaceous species, shrubs and small trees should be selected depending on the conditions to which the plants will be subjected to. Plants may receive solar radiation in different amounts depending on their position regarding shading obstacles and orientation. Concerning coverage, height is an important factor, as well as the variation in temperatures throughout the day.

2.3 Green Infrastructures

Green Infrastructures (GI) can be defined as a strategically planned network of natural and semi-natural structures. GI should be considered as a priority to integrate in the urban design and planning processes [17]. They serve different needs in the urban areas in which they are integrated, such as water purification, air quality and climate change mitigation by reducing the annual temperature increase and the heat island effect. It can also provide protection against solar radiation [8]. GI allows to soften the artificial finishing of buildings and pavements, introduces color, reduces reflections and reduces noise by increasing acoustic absorption.

GI can minimize exposure to atmospheric pollution [18] by creating natural barriers such as vertical green systems, green roofs, trees, green barriers and urban forests, protecting human health [4] [7] [18]. They can also help in urban stormwater management [19]. Dover [8] refers that by increasing the permeable soil area the capacity of precipitation absorption is also increased, and so the probability of floods is reduced.

Being surrounded by a more natural environment, people are motivated to perform outdoor exercise and leisure activities and to socialize, reducing stress. The proximity of green areas together with the creation of ecologic routes, such as pedestrian and cycle eco-paths, encourage the use of environmentally friendly transport to the detriment of vehicles powered by fossil fuels. Contact with nature helps to foster environmental awareness, especially for younger generations. Urban gardens are an increasing trend in large cities. They allow to produce organic and healthy food associated with reducing industrial production and less waste. Local food production also help to reduce pollutant emissions resulting from the transport of goods.

Investment in GI can contribute to local economic growth. Gore et al. [20] state that GI enhance the attractiveness of neighborhoods. According to Leskinen et al. [21] (2020), sustainability is a significant success factor for real estate, for example certifying green buildings and neighborhoods had a positive impact on property value.

3 Case studies

In this section, a brief description of the sampling sites, monitoring program and procedures are presented. The adopted methodology was focused on measuring and forecasting the ability to capture air pollutants through photosynthetic surfaces. The procedures were based on Singh et al. [22] and Yanmei et al. [23].

3.1 Sampling site location

The experimental work was carried in Guimarães, North of Portugal. Guimarães' climate is characterized by cool winters and moderate to hot summers. The average minimum temperature of the coldest month varies between 2 and 5 ºC, the average maximum temperature of the hottest month varies between 23 and 32 ºC. Guimarães presents high levels of precipitation due to the passage of frontal surfaces, combined with the effect of the mountains, presenting annual precipitation totals above 1500 mm. It has intense economic and tourist activities, and therefore is an urban center subject to increasing levels of pollution. Collection sites were selected based on exposure to polluting sources such as road traffic. More details are available in Martins [24].

Sampling took place in the parishes of Urgeses and São Paio. The first sampling area, shown in Figure 3 a), was Dr. Ricardo Marques Street in the city center. The species at the M1 site was Parthenocissus Quinquefólia deciduous. In this location, there were no barriers or obstacles between the receiver and the source. The main source of air pollution was road traffic in the city center.

a) b)

Fig. 3. a) Dr. Ricardo Marques Street, Guimarães – 41°26'28.1"N 8°17'20.6"W, source CM-Guimarães; b) Road N105 6-8, Guimarães - 41°25'30.6"N 8°18'15.8"W, source first author.

The second sampling zone (Figure 3 b)), is located in an industrial zone in Guimarães, next to the national two-way road EN105. The species in this zone is the persistent leaf Hedera Helix. The harvests were carried out at 1.5 m from the ground, and the main polluting source was road traffic. No barriers or obstacles exist between the receiver and the source.

For each selected site, three harvest points spaced 10 meters and with a height of 1.5 meters were defined, based on the methodology preconized by Singh et al. [22]. The selection of several collection points prevents the destruction of the samples due to abnormal events such as pruning or cutting during maintenance actions.

The harvests were carried out at intervals of 3 to 4 days. The first harvest was performed after 3 days of exposure, the 2nd after 7 days, the 3rd after 10 days and the 4th after 14 days. Laboratory tests were performed on the same day as the collection, avoiding sample degradation. The leaves used for PM capture measuring were cleaned with water and dried with tissue paper, what established the temporal beginning of the campaign. The average temperature registered during the campaign was 26.5 ºC, with an average relative humidity of 45 %, with no precipitation registered.

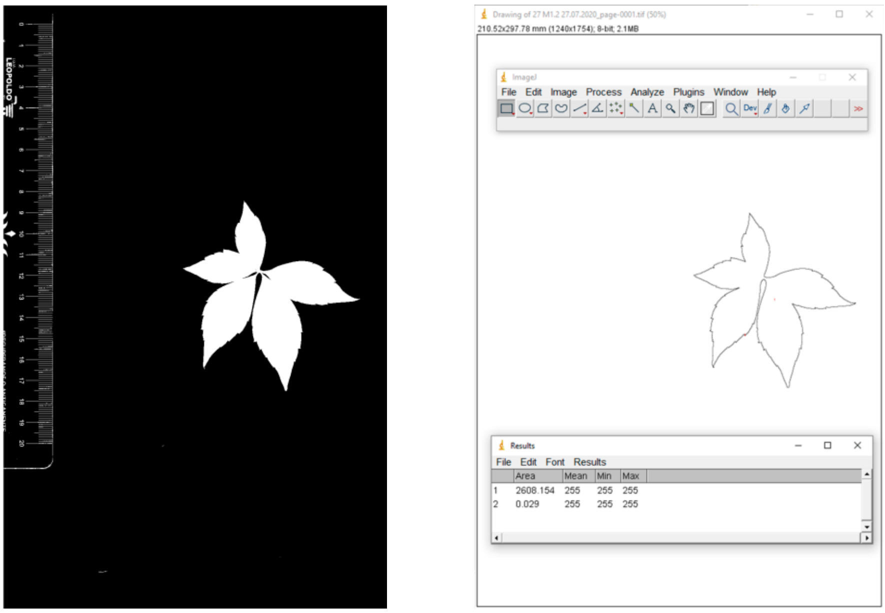
During the test, the collected pollutant particles with dimensions greater than 8 µm were weighed. In order to perform that, paper filters with 8 μm porosity were used, submitted to drying and weighing procedures before use. Filters were placed in an oven at 60 ºC between 8 to 16 hours to dry. The cooling time of the filters was respected, and they were weighed quickly so that the filter remains were free of humidity.

After collecting the leaves "in situ", the samples were taken to the laboratory and placed in glass beakers with a previously measured amount of distilled water (depending on the leaf sizes, different amounts of solution were used) and magnetic stirring was used to start the washing process. The leaves were then drained between two glass rods to minimize the loss of pollutants that were still attached to the leaf surface.

After finishing the filtration, the filters were not removed immediately because they were damp and still very fragile. They were allowed to dry a little inside the funnel and were then removed using metal tweezers. Metallic tweezers were used to handle the filters in order to avoid transmission of particles and any grease on the skin or gloves.

When the filters were ready, they had to be put back in the oven to dry between 8 am and 10 am. After filtering, the used filters are dried. After drying, the filters are weighed and the test ends.

Leaf Area (LA) was also calculated. LA is the surface of the plant with photosynthetic capacity. According to Favarin J. et al. [25], the LA is a parameter indicative of the productivity of a plant, considering that its photosynthetic yield is directly linked to the number of leaves per unit area. The leafs were scanned and the images obtained were transformed into JPEG, monochrome files (Figure 4 a)) The determination of the area of leafs was made using ImageJ® image analysis software (Figure 4 b)).



a) b)

Fig. 4. Determination of the area of Hedera Helix leaf using: a) scanner and monochromatic image manipulation; b) image analysis software ImageJ® [23].

3. Results and Discussion

The obtained results were compiled and analyzed in order to assess the relation between atmospheric deposition overtime of the different species of vegetation.

The Leaf Area calculated of the species tested is presented in Table 1.

Table 1. Leaf Area (LA) of species tested.

Species	Sample	LA(m^2)	Accumulated LA (m^2)	Average LA (m^2)
	M1.1	0,0042		
	M1.2	0,0052		
P. Quinquefólia	M1.3	0,0072	0.023	0.0054
	M1.4A	0,0057		
	M1.4B	0,0048		
	M2.1	0,0061		
	M2.2	0,0027		
Hedera Helix (L2 Site)	M2.3	0,0025	0.014	0.0034
	M2.4A	0,0029		
	M2.4B	0,0030		

In the tests carried out, the process of capturing air pollutants with an equivalent diameter approximately greater than 8 µm (PM) is presented in Table 2 and Figure 5.

Table 2. Results of PM8 captured by tested species.

Species	Sample	Exp. Days	PM8 Capt.(mg)	Total PM8 Cap(mg)
	M1.1*	3	-0,50	
	M1.2	7	0,60	
P. Quinquefólia	M1.3	10	2,40	14,30
	M1.4A	14	5,80	
	M1.4B	14	5,50	
	M2.1	3	0,20	
	M2.2	7	1,10	
Hedera Helix	M2.3	10	5,10	10,80
	M2.4A*	14	10,30	
	M2.4B	14	4,40	

*samples rejected

The relationship between the capacity to capture PM and the various characteristics of the plants was observed, such as the leaf area, type of plant, location, emission of the polluting source.

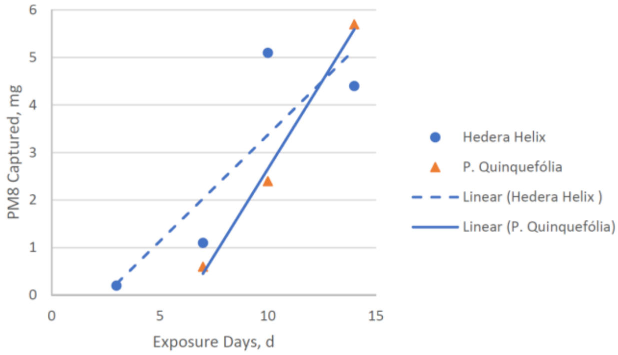


Fig. 5. Results of PM8 captured by tested species

When analyzing the specific removal values (mg / m2) of each analyzed species, it was observed that the exposure time influences the amount of pollutant captured, this relationship is shown in the following trend line equations:

Parthenocissus Quinquefólia: SR = 175.81d (R^2 = 0.643)

Hedera Helix M: SR = 425.57d (R^2 = 0.625)

Where,
SR – Specific Removal mg/m^2
d- Days of exposure

By analyzing Figure 5, the exposure time influences the amount of pollutant captured. The Hedera Helix has the best line fit for the data analysed

4. Conclusions

This research aimed to observe the ability of vegetation to capture pollutants in an urban context. This ability is influenced by several factors, such as the type of green infrastructure, total leaf area, plant species, location, time of exposure and the polluting source type.

In this study, two sampling sites were selected and the capacity for capturing PMs by plant leaf surfaces was calculated. Two species of plants were tested, Parthenocissus Quinquefólia and Hedera Helix. Plants are able to retain Particulate Matter (PM) through the process of atmospheric deposition of PM on the leaf surfaces as a result of gravity sedimentation.

In the tests performed, the samples of Parthenocissus Quinquefolia located at M1, captured a total of 14.3 mg of PM8 with an accumulated leaf area of 0.023 m^2. The Hedera Helix species, located in M2, captured a total of 10.8 mg of pollutants with an accumulated leaf area of 0.014 m^2. The Parthenocissus Quinquefolia species has the higher value of PM8 captured. It was also noticed that, although the species Hedera Helix registered the lowest values of tested leaf area, this species recorded high values of captured PM8. According to the observed results, the time of the exposure of vegetation to the polluting sources influences the amount of pollutant captured by leaf surfaces.

Analyzing the daily removal of pollutants, the following values were collected: the Parthenocissus Quinquefólia species (M1) had an average leaf area of 0.0054 m^2 and the average specific daily removal was 40.83 mg/m^2.24h; the Hedera Helix species (M2) had an average leaf area of 0.0034 m^2 and the average specific daily removal was 94.47 mg/m^2.24h. Therefore, Hedera Helix proved to be the most efficient in daily retention of polluting particles.

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