D 2.4

Report on the selection of plant species for enhancing NBS performance on air quality and climate neutrality

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ACRONYMS AND ABBREVIATIONS TABLE

Acronym / Abbreviation	Meaning
E-Institute	E-ZAVOD, ZAVOD ZA PROJEKTNO SVETOVANJE, RAZISKOVANJE IN RAZVOJ CELOVITIH RESITEV
UNIPASSAU	UNIVERSITAT PASSAU
ICS	INSTITUTE OF COMMUNICATION STUDIESSKOPJE
LEITAT	ACONDICIONAMIENTO TARRASENSE ASSOCIACION
GCE	UNIVERSITEIT ANTWERPEN
PATRAS	DIMOS PATREON
POR	POR CONSULT DOO ZA POSLOVNO SAVJETOVANJE
PRATO	COMUNE DI PRATO
AITIIP	FUNDACION AITIIP
OC	OPENCONTENT SOCIETA COOPERATIVA
Belfast Council	Belfast City Council
BURST	BURST NONPROFIT KFT
ICLEI	ICLEI EUROPASEKRETARIAT GMBH
RRA-PODRAVJE	REGIONALNA RAZVOJNA AGENCIJA ZA PODRAVJE – MARIBOR
BOKU	UNIVERSITAET FUER BODENKULTUR WIEN
BP18	BUDAPEST FOVAROS XVIII. KERULET PESTSZENTLORINC-PESTSZENTIMRE ONKORMANYZATA
BREDA	GEMEENTE BREDA
BeeoDiv	BEEODIVERSITY
QUB	THE QUEEN'S UNIVERSITY OF BELFAST
OPERATE	FONDAZIONE OPERATE
UniLeeds	UNIVERSITY OF LEEDS
IETU	INSTYTUT EKOLOGII TERENOW UPRZEMYSLOWIONYCH
Katowice City	KATOWICE - MIASTO NA PRAWACH POWIATU

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EC	European Commission
GA	Grant Agreement
M no.,	Month, e.g. 1 of project implementation
NBS	Nature Based Solutions
EU	European Union
KPI	Key performance indicator
GI	Green Infrastructure
PM	Particulate Matter
VOCs	Volatile Organic Compounds
BVOC	Biogenic Volatile Compound
BVOCs	Biogenic Volatile Compounds
SOA	Secondary organic aerosols
NHMCs	Non-methane volatile organic compounds
GC-MS	Chromatography with Mass Spectrometry

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EXECUTIVE SUMMARY OF DELIVERABLE

Purpose and scope

This deliverable (D2.4) represents the outcome of task 2.4, 'Selection of plant species to enhance NBS performance, which is part of WP2, "Overall NBS Assessment". The objective of WP2 is to develop various tools and documents related to the selection of NBS best suited for urban challenges (T2.3), the assessment of the benefits of their implementation (T2.1 and T2.2), and the optimization of their air remediation capabilities (T2.4).

In this context, the deliverable presents the results of a study that combines literature research and laboratory experiments to identify plants with the most promising air phytoremediation properties. This contributes to the WP2 objective O.2.3, "To enhance NBS performance by testing at laboratory scale different plant species and their effectiveness on removing air pollutants", which falls within the LC-CLA-11-2020 scopes "Contribution of NBS to combatting air pollution, reducing allergy potential and mitigating GHG" and "optimal solutions and appropriate typologies fitting to different contexts (climatic, environmental and socio-economic) and different urban designs".

Intended readership/users

This deliverable is a valuable resource for a large range of audiences inside and outside the UPSURGE project:

- Cities partners: the first objective of T2.4 is to assist the UPSURGE cities in their plant selection to implement in their demo sites. Therefore, cities and UPSURGE partners working in close collaboration with the cities are the main readership of this report. At the beginning of the task, the plants usually planted in the 5 partners cities were communicated, and the determination of their air phytoremediation properties were prioritized.
- European Regenerative Urban Lighthouse: the present deliverable brings valuable knowledge to the Urban Regenerative Urban Lighthouse developed in UPSURGE by allowing it to assist the cities in plant selection in their NBS site.
- Researchers: the deliverable consists of state of the art on-air remediation by plant species and presents experimental work conducted with different pollutant categories (gas and particles). It is intended to provide scientific value that can support research on phytoremediation and NBS implementation.

Contribution to other WPs and Deliverables

The deliverable primarily contributes to WP5, where cities implement various NBS on their demonstration sites. The work presented in this document has contributed to the selection of plants that the cities will plant on their respective sites. At the beginning of task 2.4, each partner city provided a list of plants commonly used in their municipality. The collection of pollution-reducing properties of these species were prioritized, and other species were recommended based on the results of task 2.4.

Summary of key findings and recommendations

Keys findings

Considering the main urban air contaminants (particles, NO_2 and VOCs), results have shown that the plants exhibit significantly different phytoremediation properties from one another.

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Regarding particles, it was shown that coniferous present superior trapping capability due to the morphology of their leaves compared, for example, to broadleaved species. Moreover, it was observed that trees planted in cities are not usually the best particles remover. Therefore, improving particle removal in urban green areas might be possible through a better selection of plant species.

Data on gaseous pollution removal, such as NO_2 and VOC, was more difficult to obtain, but it was possible to identify some species with higher removal potential.

When selecting plant species, it is important to consider their potential emissions of polluting and allergenic compounds. Some plants emit above-average levels of BVOC. These pollutants can interact with other chemical compounds to form ozone or organic aerosols that are harmful to air quality. Pollen is another compound emitted by plants that can directly affect human health because of its allergenicity. Data on BVOCs and pollen emitted by plants were searched and presented in this document.

Finally, experimental work was conducted in the laboratory on a selection of plant species, but no conclusive results were obtained, and further development is necessary.

Recommendations

A table summarizing the air phytoremediation potential of various plant species on the main pollutants of the urban environment, as well as their potential for pollen emission and biogenic volatile organic compounds, has been shared with the partners and is also presented in this document.

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1 Deliverable overview

Considering air quality in the urban planning process is of growing interest as most urban areas currently exceed recommendations and standards (WHO, 2021) on air contaminant level. Careful integration of vegetation in urban areas can improve air quality (EEA, 2018).

Nature-Based solutions (NBS), implemented into the urban environment (parks, gardens, green corridors, green spaces, blue spaces, etc.), provide multiple benefits such as climate change adaptation, biodiversity conservation, health and wellbeing, economics benefits, social equity, and community engagement (Kolokotsa, et al, 2020).

Upsurge project provides the solution by a European Regenerative Urban Lighthouse as a reference framework and network to enable targeted NBS implementation supported by a multi-modal sensing system and blockchain-based AI digital ecosystem for cities, providing them knowledge and guidance in regenerative transition.

In the WP2 "Overall NBS Assessment", the actions described in this deliverable support plant species selection for optimising NBS performance on air quality and climate neutrality. Results complement other Upsurge outputs like the NBS Registry and the NBS Matchmaking matrix, giving the cities a complete decision tool.

This deliverable D2.4 contains a systematic literature review conducted to summarize the understanding of relevant air phytoremediation processes and to identify the most efficient plant species for removing urban air pollutants (particle matter (PM), nitrogen oxides (NOx), and volatile organic compounds (VOCs)). This study identifies papers assessing different kinds of plant species (trees, shrubs, and herbaceous) and their pollutant removal capacity. The characteristics of the species affecting the removal of pollutants are presented, and an exhaustive list of plant species, along with their efficiency, in the form of a classification, is presented in Annex.

Laboratory experiments complemented the review, 15 herbaceous plant species were selected, and their abilities to remove NO_2, VOC and particles were evaluated under controlled conditions in fumigation chambers experiments. The results aim to support the plant selection to be implemented in the Upsurge demos site and to become a tool for the lighthouse consultancy service (WP7).

2 Introduction

Air pollution in urban areas is a serious problem for health and has become an urgent global concern with the fast development of urbanization and industrialization. Although clear signals of this problem are evident in large and megacities (Karagulian et al., 2015; Gargiulo et al., 2016), smaller cities, towns, and even small human settlements in remote Antarctica (Chaparro et al., 2007) experience pollution as well. Air pollution has detrimental negative effects on human health (Silva et al., 2016), crop production (Lapina et al., 2016), ecosystems (Liu et al., 2013) and biodiversity (Clark and Tilman, 2008).

This has stimulated a large amount of research on the best approaches to counter urban environmental pollution (Zhang et al., 2015). It has been proven that the implementation of green areas, such as urban forests and others green spaces, positively affects air quality and climate remediation. Green infrastructure (GI) significantly reduces air pollution by effectively capturing dust particles, absorbing pollutants, and preventing dust transportation. Many studies have shown that plants can significantly affect air quality by absorbing atmospheric pollutants (Zhou et al., 2010). Appropriate GI also brings other benefits, including microclimate regulation, stormwater attenuation and improved mental and physical health (Baraldi et al., 2019).

To optimize the impact of GI implementation, understanding the positive and negative aspects of each considered species is crucial (Yang et al., 2015; Hirons et al., 2018). To this end, this deliverable identifies plant species with superior air pollutant removal capabilities.

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In the first section, the main air pollutants in urban areas were identified, the phytoremediation processes described, and the plant characteristics that affect their effectiveness at removing pollutants. The second section presents some studies that identified specific species relevant for their impact on air pollutant removal (a more complete presentation of species is given in the Annex). The last section describes the laboratory experiments conducted in the frame of WP2 that study the capacity of a selection of plant species to remove NO_2, toluene and particles.

3 AIR PURIFICATION BY PLANTS

3.1 POLLUTANTS OF INTEREST

3.1.1 NITROGEN DIOXIDE

Nitrogen dioxide (NO_2) is a highly reactive and toxic gas and a major contributor to air pollution. The major source of NO_2 is the combustion of fossil fuels by power generation and transportation devices like aeroplanes and cars (Baumbach, 1994; Butterbach-Bahl et al. 2011). NO_2 is not only a critical primary pollutant but it can also be converted into various secondary pollutants, such as ozone (O_3) and fine particulate matter ($PM_{2.5}$) under specific photochemical conditions (Honour et al., 2009; Yu et al., 2019). NO_2 is a potent irritant to the respiratory system and has been linked to various health problems, including asthma, bronchitis, and cardiovascular disease. It is particularly harmful to vulnerable populations such as children, the elderly, and those with pre-existing respiratory or cardiovascular conditions.

The concentration of nitrogen dioxide (NO_2) has increased in the air with a growing economy and the increased use of urban motor vehicles, becoming a major pollutant in urban areas. The World Health Organisation (WHO), EU Commission and the Department for Environment, Food and Rural Affairs (DEFRA) all set a chronic NO_2 health guideline aiming to prevent respiratory illnesses and decreases in lung function, the main symptoms of long-term exposure (especially in children) (Gubb et al. 2022). In recent years, efforts have been made to reduce NO_2 emissions through improved fuel efficiency standards, promoting alternative transportation modes, and using clean energy sources. However, NO_2 remains a significant public health concern and a major global challenge for air quality management.

3.1.2 PARTICULATE MATTER

Particulate Matter (PM) is one of the most important atmospheric pollutants worldwide, a major problem in urban environments that poses a significant threat to public health. PM is a complex mixture of solid and liquid particles suspended in the air, with sizes ranging from a few nanometres to tens of micrometres. PM is generated by a wide range of sources, including traffic, residential burning, industry, construction, and natural sources such as dust and wildfires. In urban areas, traffic-related PM is often the most significant source (Karagulian et al. 2015). PM is also generated in the atmosphere (secondary particle) by reaction of gaseous compounds including nitrogen oxides (NOx), sulphur dioxide (SO_2), ammonia, and volatile organic compounds (VOCs) (Bosco et al., 2005).

PM often contains highly toxic components, such as heavy metals, polychlorinated biphenyls, polycyclic aromatic hydrocarbons, and other potential carcinogens (Mo et al., 2015), increasing public exposure to hazardous air pollutants related to cardiovascular and neurodegenerative diseases (Du et al., 2014; Maher et al., 2019).

Smaller particles can penetrate deep into the lungs and enter the bloodstream, leading to a range of health problems, including respiratory and cardiovascular disease, cancer, and premature death. PM's composition and size distribution can vary widely depending on the source and atmospheric conditions. In urban areas, $PM_{2.5}$ and PM_{10} are monitored (refer respectively to PM with a diameter of 2.5 microns and 10 microns or less). Ultrafine particles, which are less than 0.1 micrometres in

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diameter, are of particular concern as they can penetrate deep into the respiratory system and may be more harmful than larger particles.

PM is subject to regulation in many countries, with national and international air quality standards aimed at reducing exposure to these harmful particles. Mitigation measures include improved public transportation, encouraging the use of electric vehicles, and promoting energy-efficient buildings. However, the problem of PM pollution in urban areas remains a significant public health challenge and requires continued efforts to reduce emissions and protect vulnerable populations from exposure. In response to the health risks posed by particle contamination, many countries have implemented regulations to reduce PM levels in urban areas. These regulations often include setting limits on the amount of PM allowed in the air, as well as measures to control the sources of PM.

In the European Union (EU), for example, there are regulations to limit the amount of $PM_{2.5}$ and PM_{10} in the air. The EU's Air Quality Directive sets legal limits on these pollutants, and member states are required to take action to meet these limits such as reducing emissions from industrial and transport sources, promoting clean energy use, and encouraging public transport. Similarly, in the United States, the Environmental Protection Agency (EPA) sets National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$ and PM_{10}. The NAAQS specify the maximum amount of PM allowed in the air, and states are required to develop plans to meet these standards.

Despite these regulations, particle contamination remains a significant challenge in many urban areas. In some cases, PM levels may exceed legal limits, particularly in regions with high industrial or traffic-related pollution levels. To address this issue, ongoing efforts are needed to reduce PM sources and improve air quality in urban areas. For example, by a combination of policy interventions, technological innovations, and community engagement to promote sustainable and healthy urban environments.

3.1.3 Volatile organic compounds

Volatile Organic Compounds (VOCs) are a group of organic chemicals that have low boiling points and can easily vaporize into the air at room temperature. They are commonly found in many everyday products, such as paints, cleaning agents, solvents, and adhesives. In urban environments, VOC contamination is a major concern due to the large number of emission sources, such as factories, transportation, and construction activities. Once released into the atmosphere, VOCs can react with other pollutants to form secondary pollutants, such as ground-level ozone, which can have detrimental effects on human health and the environment. Additionally, VOCs can cause short- and long-term health effects such as eye irritation, headaches, respiratory issues, and even cancer.

3.1.4 Biogenic Volatile organic compounds

Biogenic volatile organic compounds (BVOCs) are a class of biological contaminants emitted by vegetation, leading to the formation of ozone, secondary organic aerosol (SOA) and others (Calfapietra 2013). BVOCs play a crucial role in signalling between plants and the environment, acting as attractants for pollinators and distractions for herbivores, and can include compounds such as isoprene, monoterpenes, ethylene, fatty acids, and constituents of essential oils. Trees and other vegetation can serve as sources of BVOC emissions in urban environments. The amount and composition of BVOCs emitted by plants can vary widely depending on factors such as temperature, humidity, light intensity, and plant species. BVOC emissions can be enhanced by environmental stresses such as drought, temperature extremes, and air pollution. In urban areas, trees and other vegetation can help mitigate air pollution's effects by removing pollutants from the air. However, they can also contribute to secondary organic aerosols (SOA) formation, worsening air quality. Some BVOCs have been found to be highly reactive and can contribute to the formation of ground-level ozone, a key component of smog. To mitigate the effects of BVOC emissions in urban areas, some researchers have suggested planting low-BVOC-emitting trees in urban environments. More research

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is needed better to understand the role of BVOCs in urban air quality and to develop effective strategies for mitigating their effects.

Because biogenic emissions are evaluated to be about 9 times greater than anthropogenic ones, it is important to consider the emission potential of urban plants to emit BVOCs (Wróblewsk y Jeong 2021). Monoterpenes account for the largest proportion of secondary organic aerosol (SOA) formation (35-40%), followed by isoprene (15-32%) and sesquiterpenes (10%) (Wróblewsk y Jeong 2021). As a result, numerous studies recommend planting trees in urban settings that emit low levels of BVOCs.

3.1.5 Carbon dioxide

Carbon dioxide (CO_2) pollution is a major concern in urban environments due to the large amount of emissions produced by human activities such as transportation and industry. High levels of CO_2 in the atmosphere can negatively impact human health and the environment. However, plants have the ability to remediate CO_2 through the photosynthesis process naturally.

Photosynthesis is the process by which plants use sunlight, water, and CO_2 to produce energy and release oxygen. During photosynthesis, plants absorb CO_2 from the air through tiny pores on their leaves called stomata. The CO_2 is then used to create glucose, a type of sugar that the plant uses for energy. The by-product of this process is oxygen, which is released into the atmosphere. In urban environments, plants can play a crucial role in mitigating the effects of CO_2 pollution. Trees and other greenery can absorb large amounts of CO_2, reducing the overall levels in the air.

However, it is important to note that not all plants are equally effective at remedying CO_2 pollution. Some plant species are better adapted to absorb CO_2 than others. Planting new green spaces is important to maintain and preserve existing urban forests and greenery. Urban development and land use changes can lead to the loss of green spaces, which could result in increased levels of CO_2 in the air.

3.2 Phytoremediation mechanisms

Phytoremediation is a process that uses plants to remove or neutralize pollutants from the soil, water, or air. Plants extract, accumulate, immobilize, and transform the pollutants present in the environment, reducing their toxicity. The entire phytoremediation process involves several separate but complementary processes, which vary considerably depending on the nature of the pollutant and the physiology of the plant (Agarwal et al. 2019).

Plant leaves are the part of the plants that interact the most with air pollutants. A plant leaf has a complex structure and is composed of several layers of tissues, each with specific functions. The key constituents of a plant leaf are listed below:

- Cuticle: The cuticle is a waxy layer that covers the upper and lower surfaces of the leaf, which helps to prevent water loss and protect the leaf from damage.
- Upper epidermis: This is a single layer of cells that covers the upper surface of the leaf. It is transparent to allow light to pass through and contains stomata, small openings that allow gas exchange.
- Palisade mesophyll: The palisade mesophyll is a layer of cells beneath the upper epidermis that contains many chloroplasts, which are responsible for carrying out photosynthesis.
- Spongy mesophyll: The spongy mesophyll is a layer of loosely arranged cells interspersed with air spaces. This layer also contains chloroplasts and is responsible for gas exchange and photosynthesis.
- Lower epidermis: This is a single layer of cells covering the leaf's lower surface. It contains stomata and is responsible for gas exchange.
- Stomata: Stomata are small openings on the leaf's surface that allow for gas exchange, including carbon dioxide intake for photosynthesis and releasing oxygen and water vapour.

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- Guard cells: Guard cells are specialized cells that surround each stoma and regulate its opening and closing. They control the exchange of gases and the loss of water from the leaf.
- Trichomes: trichomes are small hair-like structures that can be found on the leaves, stems, and other parts of many plants. These structures are often visible to the naked eye and can be found in many shapes and sizes. Trichomes serve several functions, including protection from herbivores and other environmental stresses, water conservation, temperature regulation, and absorption of water and nutrients.

Overall, the leaf structure allows efficient gas exchange and photosynthesis while minimizing water loss and protecting the plant from damage.

Plant leaves and stems act as adsorbers for particles and can fix them in their waxy layer (Beckett et al. 1998). The filtration process is plant specific and depends on leaf characteristics such as the density of trichomes and the structure and composition of epicuticular waxes (Weyens et al., 2015).

Regarding gaseous pollutants like CO_2, CO, NO_x and O_3, the plants' main entry points are the stomata, wax, and cuticles (Agarwal et al. 2019). High pollution levels can induce plant stress and disturb their growth and metabolism (Weiyuan et al., 2020; Chaparro et al., 2011; Kapuganti, 2020; Sheng and Zhu, 2018). For NO_2, studies have shown that the degree of plant injury is directly proportional to the time and intensity of NO_2 exposure (Sheng Q., 2019a, 2021b) and that amino acid metabolism is inextricably bound with abiotic stress tolerance (Batista-Silva et al., 2019), being peroxidase (POD), catalase (CAT), and superoxide dismutase (SOD) are plant cells main protective enzymes that help prevent oxidative damage caused by scavenging oxygen free radicals and peroxides and intercept or reduce their formation (Zhong, 2013).

Therefore, alterations in malondialdehyde (MDA) levels occur due to lipid peroxidation. This process involves the interaction of free radicals with polyunsaturated fatty acids within cell membranes, generating reactive aldehydes like MDA. MDA is often used as a biomarker for oxidative stress and lipid peroxidation; its content is an index of the degree of plant membrane injury and senescence (Qu et al., 2018). Lower MDA content in plants has been shown to improve drought resistance (Hu et al., 2018).

Experiments using ^{15}N have demonstrated that vegetation surfaces act as a NO_2 sink transforming it into leaf nitrite, nitrate, and amino acids. This indicates that either NO_2^- is converted to NO_3^- in the apoplast and/or is transferred into the cytoplasm (Chaparro-Suarez et al., 2011). Gebbler et al. (2000) reported that NO_2 uptake depends mainly on stomatal aperture, and deposition through cuticle or water films is almost negligible. NO_3^- enters the leaves through stomata and generates NO_3 by nitrate reductase in the cytosol, where it enters the chloroplasts. NH_4^+ is formed under near infrared activity and enters the assimilation pathways as an ammonium salt, this enrichment can cause damage to plant growth (Chuan et al., 2020), yellowing and shedding of leaves (Sheng et al., 2022). Nitrogen metabolizing enzymes activity reflects plants' health status and nitrogen assimilation capability. Asparagine plays an important role in the long-distance transport of N and acts as an N storage pool in plants under adverse environments (Ahanger and Agarwal, 2017). Plants could enhance the tolerance to NO_2 by increasing N assimilation (Abhinandan et al., 2018).

Regarding VOCs, a plant should be selected based on its low BVOC emitting capacity. Plants generate BVOC to protect themselves against pathogens, herbivores, and other environmental stresses and attract pollinators. Overall, plants generate BVOCs through complex metabolic pathways influenced by various environmental and genetic factors. Plant production and emission of BVOCs can have significant ecological and atmospheric implications, as they can affect climate, air quality, and the interactions between plants and other organisms.

However, plants are also able to uptake VOCs from the atmosphere via leaf stomata or cuticles. VOCs enter the plant system where they are degraded, stored, or excreted (Weyens et al., 2015). Plants can metabolize VOCs through various enzymatic and non-enzymatic reactions, which can transform the VOCs into less toxic or more easily excreted compounds. For example, some VOCs can be oxidized to

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form carbon dioxide and water, while others can be conjugated with other compounds to form less volatile substances. Once metabolized, the plant can excrete the VOCs through various pathways, including the stomata, roots, or cuticles. Plant roots and related microorganisms also play an important role in assimilating and degrading VOCs.

Similar to NO_2, exposure to a high concentration of VOCs and ozone can be harmful to plant metabolism and can cause various symptoms of stress and damage, like leaf injury, reduced photosynthesis, and necrosis (cell death) in plants. Exposure to VOCs can also lead to reduced plant growth, crop yield, and increased disease susceptibility.

3.3 Plants characteristics for air purification

3.3.1 Characteristics

3.3.1.1 Particulate matter

Air pollution is removed from the air by three main processes: wet deposition (e.g., transfer of pollutants by falling rain/snow), chemical reactions (e.g., gas phase reactions in the atmosphere), and dry deposition (e.g., transfer of gaseous and particulate pollutants to various surfaces, including trees) (Rasmussen et al., 1975). Plants remove gaseous air pollution by uptake via the leaf stomata after surface deposition. Trees also remove pollution by intercepting airborne particles, which are retained on the plant surface. However, the intercepted particles are often resuspended into the air or transported to the ground by rain or leaf and twig fall (Nowak, 1994).

The surfaces of leaves and bark of vegetation accumulate PM, and this accumulation increases with air turbulence in the tree crowns. Therefore, trees collect more pollutants, including the coarse and fine PM, because of their size than shorter vegetation (Fowler and Cape, 1989).

Species with trichomes and/or rough leaf surfaces are considered more effective PM accumulators (Burkhardt, 2010). In general, conifer trees have a rough surface and a higher stomata density, allowing more particle adsorption on the leaf surface. Freer-Smith et al. (2005) attributed the differences in particle adsorption and accumulation in conifer and broadleaf trees to the leaf structure. Differences in leaf morphology and structure contribute to differences in particle retention ability due to leaf surface roughness. The morphology of the leaf surface allows the particles retention ability of conifers to be stronger than tree species with glossy leaf surfaces (Chai et al., 2002; Gao et al., 2007). Beckett et al. (2000) have published similar findings regarding broad-leaved species, highlighting that rough leaf surfaces accumulate PM more effectively than those with smooth surfaces. In addition, needles of coniferous trees, which have a unique microstructure and produce a thicker epicuticular wax layer, generally capture PM more effectively than broadleaved species (Beckett et al., 1998).

In summary, plant particle adsorption ability is affected by plant size and leaf characteristics, leading to significant differences in particle retention between species (Dai et al., 2013; Fang et al., 2007; Chavez-Garcia et Gonzalez-Mendez, 2021). Larger stomata increase particle retention ability (Wang et al., 2010a, b, Liu et al., 2013; Yao et al., 2014)) high leaf roughness (Jia et al.,2012) and size of microstructure increases dust retention ability.

Furthermore, the plant adaptation to the environment will affect the strategy (Pal et al., 2002) found that plant leaf pubescence becomes longer, and leaf texture becomes rougher in seriously polluted regions; Shaowei et al. (2012) reflects the effect of the external atmospheric environment on the plant leaf shape structure. In the seriously polluted region, the stomata can be blocked or half blocked by particles, and the pubescence becomes longer and softer. To adapt to the environment, the plant speeds up its metabolism (Nowak et al., 2013); in a less polluted region, where the $PM_{2.5}$ concentration is relatively low, the plant to adapt to the environment, the chance of the plant surface contact particles is small, the friction is small, so the surface roughness is low.

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3.3.1.2 Gaseous pollutant

Regarding gaseous pollutants, studies showed that trees can reduce concentrations of gaseous contaminants by deposition to plant cuticles and stomatal uptake (Tiwary et al., 2006; McDonald et al., 2007;). One study shows that urban vegetation in Guangzhou, China can remove 312.03 Mg of SO_2, NO_2 and particles on an annual basis (Jim and Chen, 2008).

Some plants exhibit high tolerance to NO_2 and have great potential to absorb it. This can contribute to lower NO_2 levels in ambient air and alleviate environmental problems, including haze and acid rain (Erin and Ronald, 2019; Grundstrom et al., 2015). The NO_2 exchange flux between plants and the atmosphere has been widely researched. The main factors that influence these fluxes are the ambient NO_2 concentration and the stomatal conductance of different plants (Johansson, 1987; Thoene et al., 1996). Stomatal conductance, and therefore NO_2 assimilation, can also be impacted by ambient factors such as temperature, photosynthetic active radiation, and relative humidity.

Plant characteristics are not the only control on the effectiveness of the NBS for air quality benefits, but other parameters should also be considered; for example, seasonal variation (temperatures, humidity, heating, precipitation, wind), pollution level, pollutant characteristics (water soluble, anion and cation levels, sources, mobility) and chemical reactions, city design, topography, solar radiation, radiation cooling, or heat circulation among others, will also condition the effectiveness of the measure established.

Another important characteristic of the plant that influences air quality is its BVOC emission level. The detrimental effects of BVOCs on air quality are explained in section 4.1.4. The emission of BVOCs is closely linked to several plant characteristics, including:

- Leaf: Young leaves generally emit more BVOCs than older leaves.
- Temperature: High temperatures increase BVOC emissions, while low temperatures decrease emissions.
- Light: Light intensity and quality influence BVOC emissions. For example, plants may emit more BVOCs when exposed to UV-B radiation.
- Water availability: Drought stress can increase BVOC emissions, while plants under well-watered conditions emit fewer BVOCs.
- Plant species: Different plant species emit different types and quantities of BVOCs. For example, conifers are known to emit high amounts of volatile terpenes.
- Stress and damage: Plants may increase BVOC emissions in response to stress or damage, such as herbivory or pathogen attacks.

The specific BVOCs emitted by plants can also vary depending on these factors. BVOCs play important roles in plant communication, defence against herbivores and pathogens, and regulation of atmospheric chemistry. Therefore, understanding the link between plant characteristics and BVOC emissions is important for studying plant ecology and the global carbon cycle.

3.3.2 Classification

The ability of NBS to remove pollutants is affected by tree crown morphology and city design (e.g., city canyon orientation) (Hofman et al., 2013, 2014). For the reduction of air pollutants, an important role is played not only by trees but also by the structure, texture, and location of GI components. Alonso et al. (2011) and Baumgardner et al. (2012) highlighted the role of peri-urban forests for improving air quality by removing ozone and PM in the atmosphere of large metropolitan areas (e.g., Madrid and Mexico City). In addition, Escobedo et al. (2009) studied the spatial heterogeneity and air pollution removal by urban forests, and the influence of vegetation on air quality has been reviewed in several articles (Abhijith et al., 2017; Janhall, 2015; Salmond et al., 2016 Hewitt et al., 2020). A key conclusion is that it is important to carefully plan the placement and type of urban vegetation to improve effects on urban air quality. An appropriate selection of species further optimises the implemented solution's efficiency.

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Some authors have established a ranking of the species' capacity to improve air quality (mainly on particles) based on their characteristics, concluding that the most frequently occurring tree species in the cities were not the best performers regarding particle accumulation. The capacity to remove $PM_{2.5}$ of conifer species (Yang et al., 2015) was generally above other tree species but are rarely implemented in cities.

The effectiveness of trees in directly removing particles is influenced by both environmental factors and the biophysical features of the trees themselves. Various environmental factors such as weather conditions, urban layout, and airborne particle concentration can significantly impact the number of particles that are intercepted by trees. In addition, the characteristics of trees and their configuration as a group, including planting density, spatial arrangement, and total leaf surface area, can also have an impact that can be optimized through GI design. Furthermore, the ability of individual trees to remove particles is determined by factors such as tree size, canopy texture, leaf characteristics, and growth habits (Yang et al., 2015).

According to that, Yang et al. (2015) ranked tree species by estimating their PM removal efficiencies (based on their characteristics), their potential negative impact on air quality by plants (emission of pollen and BVOC), and their tolerance to urban environments. To rank, the rating of variables was aggregated using a simple additive method of punctuation (P). Variables used for ranking removal efficiencies were Type (3P evergreen conifer, 2P evergreen broadleaf, and 1P deciduous); Size (3P height>20 m; 2P Height between 10m and 20m; 1p Height between 5 and 10 m); Growth rate (3P Fast; 2P Medium; 1P Slow); Canopy structure (3P Dense canopy, fine texture; 2P Canopy with medium density, medium texture; 1P Open canopy, coarse texture); Leaf complexity (3P Bi– or tri–pinnately compound, or scale–like leaves in conifer; 2P Pinnately or palmately compound; deeply–divided or lobed; 1P Intact single leaf); Leaf size (3P Average size of leaf less than or equal to 5 cm; 2P Average size of leaf between 5 cm and 20 cm; 1P Average size of leaf more than 20 cm); and Leaf surface feature (3P Rough, hairy, resinous, sticky, scaly, scurfy, glutinous, tufts; 2P Ciliate, velvety, pubescent, waxy, glaucous, downy, slightly hairy, fuzzy; 1P Smooth surface).

Variables used to rank the negative impact on air quality by plant species were the allergenic level of pollen (3P Highly allergenic; 2p Medium; and 1P Low) and BVOC emission rate (3P Emission rate of isoprene and monoterpenes more than 10 g day^{-1} $tree^{-1}$; 2P Emission rate of isoprene and monoterpenes between 1 g day^{-1} $tree^{-1}$ and 10 g day^{-1} $tree^{-1}$; 1P Emission rate of isoprene and monoterpenes less than or equal to 1 g day^{-1} $tree^{-1}$). To rank the suitability for urban environments, the variables used were the tolerance of poor soil drought, SO_2, O_3 and NO_2 (3P Strong; 2P Medium; and 1P Low), and the resistance to pest and disease (3P Strong; 2 P Medium and 1 P susceptible to multiple pests and diseases).

Classification of species can also be made by direct measurements. Removal efficiency of different contaminants (NO_2, VOC or particles) by plant species can be evaluated in the laboratory (from specimens collected in situ or growth in a controlled environment). For example, many studies collect plant leaves in cities and measure the amount of particles accumulated or their assimilation of NO_2 using the ^{15}N isotope. Efficient species can be identified by this method. However, a direct comparison between different studies is generally impossible because of the variability in the environmental conditions and experimental protocol. The classification is generally restricted and valid within each individual study, and the comparison between different studies must be done with care.

Atmospheric chemistry modelling is another possibility to classify plant species. Donovan et al. (2005) have developed a Quality Score (UTAQS classification) to quantify the effects of trees on urban air quality. The model considers the chemical composition of air, the concentration of species, the photochemical production, loss rates and anthropogenic emissions, the deposition velocity, the height of the boundary layer, the emission rate, changes in solar input and temperature in a typical daytime for mid-latitude continental boundary layer in midsummer, dry deposition and other specific

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consideration in the study area. Regarding vegetation parameters, foliar biomass, urban stress effect, and the species composition of the urban forests are considered.

3.3.3 Pollen emission

Pollen plays an important role in the reproductive process of plants, and various plant species produce it at different times of the year. Air pollution affect plants, and its pollen can be used as biomarkers to evaluate the genotoxicity of pollution in urban areas. Previous studies have shown that exposure to pollutants can cause anatomical deformations in plants, resulting in visible damage to their structures (Fleck et al., 2014, 2015; Cardoso et al., 2017). Pollen is also affected, and the genotoxic effects of different stressors, such as heavy metals (Calzoni et al., 2007) and atmospheric pollutants (Carneiro et al., 2011) can be evaluated by pollen abortion test, that can be used for the biomonitoring of polluted environments. The target cells can accumulate harmful substances and express lethal mutations that affect the development of pollen (Misík et al., 2006). The formation of aborted grain results from genotoxic processes that affect the maturity and fertility of the grain. Because several air pollutants are known to cause damage to genetic material, the pollen abortion assay is a reliable method for evaluating air pollution-induced genotoxicity in urban areas (Fleck et al., 2015).

Pollen can cause allergic reactions in humans and other animals and can be assimilated as an air pollutant in urban environments. Its presence in the air can lead to respiratory problems for people, when pollen is inhaled, it can cause the immune system to perceive it as a threat and release histamines to attack it. This immune response can cause symptoms such as sneezing, runny nose, itchy eyes, congestion, or asthma attacks. In an urban environment, plants should be selected to avoid generating large quantities of allergenic pollen as much as possible.

The prevalence of pollen allergy has strongly increased in the last thirty years, and air pollution is one of the incriminated factors. It has been shown that pollutants may interfere during pollen development in the plant (Schoene et al., 2004) and interact with pollen during airborne pollination. Previous laboratory works performed on the interaction between pollutants and pollen from various species with contradictory results (Motta et al., 2006; Shiraiwa et al., 2012), and studies have shown that NO_2 may induce a decrease in allergen-IgE recognition, as well as in the protein concentration of Phleum pratense pollen extracts (Rogerieux et al., 2007). NO_2 pollution increases allergic disorders, not only directly acting as an irritant affecting the mucosa of the eyes and respiratory airways but also as an adjuvant of the pollen allergic sensitization for susceptible patients living in urban areas. (Chassard et al., 2015).

The next section presents a review of studies that propose a classification or comparison between different plant species for pollution remediation. An effort was made to find species covering all categories necessary for the implementation of NBS. The criteria were size (trees, shrubs, herbaceous plants) and pollutants representative of urban contamination (Particles, NO_2, VOCs and CO_2 were covered). The potential allergenicity of those species was also researched in the literature, especially in the work of Cariñanos y Marinangeli (2021), Cariñanos et al. (2014, 2016, 2017) and Ortolani et al. (2015). Those studies present different databases useful to identify plant species (especially trees) that are susceptible to emitting large amount of allergenic pollen. The taxa with the highest allergenic potential are those included in the *Betulaceae, Oleaceae, Cupressaceae, Moraceae*, and *Salicaceae* families, which include some of the best represented genera in urban forests of the Mediterranean region, such as *Cupressus, Morus, Olea, Juniperus, Fraxinus, Populus* or *Salix*. More exhaustive information on the allergenic potential of specific plant species can be found in the paper of Cariñanos y Marinangeli (2021) (150 species classified in 4 classes of allergenicity from Nil to very high) and also on some databases such as Specifind (http://www.greeninurbs.com/p_specifind/) or i-Tree Eco (https://www.itreetools.org/tools/i-tree-eco) in which the pollen emission are given in a scale from 1 to 10). When available, the pollen emission level of the plant identified for their particle and gas removal abilities was added on a 1 to 3 scale.

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4 Identification of plant species with optimized phytoremediation properties

4.1 Removal of Particles

4.1.1 Trees

$PM_{2.5}$ removal efficiency varies among tree species. Identifying species presenting the higher removal efficiency to be implemented in NBS is important. Research has demonstrated that trees with greater leaf surface areas exhibit higher efficiency in removing particles. Trees possessing dense canopies and fine textures tend to have higher surface roughness, facilitating particle interception. Evergreen conifers possess these desirable characteristics and consequently have higher particle removal efficiency. Furthermore, as they maintain their high leaf surface areas throughout the year, their effectiveness in removing particles is consistently high (Yang et al. 2015).

Another consideration for species selection is the stress tolerance of the urban environment. An urban environment is stressful for plants because of compacted soils, droughts, diseases, and air pollutants (Pauleit, 2003; Nielsen et al., 2007; Jutras et al., 2010). A low tolerance to those conditions can lead to a tree with a poorly developed canopy that will be less effective at removing particles from the air. Negative impacts of the presence of trees must also be considered as they are sources of BVOC and pollen emission.

Considering the parameters presented above, a classification of the most suitable species for air quality can be established. One example can be found in Yang et al. (2015), who present a ranking of the most common tree species for particle accumulation according to seven biophysical variables:

- Type: Evergreen conifer, evergreen broadleaf, deciduous
- Height at maturity: (>20m, 10-20m, <10m)
- Growth rate: fast, medium, slow
- Canopy structure: Dense canopy with fine structure, medium density with medium texture, open canopy with coarse texture
- Leaf complexity
- Leaf size
- Leaf surface feature (rough, hairy, resinous, sticky)

The list established in the study of Yang et al. (2015) showed that cities tend to implement trees of common genera and species and that among the ten most frequently occurring species, the $PM_{2.5}$ removal efficiency of London plane (*Platanus acerifolia*), Silver maple (*Acer saccharinum*) and honey locust (*Gleditsia triacanthos*) were ranked above average and have a good tolerance to urban conditions. The last observation can be explained by the fact that urban tree species were mainly selected for their aesthetic values and adaptability to urban environment.

As stated above, conifer species were found to have the best properties for removing air particles. However, none were in the top 20 of the most occurring species implemented in cities. There is, therefore, an opportunity to promote the use of this kind of species in urban greening programs, for example. Some of the best coniferous trees that present optimal characteristics for particle removal are *Juniperus virginiana*, *Cupressus sempervirens*, *Juniperus chinensis*, *Thuja occidentalis* and *Pinus strobus*. However, some of these need to be avoided because of the generation of a high quantity of pollen that can be allergenic, one example being *Juniperus Virginiana*. By removing the high pollen emitter, the advisable coniferous species include *Cupressus sempervirens*, *Pinus strobus* and *Thuja occidentalis*.

According to the literature, when the use of conifer is not possible, the selection of broadleaf species should be preferred to the deciduous ones because some broadleaf species have high $PM_{2.5}$ removal efficiency, low negative impact on air quality (low BVOC and pollen emission) and good suitability for

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urban environments. Red maple (*Acer rubrum*), silver linden (*Trema tomentosa*) and American elm (*Ulmus americana*) were identified as suitable broadleaf species for optimizing PM removal.

Some species should be avoided if the intention is to optimise particle accumulation. For example, species like *Syringa reticulata, Phoenix canariensis, Lagerstraemia indica, Nyssa sylvatica, Ostrya virginiana, Prunus avium* or *Eriobotrya japonica* accumulate a significantly lower amount of particles than other tree species.

Optimal tree species selected from the work of Yang et al. (2015) are presented in Table 1 (each parameter is noted as low, medium, and high) and integrated into the database presented in the annexe.

Table 1 Optimal evergreen conifer, evergreen broadleaf and deciduous tree species for particle removal selected and adapted from the work of Yang et al. (2015)

Species	Type	PM2.5 removal	Pollen	BVOC	Tolerance to urban environment
Juniperus virginiana	Evergreen conifer	High	High	Low	High
Cupressus sempervirens	Evergreen conifer	High	Low	Low	Medium
Juniperus chinensis	Evergreen conifer	High	High	Low	High
Thuja occidentalis	Evergreen conifer	Medium	Medium	-	Medium
Pinus strobus	Evergreen conifer	Medium	Low	Medium	Low
Taxodium distichum	Deciduous	Medium	Low	Medium	Medium
Magnolia grandiflora	Evergreen broadleaf	Medium	Low	Low	High
Delonix regia	Evergreen broadleaf	Medium	-	Low	High
Ficus benjamina	Evergreen broadleaf	Medium	Medium	Medium	Low

The superior efficiency of needle-leaved species at trapping particles was confirmed by measurements in different studies. Bui et al. (2021) have compared the PM accumulation of leaves from broadleaf and needleleaf species collected on the Chungbuk National University of South Korea campus. *Pinus strobus* is a coniferous tree that develops needle-like leaves arranged in clusters of 5, the needles are bluish-green and are about 5-13 cm long. The number of particles recovered on *Pinus strobus* leaves surfaces was 17 times higher than in *Aesculus turbinata,* which was the worst performer tested by Bui et al. (2021). *Aesculus turbinata* is composed of large, compound leaves with 7-9 serrated leaflets. Among the eleven species characterized, other pine species *Pinus strobus, Pinus densiflora, Pinus parviflora*, and *Pinus abies* have demonstrated higher particle accumulation than other species (*Aesculus turbinata, Cercis chinensis, Cornus officinalis, Acer triflorum, Ligustrum obtusifolium*) on their leaves surfaces. Moreover, *Pinus strobus, Pinus parviflora, Pinus densiflora,* and

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Pinus abies demonstrated a higher in-wax particle accumulation than other species. Conversely, *C. Chinensis*, a deciduous tree with heart-shaped leaves alternately positioned along the branches, was the plant with the least total PM accumulation.

Saebo et al. (2012) measured the particulate matter accumulation on the leaves of 22 trees and 25 shrubs and found large differences between species. *Betula pendula*, *Pinus mugo*, *Pinus sylvestris*, *Salix cinerea*, *Skimmia japonica* and *Stephanandra incisa* showed high total PM accumulation, calculated as a mean value for two years, being 24–55 $\mu g.cm^{-2}$. The group that presents the lowest accumulation consisted of *Acer platanoides*, *Prunus avium*, *Prunus leurocerasus*, *Prunus padus*, *Symphoricarpus albus* and *Tilia cordata,* they presented considerably lower total accumulation of PM (6–13 μgcm^{-2}).

Shaowei et al. (2012) found that adsorbed PM2.5 was highest in *Pinus tabuliformis* and *Pinus bungeana* because of having large and uneven leaf gully size that contributes to PM2.5's adsorption. However, *Ginkgo biloba* and Populus leaf surface had less villi and were smoother, without hair and with oblong pores, leading to differences in adsorption ability. Wang et al. (2010 a,b) found that the number of leaf villi, morphology, and distribution have an important effect on the particulate matter retention ability.

4.1.2 Shrubs

A comparison of shrubs and trees did not reveal obvious differences in their ability to accumulate particles based on growth form (Mo et al., 2015). However, the foliage of shrubs is generally closer to the ground than tree foliage. Consequently, a combination of shrubs and larger trees might be advisable to reduce particle concentration near the ground as well as higher height (Saebo et al., 2012; Mo et al., 2015). Saebo et al. (2012) found that *Stephanandra Inicisa*, *Pinus mugo*. *Skimmia japonica* and *Salix cinerea* were the most efficient shrubs in a group of 47 species. One classification was made based on particle measurement deposition on several trees and shrubs (Mo et al., 2015). Significant differences were observed, and the species could be separated into 3 categories. *Cephalotaxus sinensis* performed significantly better than the other shrubs. *Euonymus japonicus*, *Malus × micromalus Makino*, *Chimonanthus praecox, Amygdalus triloba, Syringa oblata* and *Kolkwitzia* amabilis formed a group of average particle accumulation. In contrast, *Paeonia suffruticosa, Weigela florida* and *Philadelphus pekinensis* presented the lowest particle accumulation. The results are presented in Table 2 and integrated into the annexe.

Table 2 Classification of shrub species for particles accumulation, adapted from Mo et al. 2015

Shrub species	Quantities of captured PM
Cephalotaxus sinensis	High
Euonymus japonicus Thunb.	Medium
Chimonanthus praecox	Medium
Amygdalus triloba	Medium
Syringa oblata	Medium
Kolkwitzia amabilis	Medium
Prunus Cerasifera	Medium
Paeonia suffruticosa	Low
Weigela florida	Low

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Philadelphus pekinensis var. kansuensis	Low

4.1.3 Herbaceous

While studies on particle accumulation by vegetation focus on trees and shrubs, herbaceous species compose a large part of urban infrastructure. The selection of the optimal species could result in GI optimisation of particle removal. However, available studies give evidence that these plants are less potent purifiers (Weerakkody et al., 2018). Weber et al. (2014) studied particle accumulation of different grasses and herbaceous species collected on urban roadside in Berlin. All sampled species played a role in immobilizing particles, but the quantity of captured PM was influenced by the plant's height and leaf traits. Additionally, each species captured particles of various sizes and types. A key finding was that the diversity of vegetation along roadsides is crucial in immobilizing PM, with species possessing densely haired leaves proving to be the most efficient at retaining particles. Another interesting finding is that accumulated PM amounts significantly depended on the sampling height of plant leaves, tall-growing herbs with leaves regularly distributed along the whole stem collected more particles than low-growing species. Other studies on shrubs and trees showed that the accumulated particles decreased with increasing sampling height (Weber et al. 2014).

Results presented above rank species against each other, assuming similar environmental conditions. However, it must be noted that the particle amount accumulated on plants varied strongly with the traffic density level of the collection site. On European herbaceous plant leaves, particle count per mm^2 of more than 2500 was obtained in a high traffic density and decreased to 500 and 200 for medium and low traffic density, respectively. Differences between species in particle accumulation were more relevant in high traffic density zones and allowed the divide of the tested species into three groups presented in Table 3.

Table 3 Particle accumulation next to high density traffic zone measured on European herbaceous plant leaves (adapted from Weber et al. 2014)

High	Medium	Low
Artemisia vulgaris *Berteroa incana* *Polygonum aviculare*	*Achillea millefolium* *Chenopodium album* *Erodium cicutarium* *Galinsoga parviflora* *Lolium perenne* *Plantago lanceolata* *Poa pratensis* *Taraxacum officinale* *Trifolium repens*	*Festuca rubra*

Another study showed that out of twenty species growing in vertical gardens in the UK, the best herbaceous accumulators were *Thymus vulgaris* and *Carex caryophyllea* (Weerakkody et al., 2018).

The grass is a specific type of herbaceous vegetation that covers a large surface of lands, parks, and forests. Grasslands, including recreational and representative areas with mown lawns, and rough grasslands, occupy a huge percentage of city areas. In Sweden, it accounted for 15–32% of the urban area (Hedblom et al., 2017). In China, approximately 40,000 ha of lawns are established every year

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(Yang et al., 2019). Due to such a broad cover, grasses substantially contribute to PM abatement, even if they collect about 30% of PM kept by the forest (Fowler et al., 2004). Cowherd et al. (2016) gave evidence for the distinct potential of low, intensively mown lawns, which abated less than 10% of PM10 and tall grasses, which retained about 35–45%, compared to 45–67% of PM10 retained by cedar forests. Modern trends of increasing biodiversity of urban grasslands and decreasing

costs of lawn maintenance by infrequent mowing may contribute to a substantial air quality improvement (Southon et al., 2018).

Although the significant contribution of grass species to particle accumulation was demonstrated, few studies compare the efficiency of specific species. An experiment conducted on green roofs found that *Agrostis stolonifera* and *Festuca rubra* are more effective than *Plantago lanceolata* and *Sedum album* at PM_{10} capture (Speak et al., 2012). Moreover, in a semi-arid environment, *Sedum album* exhibited a higher rate of PM deposition compared to other sedum species (with *Sedum. reflexum, Sedum palmeri* and *Sedum watson* having the lowest effectiveness) and plants, such as *Pittosporum tobira (Thunb.)* W.T.Aiton and *Erigeron karvinskianus*) (Wróblewska et al., 2021).

Plant species (trees, shrubs and herbaceous) accumulation found in the studies is presented above, and others are presented in the annexe.

4.2 Gas removal

4.2.1 NO_2 removal

Few studies address the abilities of different plants to remove NO_2 from the air, although among them some are relevant for plant selection to optimize NO_2 removal. Morikawa et al. have used ^{15}N-labelled NO_2 to evaluate the NO_2 assimilation abilities of different plant leaves species. Among the 217 plants comprised of 50 wild herbaceous plants, 60 cultivated herbaceous plants and 107 cultivated woody plants, some species presented significantly higher capacity in NO_2 assimilation with a factor of 657 between the highest assimilation value (6.57 mg $N.g^{-1}$ dry weight NO_2 content) obtained for *Eucalyptus viminalis* and the lowest (0.01 mg.$N.g^{-1}$ dry weight NO_2 content) for *Tillandsia ionantha* and *Tillandsia caput-medusae*. The best species for NO_2 assimilation were found to be *Magnolia kobus*, *Eucalyptus viminalis*, *Populus nigra*, *Nicotiana tabacum* and *Erechtites hieracifolia,* these species presented NO_2-N contents that were significantly higher than other species.

Wild herbaceous plants (50 species) presented a NO_2-N content between 5.72 and 0.25 µg N/mg dry weight, cultivated herbaceous plants (60 species) a NO_2-N content between 5.72 and 0.01 µg N/mg dry weight, woody plants (106 species) a NO_2-N content between 6.57 and 0.04 mg $N.g^{-1}$. Herbaceous and woody plants that present a NO_2-N content above 2 mg $N.g^{-1}$ are presented respectively in Table 4 and Table 5.

Table 4 Herbaceous plants that are most effective at NO_2 assimilation, adapted from Morikawa et al. 1998

Plants	Family	NO_2 assimilation capacity (mg N/mg dry weight)
Erechtites hieracifolia	Asteraceae	5.72
Crassocephalum crepidioides	Asteraceae	5.07
Bidens frondosa	Asteraceae	2.98
Lactuca indica	Asteraceae	2.96
Oenothera biennis	Onagraceae	2.77

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Erigeron annuus	Asteraceae	2.73
Artemisia princeps	Asteraceae	2.53
Plantago lanceolata	Plantaginaceae	2.24
Chenopodium centrorubrum	Chenopodiaceae	2.24
Capsella bursa-pastoris	Brassicaceae	2.10
Sonchus oleraceus	Asteraceae	2.10
Aster subulatus	Asteraceae	2.02
Cotula australis	Asteraceae	2.00
Nicotiana tabacum	Solanaceae	5.72
Carthamus tinctorius	Asteraceae	3.41
Chrysanthemum sp.	Asteraceae	3.15
Arabidopsis thaliana	Brassicacee	3.03
Levisticum officinale	Apiaceae	3.02
Impatiens sp.	Balsaminaceae	2.80
Petunia x hybrida	Solanaceae	2.72
Matthiola incana	Brassicaceae	2.70
Cosmos bipinnatus	Asteraceae	2.63
Chamaemelum nobile	Asteraceae	2.26
Tanacetum vulgare	Asteraceae	2.18
Mentha x piperita	Lamiaceae	2.17
Hordeum spontaneum	Poaceae	2.08

Table 5 Woody plants most effective at NO_2 assimilation, adapted from Morikawa et al. 1998

Plants	Family	NO_2 assimilation capacity (μg N/mg dw)
Eucalyptus viminalis	Myrtaceae	6.57
Populus nigra	Salicaceae	5.14
Magnolia kobus	Magnoliaceae	4.92
Robinia pseudoacacia	Fabaceae	4.73
Eucalyptus grandis	Myrtaceae	4.57
Eucalyptus globulus	Myrtaceae	4.08
Populus sp.	Salicaceae	3.80

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Sophora japonica	Fabaceae	3.26
Prunus cerasoides	Rosaceae	2.23
Sapium sebiferum	Euphorbiaceae	2.85
Acacia dealbata	Fabaceae	2.82
Cytisus scoparius	Fabaceae	2.76
Platanus sp.	Platanaceae	2.75
Eucalyptus camphora	Myrtaceae	2.58
Stewartia pseudocamellia	Theaceae	2.49
Prunus lannesiana	Rosaceae	2.34
Gardenia jasminoides	Rubiaceae	2.27
Hydrangea macrophylla	Hydrangeaceae	2.27
Nerium indicum	Apocynaceae	2.09
Eucalyptus cinerea	Myrtaceae	2.03

Experiments conducted by Morikawa et al. (1998) also allow discarding the implementation of plant species with low NO_2 assimilation abilities. Herbaceous species such as *Tillandsia ionantha*, *Cymbidium sp.*, *Saintpaulia confuse*, and woody species such as *Codiaeum variegatum*, *Cameliia japonica* or *Thea sinensis* were among the least efficient species tested.

The full list published by Morikawa was adapted and integrated into the database in the annexe.

Similar experiments (using $^{15}N_2$) were conducted by Takahasi et al. (2005) on 70 woody plants, including 49 evergreen woody plants, consisting of 20 broad-leaf trees, 17 broad-leaf shrubs, 8 coniferous trees and 4 coniferous shrubs, and 21 deciduous woody plants, consisting of 15 broad-leaf trees, 3 broad-leaf shrubs and 3 coniferous trees. Most of them were also tested by Morikawa et al. (1998). Results showed that *Prunus yedoensis*, *Robinia pseudo-acacia, Sophora japonica* and *Populus nigra* were found to have significantly higher NO_2 assimilation capability than any of the other woody plants tested. Data showed that evergreen woody plants are generally less effective for NO_2 assimilation than deciduous woody plants. The measured NO_2 assimilation of more than 20 tested evergreen species were lower than the lowest value of the deciduous woody plant tested.

Using artificial NO_2 injection into a test chamber and constant monitoring, Gubb et al. (2022) investigated the ability of 3 different potted plant species to remove NO_2 from indoor air. Each plant species was tested at two different light intensity levels, corresponding to the light levels found in typical indoor environments. After 1-hour, a significant difference was observed, *Zamioculcas zamiifolia* removed more than *Dracaena fragrans 'Golden Coast'* and *Spathiphyllum wallisii 'Verdi'*. The study's results showed that light intensity had a significant influence on the ability of potted plants to remove NO_2 from indoor air. In general, plant species tested at the higher light intensity were more effective at removing NO_2 than those tested at the lower light intensity. The study authors suggest that the increased effectiveness of plants at higher light levels may be due to increased photosynthesis and transpiration, which can increase the rate of air purification. However, the authors also note that excessive light intensity can lead to plant stress, which may decrease their ability to remove pollutants.

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Few other studies can be used to support the plant selection for NO_2 removal. For example, Donovan et al. (2005) have classified several tree species commonly found in cities based on an Urban tree air quality score (UTAQS). This score was established using an atmospheric chemistry model (CiTTyCAT) that quantifies the effects of trees on urban air quality, considering the combined effects of both pollutant deposition and emission of BVOC. Table 6 presents the ranking of the tree species tested into three categories, high UTAQS corresponding to the species with the higher potential for improving air quality, medium UTAQS species that have some capacity to improve air quality; and low UTAQS corresponding to species that present the potential to worsen air quality. We can observe that Pinus nigra is classified in the high UTAQS category and was also found to have a high NO_2 assimilation level by Takahashi et al. (2005).

Table 6 Urban tree air quality score (UTAQS) classification for 30 most common trees in the West Midlands metropolitan area, UK (adapted from Donovan et al. 2005)

High UTAQS	Medium UTAQS	Low UTAQS
Almus glutinosa (Alder)	*Malus spp.* (Apple)	*Populus tremula* (Aspen)
Acer campestre (Fieled maple)	*Fraxinus excelsior* (Ash)	*Salix fragilis* (Crack Willow)
Crataegus monogyna (Hawthorn)	*Prunus avium* (Cherry)	*Quercus robur* (English Oak)
Larix decidua (Larch)	*Tilia europaea* (Common lime)	*Salix caprea* (Goat willow)
Prunus laurocerasus (Laurel)	*Sambucus nigra* (Elder)	*Quercus rubra* (Red Oak)
Chamaecyparis lawsoniana (*Lawson Cypress*)	*Ulmus procera* (English Elm)	*Quercus petraea* (Sessile Oak)
Acer platanoides (Norway Maple)	*Alnus incana* (Grey Alder)	*Salix alba* (White willow)
Pinus nigra (Pine)	*Corylus avellana* (Hawel)	
Betula pendula (Silver Birch)	*Ilex aquifolium* (Holly)	
	Alnus cordata (Italian Alder)	
	Cupressocyparis leylandii (Leyland Cypress)	
	Syringa vulgaris (Lilac)	

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	Sorbus aucuparia (Rowan)	
	Acer pseudoplatanus (Sycamore)	

The results presented above, completed with other studies, are presented in the database in the annexe.

4.2.2 VOC REMOVAL

The ability of plants to remove VOCs has primarily been investigated in the context of indoor air phytoremediation. Although these studies provide a starting point to optimize VOC removal through NBS, it is important to note that the results obtained in a closed testing chamber may not directly translate to the outdoor environment. Most studies on the VOC removal potential of plants involve fumigation of the compounds in a test chamber, with the concentration of VOCs monitored over time. It is essential to keep in mind that this controlled environment is not representative of the natural outdoor environment. Moreover, because of different experimental conditions and variability of the plant specimen for the same species, it is very complex to compare the results between different studies.

A significant number of VOC with different properties were affected by the presence of plants. A non-exhaustive list contains Acetone, Benzaldehyde, Benzene, Toluene, Xylene, Aldehydes, and Ketones compounds, methacrolein, octane, pentane, α-pinene, trichloroethylene (Dela Cruz et al. 2014, Kim et al. 2012). In a study by Kim et al. (2014), the effectiveness of *Fatsia japonica* in removing toluene and xylene was significantly higher than that of *Dracaena fragrans*. Similarly, *Begonia maculata* and *Ardisia. japonica* exhibited significantly higher toluene removal rates than *Ardisia crenata* in another study conducted by Kim et al. (2012).

A similar method was employed to investigate the toluene removal rates of 26 plant species of different types, including herbs, herbaceous foliage plants, and woody foliage plants (Kim et al. 2011). The results showed that woody foliage plants had the highest mean increase in removal rate, while herbaceous foliage plants had the least, and herbs were intermediate. However, woody foliage plants also exhibited the widest range in toluene removal rate between the lowest and highest species (*Pittosporum tobira* and *Pinus densiflora*, respectively). Herbs presented a slightly lower removal rate, with *Pelargonium graveolens* and *Salvia elegans* being respectively the best and worst performers. Herbaceous foliage plants showed a higher degree of performance similarity between species.

Interestingly, successive exposure tests resulted in an increase in removal efficiency after the initial exposure. This observation may be attributed to an effect on certain microorganisms in the medium that can metabolize toluene and benefit from its presence. Table 7 presents the toluene removal of the plant species after two successive exposure to the contaminant.

Table 7 Toluene removal (μg.m^{-3}.h^{-1}.m^{-2} leaf area) of different plants species, adapted from Kim et al. 2011

Type of plants	Species	Toluene removal (μg.m^{-3}.h^{-1}.m^{-2} leaf area)
Herbs	*Aloysia triphylla*	761.4 ± 3.6
	Melissa officinalis	218.7 ± 18.8

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	Mentha piperita	440.6 ± 20.4
	Mentha piperita 'citrata'	209.9 ± 10.4
	Mentha suaveolens Ehrh	733.7 ± 55.7
	Mentha suaveolens Ehrh. Variegata	422.9 ± 13.6
	Pelargonium graveolens L'H´er	510.3 ± 78.1
	Plectranthus tomentosus	108.6 ± 22.3
	Rosmarinus officinalis L.	558.7 ± 84.7
	Salvia elegans Vahl	188.4 ± 1.8
Herbaceous foliage plants	*Begonia maculata Raddi*	55.9 ± 1.8
	Davallia mariesii Moore ex Baker	190.7 ± 21.1
	Farfugium japonicum (L.) Kitam.	245.5 ± 23.5
	Fittonia verschaffeltii (Lem.)	449.8 ± 31.9
	Hedera helix L.	401.0 ± 33.5
	Philodendron spp. 'Sunlight'	183.8 ± 2.8
	Soleirolia soleirolii (Req.) Dandy	254.0 ± 12.0
Woody foliage plants	*Ardisia crenata Sims*	114.1 ± 5.0
	Ardisia japonica (Thunb.) Blume	500.1 ± 47.2
	Ardisia pusilla A.DC.	88.6 ± 5.2
	Cinnamomum camphora (L.) J. Presl	244.1 ± 45.7
	Schefflera elegantissima	174.6 ± 19.9
	Eurya emarginata	213.7 ± 24.4
	Ilex cornuta Lindl. & Paxton	429.7 ± 104.5
	Ligustrum japonicum	250.9 ± 4.6
	Pinus densiflora	919.7 ± 89.9
	Pittosporum tobira	22.1 ± 5.3
	Rhododendron fauriei	928.3 ± 135.5

Other publications that compare the VOC remediation abilities of plant species were reviewed, and relevant results are presented in the annexe.

4.2.3 CO_2 SEQUESTRATION

Urban green space provides multiple ecosystem benefits, including carbon sequestration using the assimilation of atmospheric CO_2 by the photosynthesis of plants. In this process, CO_2 is transformed

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into organic carbon through plant growth and stored as plant biomass. A tendency of trees with larger total leaf area to present higher carbon sequestration efficiency was established by different studies (Sohngen and Mendelsohn, 2003; Grulke et al., 2020). Therefore, a simple recommendation to optimize CO_2 sequestration by implementing NBS is to select NBS and plant species to maximise total leaf area.

At the individual species level, the carbon sequestration potential can be estimated by calculating the biomass of plants, as the two characteristics are related. Larger plants generally exhibit higher carbon sequestration efficiency. Al-Nabadi et al. (2022) used an approach based on measuring diameter at breast height combined with estimating the biomass using an allometric equation to determine the carbon storage potential of different tree species. They found that the most dominant species in terms of carbon sequestration potential are *Ficus spp., Azadirachta indica* and *Conocarpus erectus,* with a total of 3399.3 tCO_2eq, 2845.2 tCO_2eq, 2286.9 tCO_2eq, which represents 76.1% of the carbon sequestered by trees in the study area. The next set of species *Albizia lebbeck*, *Tabebuia rosea*, *Syzygium cumini, Pongamia pinnata, Delonix regia* contributed by 13.3%, and the remaining 22 species only by 3.0%.

Wang et al. 2021 have calculated the carbon sequestration of 47 individual plants species based on their photosynthesis rate. Among the 47 plant species, *Pinus tabulaeformis*, *Sophora japonica*, and *Lagerstroemia indica* had relatively high carbon sequestration efficiency. They were able to sequester more than 3 g of Carbon per unit leaf area on a summer day. Some deciduous tree species, such as *Magnolia denudate* and *Acer truncatum* and shrubs, including *Berberis thunbergii*, *Weigela florida*, *Clerodendrum trichotomum*, and *Viburnum opulus,* exhibited weaker carbon sequestration efficiency. The carbon sequestration was generally higher for evergreen tree species than other plant categories, followed by deciduous tree species.

Herbaceous species also present a high carbon sequestration potential. Deng et al. (2022) conducted a comparative study on woody plants and herbaceous plants. They concluded that the plantation of herbaceous is preferable to achieve rapid carbon fixation and recycling for reducing the greenhouse effect and impact on the ecological environment. To optimize the carbon sequestration of the NBS that implement herbaceous, species that present a strong ability to regenerate, high yields and large annual biomasses are preferred. For example, *Pennisetum, Pennisetum purpureum, miscanthus and imperatorial* are good choices because they present those characteristics.

Regarding ground cover type plants, significant differences in carbon sequestration capacity were found between *Sedum acre*, *Frankenia thymifolia* and *Vinca major* (Seyedabadi et al., 2021). Those species were implemented in an extensive green roof demo site and found that *Frankenia thymifolia* has the highest total carbon absorption rate and can reduce carbon emissions in the atmosphere by 9.290 kg Carbon/m^2 per year. *Sedum acre* was less effective, and *Vinca major* the weakest in absorbing carbon through photosynthesis.

4.3 BIOGENIC VOLATILE ORGANIC COMPOUNDS

Some databases and scientific articles contain information on the emission level of plant species that can be used to tailor plant selection toward a reduction of the BVOC emission level of the NBS. One example is the literature survey of the emission of non-methane volatile organic compounds (NHMCs) from plants made by Lancaster University (Hewitt et al., 1997) that contains emission rates of about 643 plant species.

Among species cultivated in Europe, it was found that *Quercus robur L., Quercus pubescens Willd*., *Populus nigra* L. and *Populus tremula L.* are high isoprene emitters, as well as *Fagus silvatica L.* as a high monoterpene emitter. On the other hand, *Acer platanoides L., Ulmus minor Mill., Fraxinus excelsior L., and Tilia platyphyllos Scop.* are considered low BVOC emitters (Fitzyk et al., 2019). The genus Quercus was also responsible for high emissions of isoprene in Japan, whereas *Cryptomeria japonica* was the greatest producer of mono- and sesquiterpenes (Chatani et al., 2018). Low emitters

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of BVOC among tropical trees in Santiago de Chile were found to be *Schinus mole L., Quillaja saponaria Poir*. and *Quercus suber L*. (Préndez et al. 2013). In studies conducted in India, *Ceiba petendra L., Cinnamomum zeylanicum Bereyn., Azadirachta indica A.Juss., Melia azedarach L., Chukrasia tabularis A.Juss., Terminalia arauna Roxb*. and *T. bellirica Roxb*. expressed low isoprene emission rates, whereas *Dalbergia sissoo Linn., Ficus religiosa L.* and *F. infectoria Willd*, emitted high levels of isoprene (Varshney et al. 2003).

BVOC emission levels were also assessed by Yang et al. (2015) and integrated into their database, that presents the particle removal capabilities of the most common tree species in cities. Data were obtained from different sources (Benjamin and Winer, 1998., Guenther et al., 1994., Kesselmeier and Staudt, 1999; Xiaoshan et al., 2000) and converted to standard emission rates. Main results are presented in Table 1.

Some species demonstrate a high capacity for particle removal but at the same time present high BVOC emission. It is the case for *Salix babylonica* and, to a lesser extent, of *Pinus sylvestris, Pinus nigra, Ficus benjamina, Platanus occidentalis, Populus tremula* and *Ficus macrocarpa*. Moreover, some species present significant pollen generation. On the other hand, some species combine high pollutant removal (particles) with a low generation of bio-contaminants, for example, *Juniperus virginiana, Cupressus sempervirens* or *Fraxinus excelsior*. Other data can be found in Barwise and Kumar (2012). When available, the BVOC emission level of species was given in the annexe.

4.4 Selection

In this report, the scientific literature was reviewed to identify the capacity of different plant species to improve air quality by the deposition, adsorption, or retention of air pollutants. Searches were oriented toward different pollutants and plant species that can be implemented in NBS.

The research was conducted around the concepts of transparency complete and accurate account (quality and certainty with the evidence). The main findings are presented above in this report and Annex that synthesises and presents the classification of species obtained by the mixed methods review applied to quantitative and qualitative studies, reviews, reports, and abstracts. The references used in this systematic review were mainly peer-reviewed articles. The search was designed to identify studies that evaluated and/or compared different plant species for their ability to remove air pollutants. Relevant research papers were identified using combinations of keywords, including "plant", "species", "trees", "herbaceous", "air pollution", "air quality", "particle", "NO_2", "VOC", "phytoremediation" or "nature based solutions". The method identified key items in each article. First, the pre-review was for the Title and Abstract, and then the article was filtered according to our interests, for example, the introduction was used to know the state of the art of the existing knowledge of different species or to provide other review addresses. Methods and results were very useful in adjusting our lab tests to know the difficulties of establishing comparisons among species and studies and rank the species' capabilities to improve the air quality.

The results were also useful for the final source information selection, establishing each study's main outcomes and precision. Other sections, such as the Introduction, have made it possible to expand the species registration. Specific search keywords were used for the search, i.e. "air-pollution", "tree species", "urban air quality", "air remediation", or "nature-based solutions", and we have noted any relevant papers in the review (to ensure further that no relevant papers were missing), but not included them in the appeared references list (Annexe 1).

Reviewed studies showed considerable variation in methodology, parameters, duration, and species investigated, this heterogeneity limited possibilities for the generalisation of results and, consequently, for the direct comparison of results. When results from different studies were comparable, we used them as reference levels to categorize the behaviour or capacity of plant species studied.

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Furthermore, a selection of trees, shrubs and herbaceous species that were identified as having superior phytoremediation capabilities was presented to the cities. When possible, cities have added to their selection some of those plant species suggested. Some constraints limited the selection, mainly availability and cost. At the beginning of the task, the cities provided a list of plant species that they commonly implemented in their infrastructure. Specific searches were conducted to evaluate their ability to remove urban air pollution.

In general, partial data on contaminant removal by specific plant species was found in the literature, particulate matter being the most studied. For example, the VOC removal abilities of the best particulate matter removers are generally unknown. Plant selection should consider the priority pollutant to be reduced and then apply other criteria to the selection (such as BVOC and pollen emissions, other pollutants removal, availability, and tolerance to the urban environment).

5 CHARACTERIZATION OF AIR PURIFICATION PROPERTIES BY LAB EXPERIMENTS

5.1 INTRODUCTION

Laboratory experiments were conducted at LEITAT to complete the literature review. The goal is to study different species' pollutant removal efficiency to optimise the NBS performance for specific air pollutants. The test method was developed to quickly assess and compare the VOC, NO_2 and particle removal abilities of plant species.

The selection of herbaceous plant species to be tested in the lab was based on the adaptive capacity of plants in terms of selected Upsurge demo sites, growth and development characteristics of species, the presence of species in cities, the preference of autochthonous sp., discarding potentially invasive species. Also, the type of NBS planned for cities, and the lack of data on their phytoremediation capabilities was considered.

Selected outdoor plant species and their characteristics of interests are described below; with the added value that a large part of the species that appear in the different cities' inventories have not been studied. Furthermore, some of the selected species, or species belonging to the same genus with similar characteristics, have been studied to be applied in other phytorremediation strategies and with proven effectiveness in NBS (Pucher et al., 2022; Bortolini and Zanin., 2019).

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Achillea millefolium

Family: Asteraceae

Common name: Common Yarrow

Description: Herbaceous, perennial plant that produces one to several stems 0.2–1 metre (8–40 inches) in height.

Leaves: Distributed along the stem, leaves have varying degrees of hairiness (pubescence). The leaves are 5–20 centimetres (2–8 in) long, bipinnate or tripinnate, almost feathery, and arranged spirally on the stems. The leaves are cauline, and more or less clasping, being more petiolate near the base.

The **inflorescence** contains ray and disk flowers which are white to pink, blooming from March to October, visited by many insects, featuring a generalized pollination system. The semall achene-like fruits are called cypsela.

Habitat and Distribution: From sea level to 3,500 m in elevation. The plant is native to Eurasia and is found

Allium schoenoprasum

Family: Amaryllidaceae

Common name: Chives

Description: Bulb-forming herbaceous perennial plant, growing to 30–50 cm tall. The stems are hollow and tubular, up to 50 cm long, with a soft texture.

Produces edible leaves and flowers. Purple and star-shaped flowers with six petals, in a dense inflorescence of 10-30 together. The herb flowers from April to May in the southern parts of its habitat zones and in June in the northern parts. Commonly found in grocery stores or grown in home gardens, with extend culinary uses.

Provides a great deal of nectar for pollinators. It was rated in the top 10 for most nectar production (nectar per unit cover per year) in a UK

Habitat and Distribution: Native to temperate areas of Europe, Asia and North America. Widespread in nature across much of Europe, Asia, and North America.

Calamagrostis epigeios

Family: Poaceae

Common name: Bushgrass

Description: Grass which is native to Eurasia and Africa. It is found from average moisture locales to salt marsh and wet habitats. The foliage is a medium green and is perennial with lengthy rhizomes. The culms are erect and are 60–200 cm long while the leaf-blades are 70 cm. Also have an erect panicle which is 15–30 centimetres long and is also oblong and almost lanceolate.

The large **inflorescence** is a rich brown colour. The flowers form dense and narrow spikes 25–35 cm long.

Habitat and Distribution: Broad distribution in temperate Eurasia, from France and Great Britain to Japan. It is cultivated as an ornamental grass for gardens.

Echinacea purpurea

Family: Asteraceae

Common name: Purple-coneflower

Description: Herbaceous perennial up to 120 cm tall. Depending on the climate, it blooms throughout summer into autumn. Its cone-shaped flowering heads are usually purple. Its individual flowers within the flower head are hermaphroditic. It is pollinated by butterflies and bees. The alternate **leaves**, borne by a petiole from 0 to 17 cm, are oval to lanceolate, the margin is tightened to toothed.

The **inflorescence** is a capitulum, formed by a prominent domed central protuberance. Surrounded by a ring of pink or purple ligulate florets. The plant prefers well-drained soils in full sun. The fruit is an achene, sought after by birds.

Habitat and Distribution: Native of eastern North America. Its natural habitats include dry open woods

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Euphorbia amygdaloides

Family: Euphorbiaceae

Common name: Wood spurge

Description: Bushy evergreen perennial, growing to a height of 80 cm, with dark green slightly hairy leaves about 6 cm long. The complex green-yellow inflorescence (cyathium), typical of Euphorbia, appears in late spring and early summer. Thrive in the dry shade of trees, where it is used as groundcover. It spreads rapidly by underground rhizomes and can become invasive, though relatively easy to remove.

The milky latex of the plant is toxic and can cause irritation in the skin.

Habitat and Distribution: Native to woodland locations in Europe, Turkey and the Caucasus.

Fragaria anannassa

Family: Rosaceae

Common name: Garden strawberry

Description: Widely grown hybrid species of the genus Fragaria. The garden strawberry was first bred in Brittany, France, in the 1750s via a cross of Fragaria virginiana from eastern North America and Fragaria chiloensis, which was brought from Chile. Straberries are grouped between "June-bearing" strawberries, which bear their fruit in the early summer and "ever-bearing" strawberries, which often bear several crops of fruit throughout the season.

Cultivation: Cultivated worldwide for their fruit, widely appreciated for its characteristics (aroma, juicy, sweetness…). In 2020, world production of strawberries was 8.9 million tonnes.

Strawberry cultivars vary widely in size, color, flavor, shape, degree of fertility, season of ripening, liability to disease, foliage and constitution of plant. On average, a

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Gaura lindheimeri

Family: Onagraceae

Common name: White gaura

Description: Perennial herbaceous clump-forming plant, growing to 50 to 150 centimeters tall, with densely clustered branched stems growing from an underground rhizome. The leaves are finely hairy, lanceolate, 1 to 9 cm broad, with a coarsely toothed margin.

The flowers are produced on a 10-to-80-centimeter-long pink and white inflorescences, with four petals 10 to 15 mm long and long hairlike stamens, and are produced from the beginning of spring until the first frost.

Commonly grown as an ornamental plant.

Habitat and Distribution: Native to Texas and Louisiana. Mainly distributed in the temperate North America,

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Geranium psilostemon

Family: Geraniaceae

Common name: Armenian cranesbill

Description: Hardy flowering herbaceous perennial plant. Forming a large clump to 120 cm (47 in) tall, it has glowing reddish purple colored flowers with prominent dark centres, and divided leaves tinted red in Autumn.

Flowering season is fairly short, in midsummer, this species has superb deeply divided foliage which makes a good foil for later summer flowers. In autumn the leaves turn fiery red and team well with autumnal fruits or berries.

Habitat and Distribution: Native to Turkey, Armenia, Azerbaijan, and the Russian Federation. Its habitat includes all temperate regions of the world including the mountainous areas of the tropics, although they are

Geranium sanguineum

Family: Geraniaceae

Common name: Bloody cranesbill

Description: The biological form is hemicryptophyte, as its overwintering buds are situated just below the soil surface and the floral axis is more or less erect with a few leaves. It has a thick rhizome. The stems are prostrate to ascending, well developed, very branched and hairy. This plant reaches on average 30–50 centimetres in height.

The flowers are purple, and flowering period extends from May through October. The flowers are hermaphrodite and pollinated by insects (entomophily). The most common flower visitors are Syrphidae and Hymenoptera, but also butterflies and Coleoptera.

Habitat and Distribution: Native to Europe and temperate Asia. It is widespread in most of Europe up to Caucasus. In the north-east of Ireland it is a rare garden escape. The typical habitat of this species is grassland, sand dunes and open woodland on calcareous soils, including rocky

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Melissa officinalis

Family: Lamiaceae

Common name: Lemon balm

Description: Perennial herb, with abundance of nectar in the flowers. Hemicryptophyte, with creeping herbaceous stems, slightly lignified at the base, quadrangular in section and up to almost one meter tall.

The leaves are borne in opposite pairs on the stems, and are usually ovate or heart-shaped and emit a lemony scent when bruised. Axillary spikes of white or yellowish flowers appear in the summer

Medicinal plant rich in biologically active compounds which is used worldwide for its therapeutic effects

Habitat and Distribution: Native to Europe and Asia but cultivated and naturalized arround the world.

Molinia caerulea

Family: Poaceae

Common name: Heidebraut

Description: Herbaceous perennial bunchgrass growing up to 120 cm tall (taller when sheltered by gorse and heather), with many closely packed stems.

The leaves are coarse, green, taper to a point, long, flat and sometimes slightly hairy on top. Due to the dense tussock it is very resistant to heath fires.

Its ligule is a ring of hairs, the long narrow purple spikelets are a major identification feature, the panicle is 15 cm long, flowers between July and September,

Habitat and Distribution: Native to Europe, west Asia, and north Africa. It grows in locations from the

Rudbeckia fulgida

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Family: Asteraceae

Common name: Goldstrum rudbeckia

Description: An herbaceous perennial growing up to 120 cm tall, with bright yellow daisy-like composite flower heads.

Spreads by both stoloniferous stems and seed. The seeds are produced in fruits called cypselae, which are 2.2 to 4 mm long and have short coroniform pappi, 0.2 mm long.

Stems are hairy, ridged, and dark green. Leaves are dark green, sparsely but roughly haired, simple, with sparsely serrate margins. Flowers are heads, with black disk florets and bright orange ray florets, borne singly on stems that extend above the foliage. Stems are glabrous or moderately covered in hirsute hairs with spreading branches. The leaves have blades that are lanceolate to broadly ovate or elliptic in shape without lobes.

Habitat and Distribution: Native to eastern North America. an herbaceous perennial growing up to 120 cm tall, with

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Salvia nemorosa

Family: Lamiaceae

Common name: Perennial Woodland Sage

Description: Hardy herbaceous perennial plant, up to 60 cm. Basal leaves oblong with heart-shaped or rounded base, toothed, of grey felt below, petiolate; cauline leaves.

The many inflorescences have closely spaced whorls of small flowers with brightly colored calyces.Vivaciou plant, it loses its stems in the cold and sprouts again in spring. Towards the end of the season it begins to bloom and does so throughout the summer, until in autumn and with the new frosts it gets rid of its foliage again.

Habitat and Distribution: Native to a wide area of central Europe and Western Asia. Its wide distribution, long history, and the ease with which it hybridizes have

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Thymus citriodorus

Family: Lamiaceae **Common name:** Lemon thyme **Description:** Lemon-scented evergreen mat-forming perennial plant, growing to 0.1 metres in height by 0.3 metres in spread. It prefers full sun and well draining soil. The bloom period is mid to late summer, with pink to lavender flowers that are a nectar source for bees and butterflies. Grown as ornamentals, culinary herbs, and medicinal plants. The plant is drought-tolerant once established. As nectar-producing plants, they are cultivated in bee and butterfly gardens. **Habitat and Distribution:** The native range of this hybrid is SW. Europe. It is a subshrub and grows primarily in the temperate biome.

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Trachelospermun jasminoides

Family: Apocynaceae

Common name: Star jasmine

Description: Evergreen woody liana growing to 3 m high. When they meet a wet surface, they emit aerial weed roots, otherwise they surround the support (they are twining). If cut, like most Apocynaceae, they exude a white latex, resembling sticky milk.

Young twigs, initially pubescent, become glabrous with age. The leaves are opposite, oval to lanceolate, 2–10 cm long and 1–4.5 cm broad, with an entire margin and an acuminate apex. Dark green in summer, the leaves turn bronze in winter.

The fragrant flowers are white, with a tube-like corolla opening out into five petal-like lobes. It is commonly cultivated as an ornamental plant, also the aromatic oil that is extracted from the flowers is highly appreciated.

Habitat and Distribution: Native to East and Southeast Asian countries, Japan, Korea, southern China and

Selected species were acclimated for several days under laboratory conditions after reception. Measurements were taken (Table 8) on plant parameters, such as its height, expansion and number of leaves, the weight of the biomass and the substrate contained in the pots.

Table 8 Characteristics of the plants tested in the laboratory

Species	Height (cm)	Aerial expansion (cm)	Biomass weight (g)	Substrate weight (g)
Achillea millefolium	14	18	9	567
Allium schoenoprasum	17	9	4	242
Calamagrostis epigeios	40	28	28	927
Echinacea purpurea	29	26	19	364
Euphorbia amygdaloides	21	19	65	384
Fragaria anannassa	11	21	5	256
Gaura lindheimeri	21	19	34	808
Geranium psilostemon	25	18	10	690
Geranium sanguineum	12	18	13	750
Melissa officinalis	23	24	12	260
Molinia caerulea	74	16	23	855
Rudbeckia fulgida	13	14	9	384

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Salvia nemorosa	44	30	25	624
Thymus citriodorus	9	12	3	243
Trachelospermun jasminoides	43	15	57	861

5.2 Experimental methods

The phytoremediation process's effectiveness in removing NO_2, toluene and particles by different plant species was studied by a fumigation test chamber method. Three chambers made of plexiglass (0.4 x 0.4 x 0.6 m, 0.092 m3) with a removable lid equipped with an O-ring were used to create the test atmosphere for the plant evaluation. A fan was set up inside each chamber to ensure the mixing of the air and homogenization of the air pollutants. Each chamber was dedicated to the evaluation of one contaminant: VOC, NO_2 and particles and were not interchanged (Figure 1). These experiments aimed to compare the phytoremediation properties of different plant species and identify the most effective one to be implemented in NBS. However, the procedure does not allow us to estimate what the effectiveness would be in a real environment. However, it can give a ranking of the plant with the best air purification potential. The selection of the best-ranked species might optimize the impact on air quality at the NBS level.

Figure 1 Photography of the plants and fumigation chambers

The VOC phytoremediation properties of plants were evaluated using toluene as a reference contaminant. At the start of the experiment, 10µL of toluene was evaporated using a micro syringe connected to a compressed air stream. 0.5mL of the chamber atmosphere was sampled using an air-tight syringe and immediately transferred to a Gas Chromatography with a Mass Spectrometry detector (GC-MS (HES High Efficiency Source)) (Agilent 7890B-5977B) for analysis. A first batch of experiments was conducted by connecting to the chamber a photoionization detector to measure total VOC (TVOC) concentration in real-time. After a few experiments, this method was discarded for two reasons: humidity built up because of plant transpiration and condensation in the connection tubing. Moreover, the method does not allow the determination of the concentration of individual

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compounds. Therefore, interferences due to VOC generated by the plant could affect toluene readings. For those reasons, the GC-MS method was preferred.

Similar experiments were conducted using NO_2 as a contaminant. Injection of the pollutant inside the chamber was done by using a high-concentration cylinder of NO_2 (100 ppm in N_2) connected to a mass flow controller. The concentration in the chamber during the first several minutes was raised to a concentration of 0.4 ppm by injecting 400 mL of gas at 50 mL/min. NO and NO_2 were analyzed using a chemiluminescence analyser (Horiba APNA370) connected to the chamber at the same time interval used in the toluene assessment test. Treatment durations were short enough to prevent a significant change in the oxygen concentration that might affect plant metabolism. To assess differences in the removal of NO_2 and toluene between plant species, the air inside the chamber was sampled at 1, 2, 4 and 6 hours after the introduction of the contaminant into the chamber. Tests without plants were performed to obtain a reference curve and assess the loss of contaminant due to leakage and adsorption on the chamber's walls. For the assessment of particle removal, a fine dust test of normalized distribution size (ISO 12103-1, A2) was spread into the chamber using compressed air. The air inside the test chamber was constantly mixed by a fan, and $PM_{2.5}$ and PM_{10} concentrations were measured using an infrared sensor (Aeroqual 500). Changes in particles concentrations over time in the chamber with plants were compared with each other and with the reference curve (chamber without plant).

5.3 Results

5.3.1 Gas removal

5.3.1.1 Toluene

Figure 2 presents the toluene concentration in the empty chamber over time (reference test) and with *Thymus citriodorus* and *Fragaria anannassa* over 24 hours after the injection of toluene. In the reference test, a slow decrease in concentration over time was observed due to leakage and adsorption on the chamber surface. For the chamber containing the plant, the same phenomena occurs in addition to the phytoremediation mechanism of the plant. After 6 hours, toluene concentration decreases by 1.5%, and after 24 hours, toluene concentration decreases by 20% in the reference chamber. After 24 h, the concentration measured in the chamber with *Trachelospermun jasminoides* was 58% lower than the concentration measured in the reference chamber.

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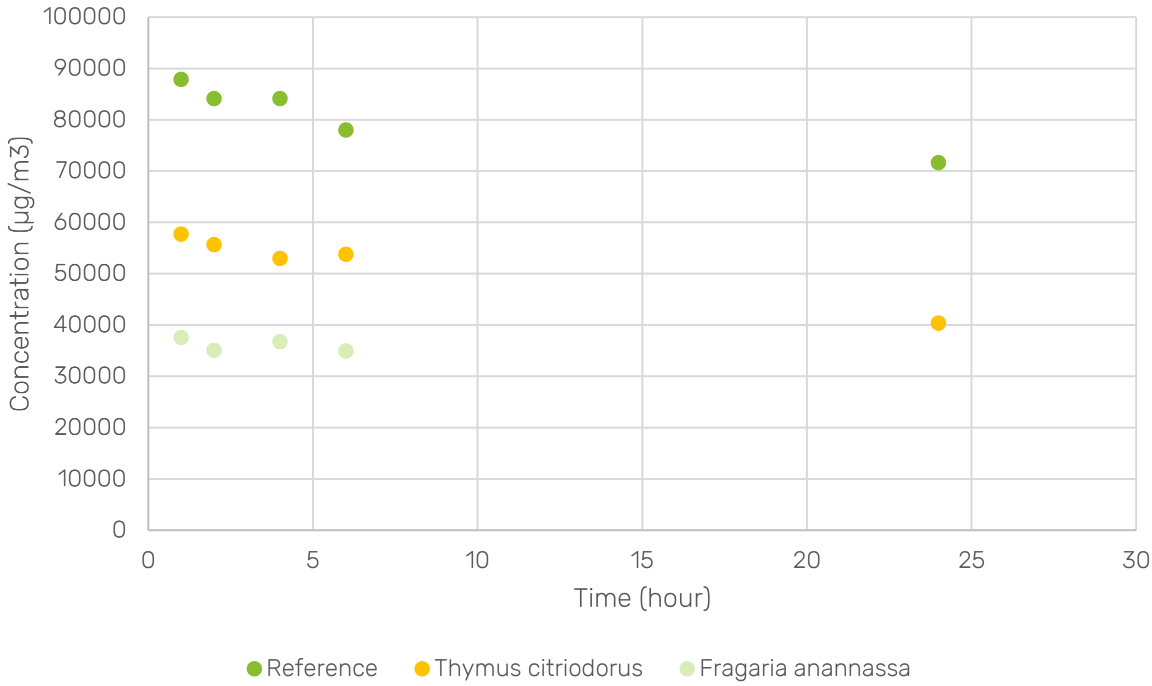

Figure 2 Evolution of toluene concentration over time in the reference chamber and with Thymus citriodorus and Fragaria anannassa

The presence of the plant inside the chamber results in a faster decay of toluene concentration, which can be attributed to the presence of the plant-soil system.

Figure 3 presents the % reduction in toluene of the different plant species compared to the reference test after 6h exposure. Standard dispersion was about 15%, calculated as an average of different replicas of different identical plant species. This uncertainty is comparable to other studies published (Yoo et al. 2006 reported a deviation of 7-15% on a similar test method with toluene as a contaminant).

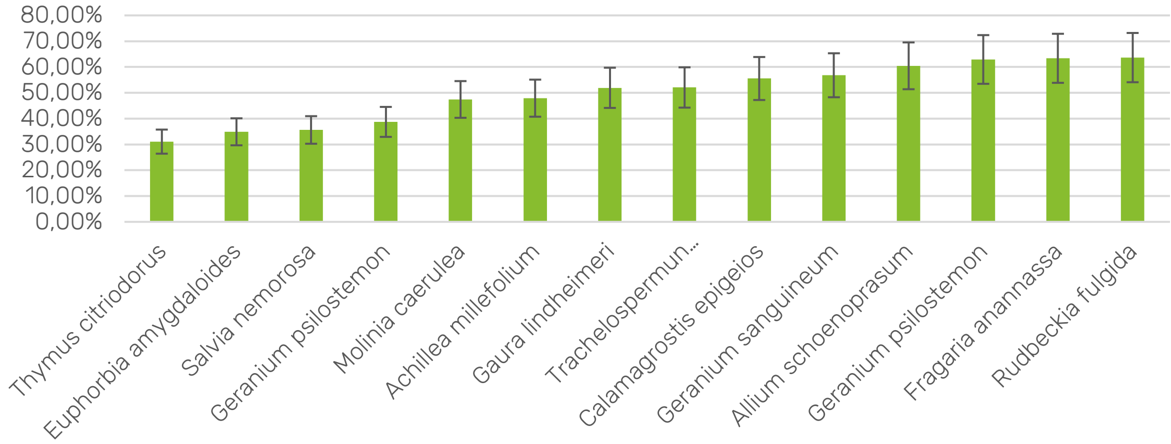

Figure 3 Toluene removal, after 6 hours, measured from the selected plant species

Most of the % reduction difference between plant species falls into the uncertainty range, and it is not, therefore, possible to give a precise ranking of the most efficient plant species. However, data can be separated into two groups: below 40% and above 40%. The low-efficiency group (<40%) is formed of *Thymus citriodorus*, *Euphorbia amygdaloides, Salvia nemorosa* and *Geranium psilostemon* and the high efficiency group (>40%) contains *Rudbeckia fulgida, Fragaria anannassa, Geranium*

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psilostemonm, Allium schoenoprasum, Geranium samguineum, Calamagrostis epigeios, Trachelospermun jasminoides, Gaura lindheimeri, Achillea millefolium and Molinia caerulea.

Moreover, it seems that the weight of the aboveground biomass was not a significant indicator of the efficiency of the species in removing toluene. *Allium schoenoprasum* had a low aerial part mass but presented similar toluene removal compared to the geranium, which had a mass 4 times higher (Table 8). However, there is unlikely a factor 4 in toluene removal per plant mass between the two species. Moreover, is has been found that the substrate part does not affect significantly the % removal when exposed to toluene, benzene, ethylbenzene or xylene (Mosaddegh et al. 2014).

The difference in toluene removal of the different plant species tested varied between 30 and 60%, but the results were affected by a deviation of around 10%. For this reason. The plants were classified into only two groups because the difference in toluene removal is quite small inside those two groups. The experimental protocol may not be sensitive enough to reveal subtle differences in plant species in removing toluene. In preliminary experiments, a longer test time (>24 hours) was used, but transpiration of the plant led to water condensation in the test chamber accompanied by an increase in temperature above 30°C. For this reason, it was decided to use a 6-hour test period. This period was also used in previous study (Yoo et al., 2006). Further experiments can be conducted studying the assimilation of toluene in the plant leaves. After fumigation in the chamber, leaves can be collected and deposited in a desorption tube. The desorption tube is then installed in a thermodesorber connected to a GC-MS, organic matter is calcinated, and organic vapour is analysed by GC-MS.

5.3.1.2 NO_2

Figure 4 presents the NO_2 concentration in the empty chamber over time. A similar behaviour to the toluene test was observed but with a faster decay over time (section 5.3.1.1), certainly due to the lower stability of NO_2. The concentration decreases over time due to adsorption and leakage. After 6 hours, the NO_2 concentration decreased by about 50%.

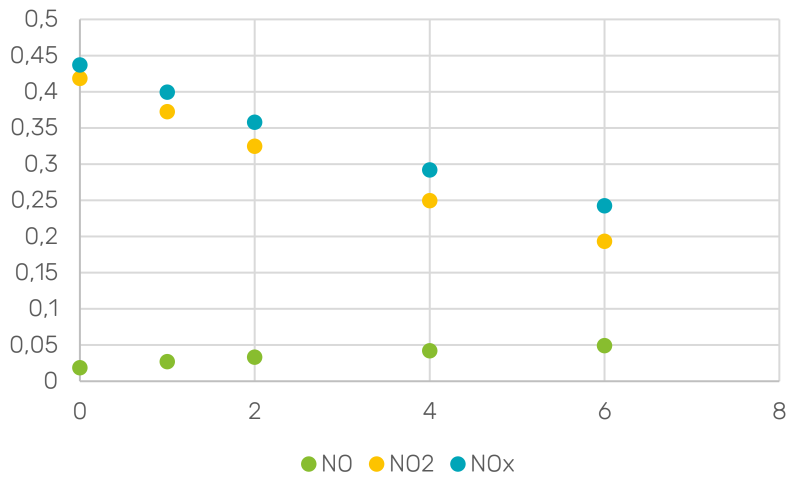

Figure 4 NO, NO_2 and NOx concentration into the reference chamber during time

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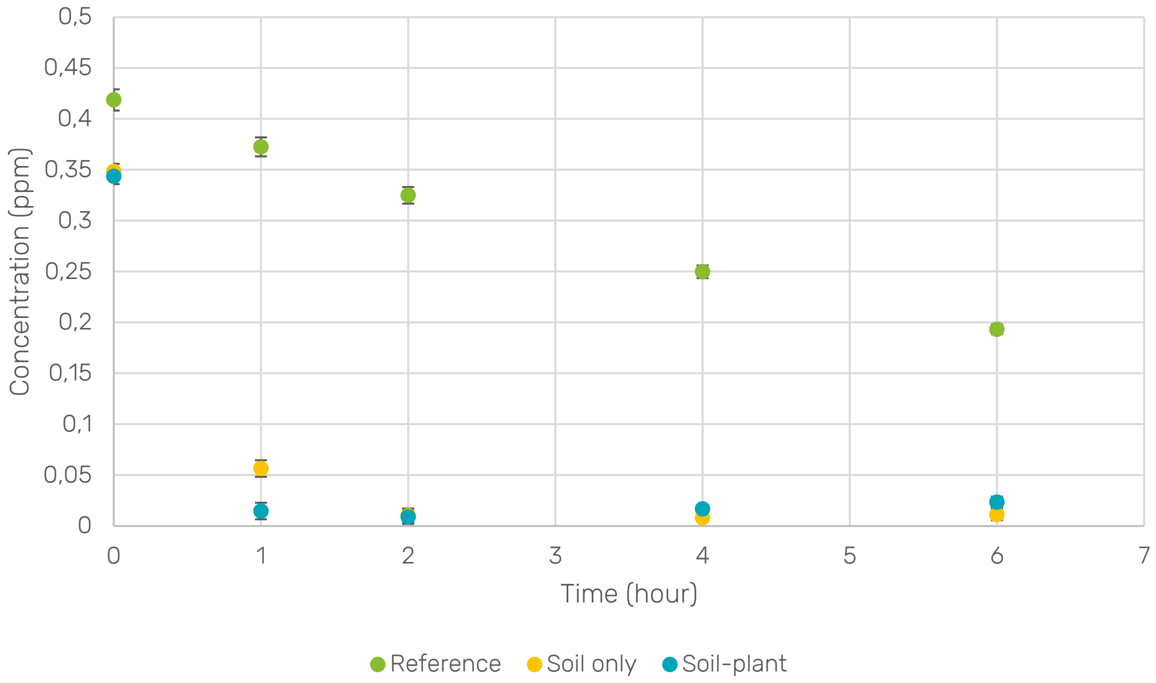

Figure 5 presents the evolution of NO_2 concentration for the empty chamber for the soil only and specie *Trachelospermun jasminoides* (plant-soil system). The presence of the plant-soil system or the soil only strongly affected NO_2 concentration from the start of the test. After 1 hour, the NO_2 concentration in the empty chamber was about 0.372 ppm, and the NO_2 concentration when the plant-soil system is present in the chamber varied between 0.014 ppm. The concentration when only the soil is present was 0.0565ppm.

Soils (without the aerial part) strongly affected the NO_2 concentration. Initial concentrations (T=0 min) for the plant-soil system and soil alone were not significantly different. After 1 hour of exposure time, a significantly lower NO_2 concentration was obtained by the plant-soil system. However, it was not the case for a 2-6 hour exposure where the concentrations were not statistically different.

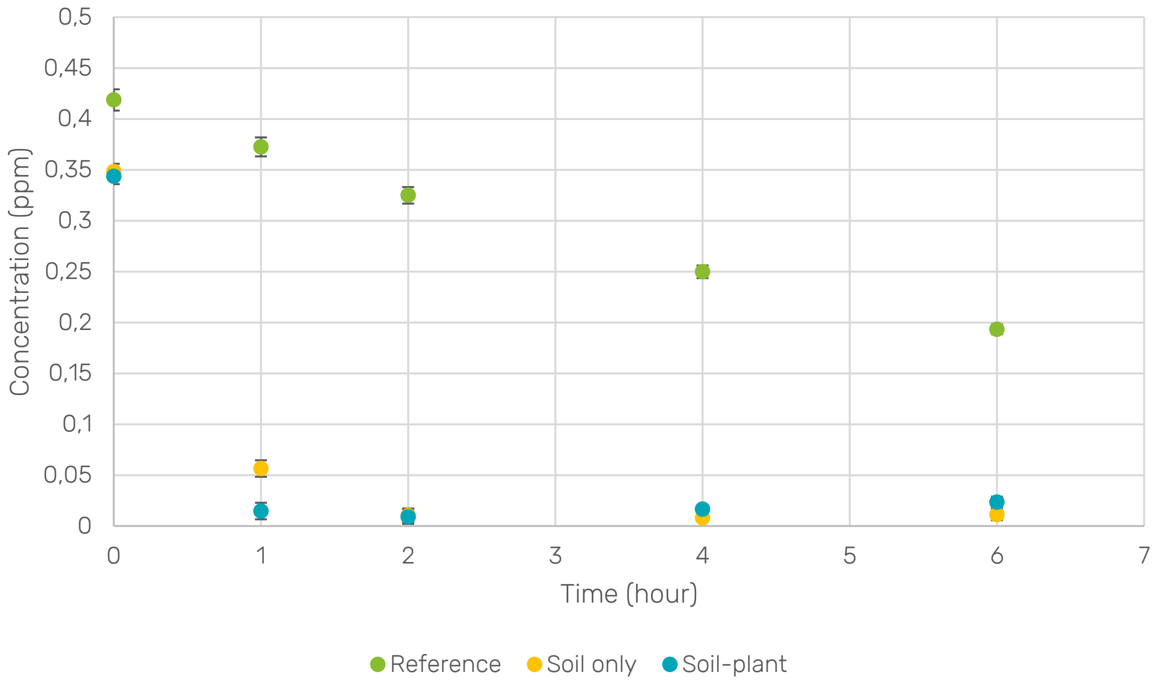

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Figure 5 Comparison of NO_2 concentration during time obtained in the empty chamber, in the presence of soil alone and in the presence of Trachelospermun jasminoides soil-plant system

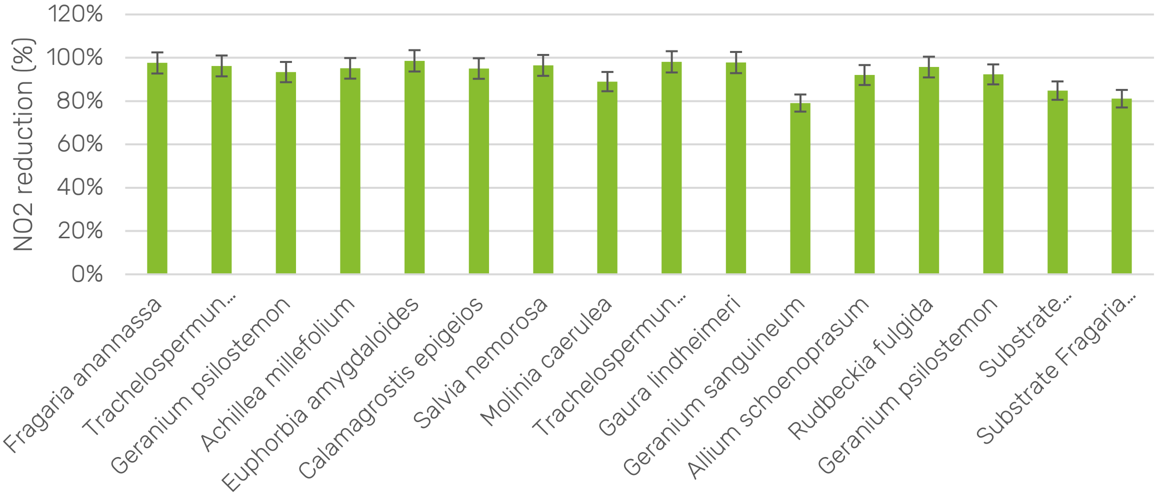

Figure 6 presents the % reduction in NO_2 concentration after 1 hour exposition for each species. The percentage reduction is calculated relative to the concentrations obtained in the empty chamber (reference experiment). A strong decrease was always observed in the plant-soil system.

The greatest reduction in concentration observed was 98.6% for *Euphorbia amygdaloides*, and the smallest reduction was 79.1% for *Geranium sanguineum*. The other species tested were in between 89.0 and 97.6% reduction with a deviation calculated to be 3%. High NO_2 removal was also obtained with the substrate alone, with a % removal comparable to the one obtained with *Geranium sanguineum*.

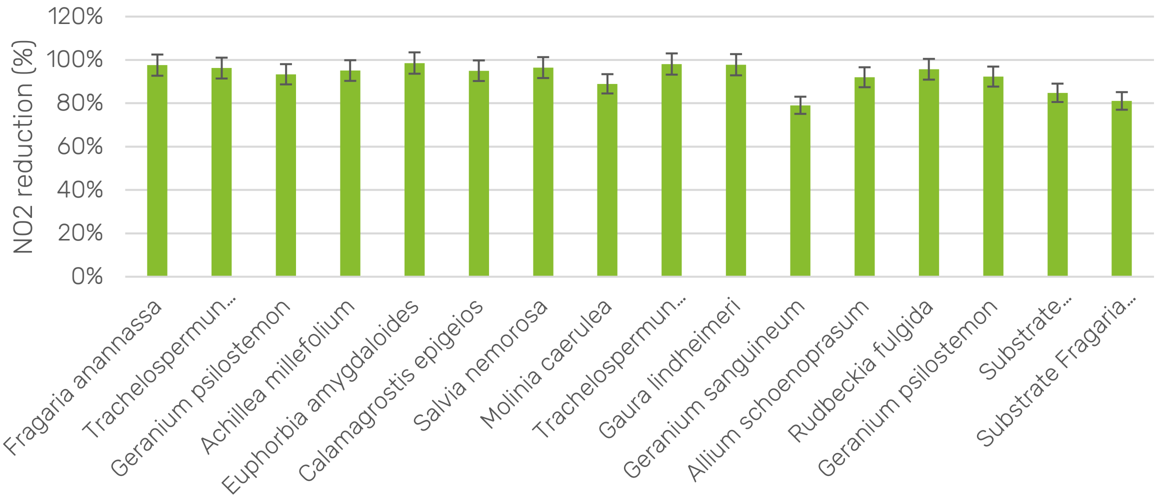

Figure 6 NO_2 reduction (%) after 1 hour time in presence of the different plant species

NO concentration did not change significantly except with some plant-soil system, which presented a different behaviour during the entire duration of the experiment. As was the case for the species *Calamagrostis epigeios* and *Allium schoenoprasum*, a conversion of NO_2 to NO was observed, as represented in Figure 7.

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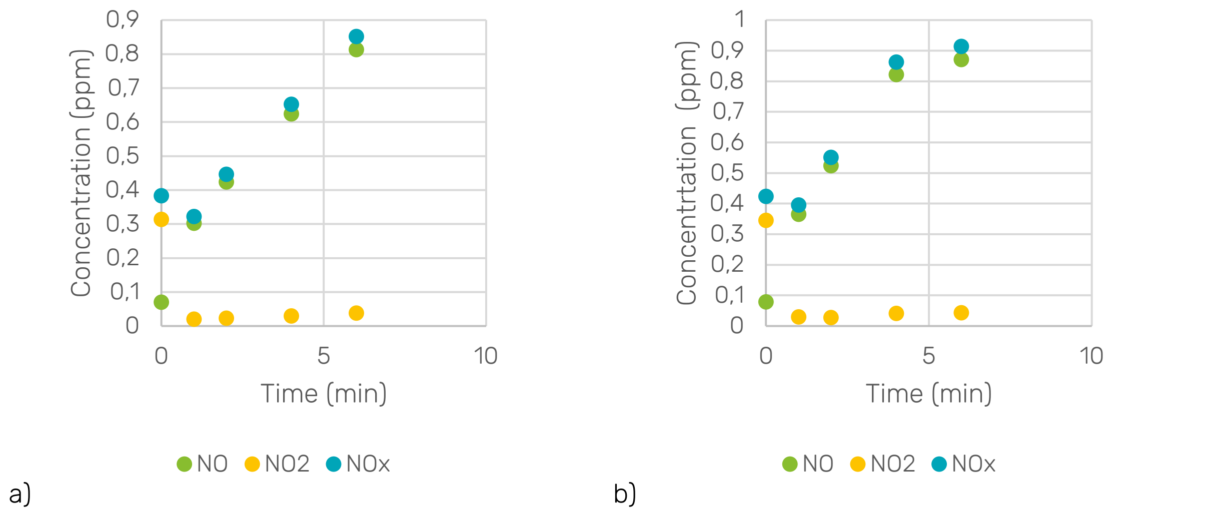

Figure 7 Evolution of NO, NO_2 and NOx concentration during the time for a) Calamagrostis epigeios and b) Allium schoenoprasum

To study this phenomenon, test with the substrate alone (without plant) were conducted. The concentrations were not significantly different from the plant and substrate results. A correction of the results by the loss of NO_2 due to the substrate resulted in non-conclusive result about the effectiveness of the aerial part of the plant to remove NO_2 for those two species. The most similar experimental protocol found in the literature was published by Gubb et al. (2022). They used a similar chamber, but only NO_2 was measured, and they observed a difference in the ability of three plant species to remove NO_2 (corrected from the substrate). However, no information on NO concentration was found in the literature.

5.3.2 Particle removal

Figure 8 presents the evolution of $PM_{2.5}$ and PM_{10} in the chamber during time in the absence of a plant. Particle concentrations decrease by about 50% after 20 minutes. This behaviour is similar to the results of Torpy et al. (2018), which generated particles from diesel fuel in a glass spirit burner.

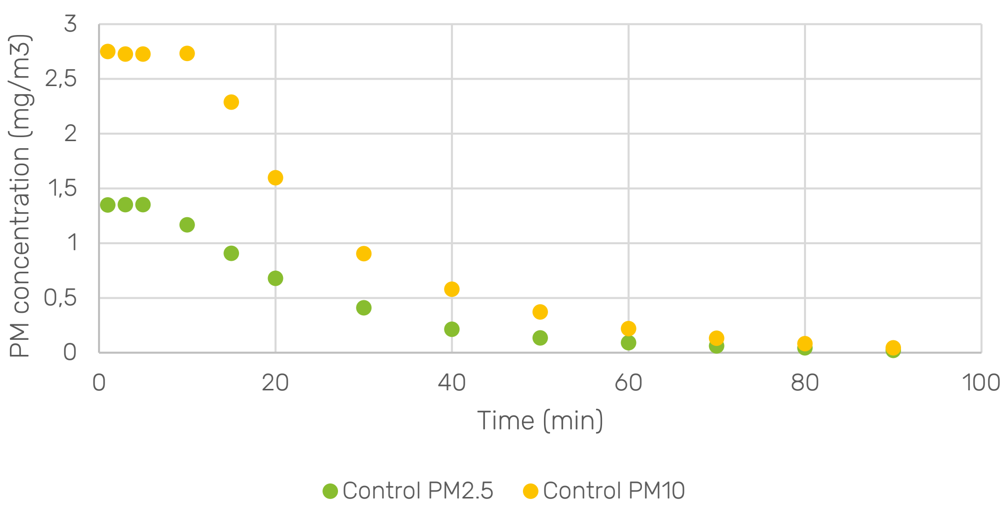

Figure 8 Evolution of PM2.5 and PM10 in the test chamber without plant species

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Table 9 presents the reduction of PM_{10} and $PM_{2.5}$ concentrations obtained with the selected plant species after 20 minutes. Results are expressed in % reduction and also in concentration reduction considering the biomass of the aerial part of the plant-soil system (mg/m³/g).

Table 9 Particle reduction of the selected plant species in relation with the reference curve after 20 min of test

Species	%$PM_{2.5}$	%PM_{10}	$PM_{2.5}$ (mg/m³/g)	PM_{10} (mg/m³/g)
Gaura lindheimeri	71	70	-0.014	-0.033
Euphorbia amygdaloides	30	45	-0.003	-0.007
Calamagrostis epigeios	65	65	-0.016	-0.037
Geranium sanguineum	70	70	-0.036	-0.083
Trachelospermun jasminoides	60	57	-0.007	-0.016
Allium schoenoprasum	18	23	-0.031	-0.094
Rudbeckia fulgida	13	18	-0.010	-0.033
Salvia nemorosa	78	76	-0.021	-0.049
Molinia caerulea	21	31	-0.006	-0.021

The presence of the plant in the test chamber affected the particle concentration when compared with the reference test (empty chamber). Some plants presented significantly higher retention of particles. *Geranium sanguineum*, *Calamagrostis epigeiosm, Salvia nemorosa* and *Gaura lindheimeri* were the best performers, with a reduction of 71 and 70% of $PM_{2.5}$ and PM_{10}. Worst performers were *Allium schoenoprasum*, *Rudbeckia fulgida*, *Molinia caerulea*, and *Euphorbia amygdaloides. If the selection is based on the reduction of concentration per aerial part biomass, the best performers are Geranium sanguineum, Allium schoenoprasum and Salvia nemorosa.*

Allium schoenosprasum was one of the worst performers in % reduction but showed a particle concentration reduction per biomass above other species.

6 Selection of plant species for air quality

Using all the information and references presented above, the most effective plant species for air quality improvement were identified and presented in the tables below (Table 10, Table 11 and Table 12). The air purification properties and emission of contaminants have been categorized by types of plants (trees, shrubs and herbaceous plants). When available, their emissions of detrimental compounds to the environment and human health (BVOCs and pollen) are estimated.

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Table 10 Best trees identified for air purification properties

Specie	Common name	Plant family	PM removal	NO_2 removal	BVOC emission	Pollen
Cupressus sempervirens	Mediterranean cypress, Graveyard cypress	Cupressaceae	High		Low	Low
Juniperus chinensis	Chinese juniper	Cupressaceae	High	Low	Low	high
Juniperus virginiana	Eastern red cedar	Cupressaceae	High		Low	High
Pinus bungeana	Bunge's pine	Pinaceae	high			
Pinus strobus	Eastern white pine	Pinaceae	High			
Pinus tabuliformis	Manchurian red pine	Pinaceae	High			
Taxodium distichum	Bald cypress	Cupressaceae	High	Low	low	Low
Thuja occidentalis	Northern white-cedar	Cupressaceae	High			High
Tsuga canadensis	Eastern hemlock	Pinaceae	High		Low	Low
Metasequoia glyptostroboides	Dawn redwood	Cupressaceae	high	high		
Acer campestre	*Field maple*	Sapindaceae	average	Low	Low	
Acer monspessulanum	*Montpellier maple*	Sapindaceae				

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Acer platanoides	*Norway maple*	Sapindaceae	Average		Low	Average
Alnus glutinosa	*Common alder*	Betulaceae		High	Low	
Alnus spaethii	*Spaeth alder*	Betulaceae			Low	
Betula pendula	*Silver birch*	Betulaceae	Low/average	average	Average	Average
Fraxinus sp.	*Ash*	Oleaceae				
Ginkgo biloba	*Gingko*	Ginkgoaceae	Average		Average	Low
Gleditsia triacanthos	*Thorny locust*	Fabaceae	average		low	Low
Larix decidua	*European larch*	Pinaceae				
Pinus sylvestris	*Scot's pine*	Pinaceae	Average		average	Low
Thuja plicata	*Western redcedar*	Cupressaceae			Low	
Tilia americana	*American basswood*	Malvaceae	Average		Low	Average
Tilia cordata	*Small-leaved lime, Littleleaf linden*	malvaceae	Average		Low	Average
Tilia plathyphyllos	*Largeleaf linden, Large-leafed lime*	malvaceae	Average			Average
Ulmus sp.	*Elm*	ulmaceae				
Zelkova serrata	*Japanese zelkova*	ulmaceae	Average		Low	High

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Populus nigra	*Black popular*	Salicaceae	Average	High	average	Average
Magnolia kobus	*Kobus magnolia*	Magnoliaceae		high		
Robinia pseudoacacia	*Black locust*	Fabaceae	Average	high	low	Low
Sophora japonica	*Japanese pagoda tree, Styphnolobium japonicum*	Fabaceae		high		

Table 11 Best shrubs identified for their air purification properties

Specie	Common name	Plant family	PM removal	NO_2 removal	Pollen
Aralia elata	Japanese angelica	Araliaceae	average		
Buddleja davidii	Butterfly Bush	Scrophulariaceae	High		
Buxus sempervirens 'Rotundifolia'	Boxwood	Buxaceae	Average		
Elaeagnus ebbingei	Ebbing's Silverberry	Elaeagnaceae	High		
Photinia fraseri	Christmas berry	Rosaceae	High		
Pinus mugo	Bog pine	Pinaceae	average		average
Viburnum tinus	Laurustinus	Adoxaceae		high	low
Cytisus scoparius	Scotch broom	Fabaceae			
Gardenia jasminoides	Common gardenia	Rubiaceae			

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Nerium indicum	Indian oleander	Apocynaceae			

Table 12 Best herbaceous species identified for their air purification properties

Specie	Common name	Plant family	PM removal	CO_2 assimilation	Other properties
Achillea millefolium	Common Yarrow	Asteraceae	Low	High	May cause allergies and headache
Euphorbia amygdaloides	Wood spurge	Euphorbiaceae	Average		Produces a toxic white resin
Gaura lindheimeri	White gaura	Onagraceae			Great ornamental value
Geranium macrorhizum	Bigroot geranium	Geraniaceae	Average		
Persicaria amplexicaulis	Red bistort	Polygonaceae	Low		Long flowering
Salvia nemorosa	Woodland Sage	Lamiaceae			Flower spikes
Veronica longifolia	Long-leaf speedwell	Plantaginaceae	average		Flower spike

The results presented in the tables above show that Cupressaceae and Pinaceae are generally good particle remover, but some species in this taxon can exhibit a significantly elevated pollen emission. This is, for example, the case of *Juniperus virginia,* which exhibits high particle removal and low BVOC emissions but high pollen liberation. The selection of *Cupressus sempervirens* might be a better choice as it was classified as a good particle remover and low pollen emitter.

Moreover, it was often impossible to obtain data on all the contaminants for each species, with particulate matter being the most studied contaminant, especially regarding tree species. One good practice for species selection would be to select species that offer a good compromise between eliminating the target pollutant and low BVOC and pollen emissions.

7 Conclusion

A literature review was conducted to identify plant species with the highest air phytoremediation properties to remove the main urban air pollutants. The review was completed by a laboratory test to develop a relatively simple and quick test method to compare the phytoremediation capabilities of plants with each other.

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In addition to describing the main phenomena of phytoremediation and the key characteristics of plants to optimise air remediation, the main outcome of this task is creating a database for the individual selection of plants with the best phytoremediation capabilities. This tool fits well with the main objective of UPSURGE, which is to assist cities in implementing nature-based solutions in the context of the transition to a sustainable future.

The final database includes plants species with their ability to remove specific air pollutants. This database completes the NBS registry (T2.1), which builds a catalogue of different NBS, the KPIs list (T2.2) and the matchmaking matrix (T2.3), which selects appropriate NBS of the catalogue to the cities' challenges. The air purification and climate remediation properties of the NBS selected by the matchmaking process can be optimised by selecting the most appropriate species in the database presented in this deliverable. This set of tools will constitute a part of the Urban Regenerative Development Clearinghouse and Lighthouse.

This task was also useful for the implementation of the Upsurge demo sites. It was possible to orient the selection of the plant species to a certain extent. Some constraints regarding the plant's availabilities, cost or characteristics have forced the cities to choose additional plants absent from the list.

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9 Annex

Database (separate file)

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