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University Clermont Auvergne, CNRS, Clermont Auvergne INP, Institut de Chimie de Clermont-Ferrand F-63000 Clermont-Ferrand, France

Yara.arbid@etu.uca.fr

Claire.richard@uca.fr

Mohamad.sleiman@sigma-clermont.fr

*Corresponding author: Mohamad Sleiman – University Clermont Auvergne, CNRS, Clermont Auvergne INP, Institut de Chimie de Clermont-Ferrand F63000 Clermont-Ferrand, France; orcid.org/0000-0002-2273-1053; Email: Mohamad.sleiman@sigma-clermont.fr

ABSTRACT

Green roofs are a promising approach to mitigate air pollution in urban environments, but limited experimental data is yet available. In this study, we developed a laboratory-scale setup to measure the removal nitrogen dioxide (NO_2) and ozone (O_3) using a variety of common green roof species. Experiments were conducted on detached leaves and whole plants using two chambers (0.6 L and 12 L), visible lighting, NOx/O_3 sources and online analyzers. Three species were the best performant (Thymus vulgaris, Sedum sexangulare and Heuchera Americana L.) with deposition velocities (v_d) ranging from 1.6 to 4.82 m/h for NO_2, and 1.7 to 5.56 m/h for O_3. In both cases, thyme was the most effective plant likely due to its higher stomatal area and the reactivity of its volatile metabolites with O_3 leading to several oxidized by-products. Furthermore, NO_2 uptake was found to be enhanced by surface water released by leaf transpiration leading to the production of nitrous acid (HONO). Similar values of (v_d) were observed (3.84 – 4.65 m/h) when whole thyme plant was used. The soil was also found to be competitive in removing O_3 but less performant in capturing NO_2. Using a dry deposition model, we estimated that the three plant species can uptake up to 9 kg/ha/year of NO_2 and 13.6 kg/ha/year, which fall in agreement with previously reported modeling data. Our experimental approach can be a rapid tool for screening the depollution performances of green roof species enabling an effective prioritization for deployment in urban environments.

Keywords: Green roofs, air pollution, NOx, O_3.

1. INTRODUCTION

Outdoor air pollution causes up to 10 million deaths annually, and around 90 % of the world population live in urban environments where air pollution exceeds the World Health Organization (WHO) limits [1]. Air pollution mitigation strategies such as source reduction (electrical vehicles [2], fuel and traffic regulations [3], renewable energy resources [4], etc.), and depollution technologies have been increasingly adopted in the recent years. Among depollution methods, the use of highly reflective

photocatalytic roofs and walls [5] have been shown to be effective in reducing the urban heat island effect, and in the removal of Volatile Organic Compounds (VOCs) and Nitrogen Oxides (NOx) [6,7]. However, photocatalytic oxidation process can lead to the formation of toxic intermediates and the VOC removal performance can decrease over time [8]. Another promising alternative is the use of natural walls and roofs such as vertical greening systems or green roofs which can be a replacement to conventional roofs especially in crowded urbanized areas [9]. Green roofs have been receiving attention recently as effective nature-based solution to eco-environmental problems arising from climate change and rapid urbanization [10]. They can retain storm water via absorption into the substrate [11,12], reduce the building energy demand by improving the thermal insulation [13], lower noise pollution [14], in addition to improving the roof aesthetic values.

Plants used in such green roofs are able to mitigate air pollution [15] by absorbing the pollutants through their stomata via dry deposition on the surfaces of leaves [16]. Urban trees and shrubs are known to remove efficiently air pollutants [17]. Reactive pollutants (O_3, NOx, SO_2) can be removed by absorption via stomata or by surface uptake via potential chemical reactions with volatile metabolites such as terpenes. On the other hand, the formed particulate matter (PM) can be removed via deposition on the leaf surface. The performance depends on various factors such as the proximity of the vegetation to the road and its height [18]. Although trees are a very effective strategy in controlling pollution, planting trees in crowded cities with high percentages of impervious areas is challenging. Thus, in metropolitan cities, green roofs can be an alternative solution to make use of rooftops [19]. Several modelling studies showed that green roofs can be efficient in removing various prevalent air pollutants. According to Yang et al., 22.8 kg/ha/year of NO_2 and around 44 kg/ha/year of O_3 can be eliminated using green roofs [16]. Grass was found effective in removing O_3 (5.2 kg/ha/year) whereas, shrubs have the potential to eliminate 18 kg/ha/year of PM_{10} [20]. Speak et.al [21] showed that sedum, a widely used plant species on extensive green roofs, could remove 4.2 kg/ha/year of PM_{10}. However, most aforementioned studies were based

solely on modelling using estimated deposition velocities (v_d) which can vary significantly depending on the plant species, seasonality, climate, etc.

To the best of our knowledge, the air depollution performance of green roofs species has been very little investigated, and only limited recent data exist on their efficiency in the laboratory and in the field [22,23]. Performance-based laboratory screening measurements –in combination with field campaigns- are thus needed to improve the precision of models and to provide a valuable tool for implementing the best performant species as a function of target pollutants. In this study, we developed an experimental setup to measure the NOx/O_3 uptakes of 13 plants commonly used on green roofs. After initial screening, 3 species were selected (*Sedum sexangulare*, *Thymus vulgaris*, and *Heuchera micrantha palace purple*). The removal rates of these plants were investigated using detached leaves as well as full size plants. This work aimed to guide in the choice of plants to be used on green roofs according to the need of targeting a specific pollutant in an urbanized area, and to get insight into the mechanisms taking place.

2. MATERIALS AND METHODS

2.1. Chemicals and materials

Imidacloprid (IMD) was purchased from Sigma Aldrich, Switzerland (Pestanal^{TM}, analytical standard, ≥98.0% purity HPLC area %). Sodium carbonate anhydrous was purchased from Fluka, Germany (≥99.5% purity ACS). Both were used without further purification. Water was produced using a reverse osmosis RIOS 5 and Synergy (Millipore) device (resistivity 18 MΩ cm, DOC<0.1 mg L^{-1}). Acetonitrile (ACN) was purchased from Carlo Erba Reagents (HPLC Plus Gradient grade-ACS-Reag.

Process of plant selection: Green roofs vary from intensive to extensive roofs differing in the maintenance needs, substrate depth, plants implemented, etc. Contrarily to intensive ones where shrubs or even trees may be implemented, extensive green roofs use shallow root plants and thus are more commonly used due to their low maintenance needs and lightweight. Hence, in this study, we solely focused on extensive green roof species which are drought tolerant such as grasses, perennials, and succulents. Based on

literature review, and after careful consideration of weather conditions in central France, 13 species were selected for screening: *Achillée millefeuille paprika, Achillea umbellate à feuillage gris, Alchemille jaune, Aster des alpes rose,Heuchera americana L., Joubarbe calcareum, Joubarbe rubin, Thymus nummularius, Sedum floriferum jaune, Sedum reflexum jaune, Sedum sexangulare, Sedum spurium, and Thymus vulgaris*. After pre-screening, three species were chosen to further investigate their performance for the removal of O_3 and NO_2: *Sedum sexangulare, Thymus vulgaris, Heuchera americana L.*

Conditions for plant storage and care: Plants were stored in an indoor greenhouse exposed to outdoor sunlight through a large window and were watered every two days. Temperature was between 20-25 ^{0} C in the greenhouse during storage and around 23°±2 C when used in the laboratory. Relative humidity (RH) was ranged between 30-55%.

Sedum sexangulare, Thymus vulgaris, and *Heuchera micrantha palace purple* were purchased from a plant nursery (Botanic®, Beaumont, France) and watered every two days. These species are used on green roofs and different studies report their performance towards different air pollutants [24–26].

Sedum sexangulare (sedum): Sedum species are considered as appropriate plants to be applied on extensive green roofs. They are drought tolerant and can survive in harsh climate conditions. In the literature, *Sedum sexangulare* showed a good performance under severe climate conditions and that it is suitable to be implemented in a Mediterranean climate [24].

Thymus vulgaris (thyme): Thyme is an odorous perennial plant used on green roofs. It emits different VOCs (**Fig.SI-1.**) which can react with air pollutants [25].

Heuchera Americana L. (heuchera): Heuchera species are used in vertical greenery systems and green roofs because their colorful glossy leaves give them important aesthetics values. Heuchera retains different elements and particulate matter (PM) due to its hairy undersides [26].

Plants were stored in an indoor greenhouse with direct solar light. They were either used directly as a full-size plant (pot size: 9-15 cm) or their leaves cut using scissors into pieces of 0.9-1.2 g prior to the experiment.

To avoid changes induced by diurnal cycles, all experiments using plants were performed during the day from 10 am to 3 pm. The planting soil was a universal soil with a water retention capacity of 75%, pH=6.5, and N, P, K values of 5.5, 2.5, and 1.5 for 2 kg/m^3 respectively.

Fig.1. Pictures of the 3 studied plants: *Sedum sexangulare, Thymus vulgaris, and Heuchera Americana L.* (left to right).

2.2. Experimental setup

A new experimental setup was designed to measure the uptakes of leaves and the full-size plant under irradiation with NOx and O_3 configurations.

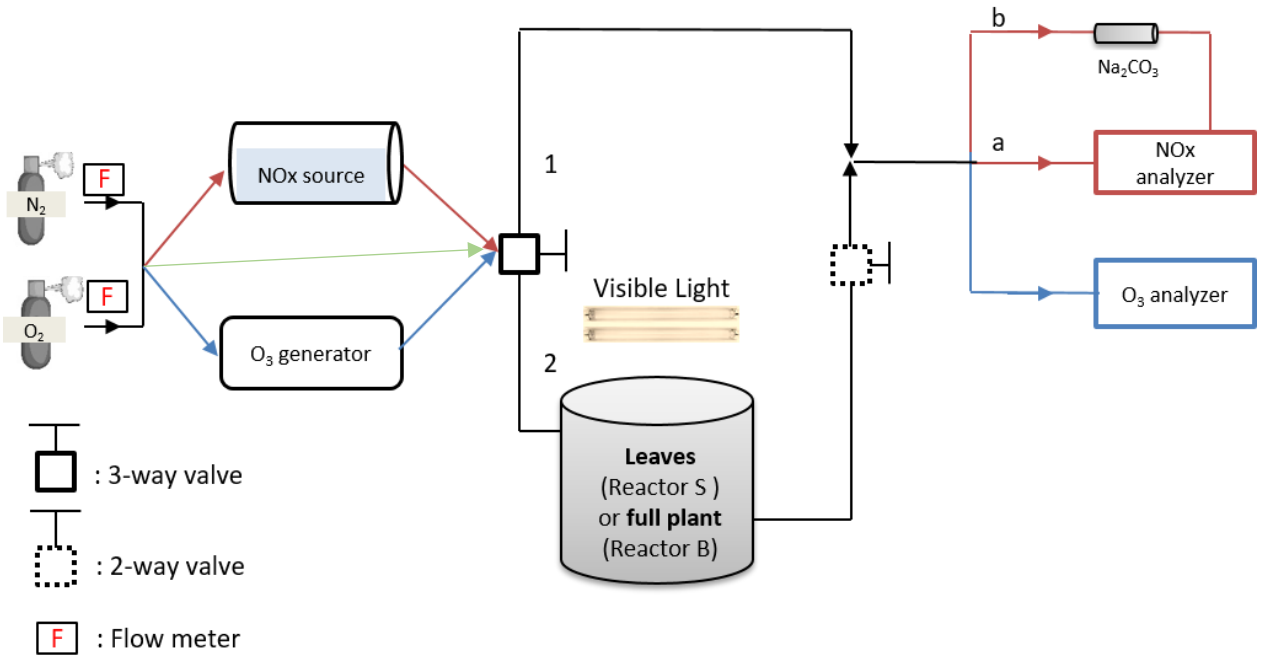


Fig.2. Experimental setup used for measuring the uptake of NO_2 (red) and O_3 (blue).

NOx/O_3 setup The setup includes:

1. Two flow meters (Brooks 4800 series/ 50-500 ml/min) to regulate the flow of O_2 and N_2 simultaneously mimicking the ratio of these gases in ambient air.
2. An NOx source via a 200 ml solution of IMD (10^{-5} M) producing 40-50 ppbv of NO_2 and 0.1-0.5 ppbv of NO contained in a cylindrical Pyrex glass flow-reactor (0.65 L, length 27 cm and internal diameter 5.7 cm). This was based on our previous study showing that irradiating a solution of IMD with a polychromatic light (λ_{max}= 365 nm) leads to the production of NOx (NO + NO_2) with NO_2 being the major product [27].

   A UVP ozone generator equipped with a UV pen-ray lamp that uses the photochemical reaction of O_2 under UVC (185 nm) to produce the continuous flow of O_3.

3. Two air-tight stainless-steel reactors (see **Fig.SI-2.**) that are cylindrical with a Pyrex glass top window for irradiation. A small one (Reactor S- 0.6 L) for leaves and a big reactor (Reactor B- 12 L) for the full-size plant.

4. 2x55W Starlite tubes (λ= 400-800 nm) that were placed at a distance of ≈30 cm above the reactors for irradiation. Absolute Irradiance at this distance was 6-7 μW/cm^2/nm @ 610 nm. This lamp is commonly used for growing plants indoors where it covers the light range needed for photosynthesis (see spectrum **Fig.SI-3.**).
5. A NOx Thermo scientific 42i model-NO NO_2 NOx analyzer (chemiluminescence analyzer). To measure the nitrous acid (HONO) and estimate its contribution to the NO_2 measured levels, a Na_2CO_3-impregnated quartz filter was installed upstream of the NOx monitor, to trap HONO. Its concentration was then calculated by measuring the difference between measured NO_2 values with and without the HONO scrubber.

   An O342e ozone analyzer O_3 (Environnement S.A). Both analyzers were online real-time analyzers with a 10 s temporal resolution.

The tubes used were PTFE (Teflon) to minimize secondary reactions, the fitting and valves were stainless steel from Swagelok (Lyon-France), and the temperature was regulated to 23 °C by an air conditioner.

2.3. Calculation of deposition velocities and plant uptake coefficients

For the plants tested in this study, transient deposition velocities (v_d) for NO_2 and O_3 were calculated, similar to Poppendieck et al. [28] and Abbass et al.[29], based on a mass balance that is shown in equation (1):

$$\frac{dC_{out}}{dt} = \lambda(C_{in} - C_{out}) - v_{d(p)}C_{out}\frac{A_{(p)}}{V} - v_{d(c)}C_{out}\frac{A_{(c)}}{V} \quad (1)$$

Where $\frac{dC_{out}}{dt}$ represents the change in the outlet O_3 or NO_2 concentration (ppb h^{-1}), C_{in} and C_{out} are the outlet concentration of NO_2 or O_3, in the inlet and the outlet of the exposure chamber (ppbv), respectively, λ is the air exchange rate for the chamber (h^{-1}), $v_{d(p)}$ and $v_{d(c)}$ are the deposition velocities for a plant and chamber (m/h), respectively, $A_{(p)}$ and $A_{(c)}$ are the exposed

area of the plant and chamber walls (m^2), respectively. Eq. (1) was solved for the transient deposition velocity shown in equation (2):

$$v_{d(p)}^{t} = \frac{V}{A_{(p)}} \frac{1}{C_{out}^{t}} \left[\lambda \left(C_{in}^{t} - C_{out}^{t} \right) - v_{d(c)} C_{out} \frac{A_{(c)}}{V} - \frac{C_{out}^{t} - C_{out}^{t+1}}{\Delta t} \right] \quad (2)$$

Where $v_{d(p)}^{t}$ is the time varying deposition velocity for a plant, t and t indicate consecutive data points (h), V is the volume of the test chamber. The deposition velocity associated with chamber walls $v_{d(c)}$ was observed to be negligible for all experiments. To facilitate comparison across plants, the near steady-state deposition velocity was calculated when the rate of change in exit concentration was less than 2 ppb over 15 min. The uptake coefficients U_p^t were then calculated by multiplying the deposition velocity $v_{d(p)}^{t}$ by the inlet concentration of NO_2 or O_3 (C_{in}^{t}) after its conversion from ppbv to $\mu g/m^3$ (eq. 3).

$$U_p^t = v_{d(p)}^{t} \left(C_{in}^{t} \right) \quad (3)$$

2.4. Analytical methods

VOC analysis. The composition of VOC produced by the three plant species was determined using headspace gas chromatography coupled with mass spectrometry detection (HS-GC/MS; Shimadzu HS-20 coupled with QP2010SE). 1 g of leaves from each species was transferred into a 20 mL headspace glass vial and incubated for 10 min at 80 °C. The analytical column (Mega 5-MS 30 m × 0.25 mm) was operated initially at 60°C for 1 min, followed by an 8°C min^{-1} ramp to reach 240°C and held for 4 min. The mass spectrometer source was heated to 200°C, and signals were detected between mass to charge ratios (m/z) of 50 and 350. Identification of the major constituents was carried out using the NIST 17 database and when necessary, using authentic standards.

ATD-GC-MS. After the ozonation of thyme leaves, the reactor gas phase was sampled for 3 min at a sampling rate of 100 mL min^{-1} into the Tenax sorbent tubes. After sampling, the tubes were thermally desorbed using TurboMatrix thermal desorption unit (ATD 150, Perkin Elmer) equipped with a cold trap (Carbotrap 300) and coupled to an Agilent 6890 gas chromatograph and an Agilent 5973 mass spectrometry detector. The separation of desorbed volatiles was carried out using a HP-5 μs column (25 m × 0.25 mm × 0.25 μm) operated initially at 50 °C for 1 min, followed by a 10°C/min ramp to reach 230°C. Mass spectra were scanned between m/z 35 and m/z 350 with the source temperature set at 20°C.

HPLC-DAD. HPLC analyses were performed using a NEXERA XR HPLCDAD apparatus. Separation was conducted using a phenomenex reversed phase C18 column (100 mm × 2.1 mm, 2.6 μm particle size) and a binary solvent system composed of 10% acetonitrile and 90% water at a flow of 0.2 mL/min. Analysis time was 10 minutes. HPLC analyses allowed the monitoring of thymol disappearance as well as its absorption spectrum.

Scanning electron microscopy (SEM). The structure of thyme cuticular surfaces before and after ozonation were characterized using scanning electron microscope. Leaves were mounted on aluminum stubs using double-sided adhesive tape and sputter-coated with 10-15 nm gold-palladium (20 s, 25 mA, partial argon pressure 60 mTorr, Denton Desk V. The samples were investigated with a field-emission scanning electron microscope (SH 4000 M) using a 20 kV acceleration voltage and a 10 mm working distance. Pictures were taken from adaxial and abaxial leaf surfaces.

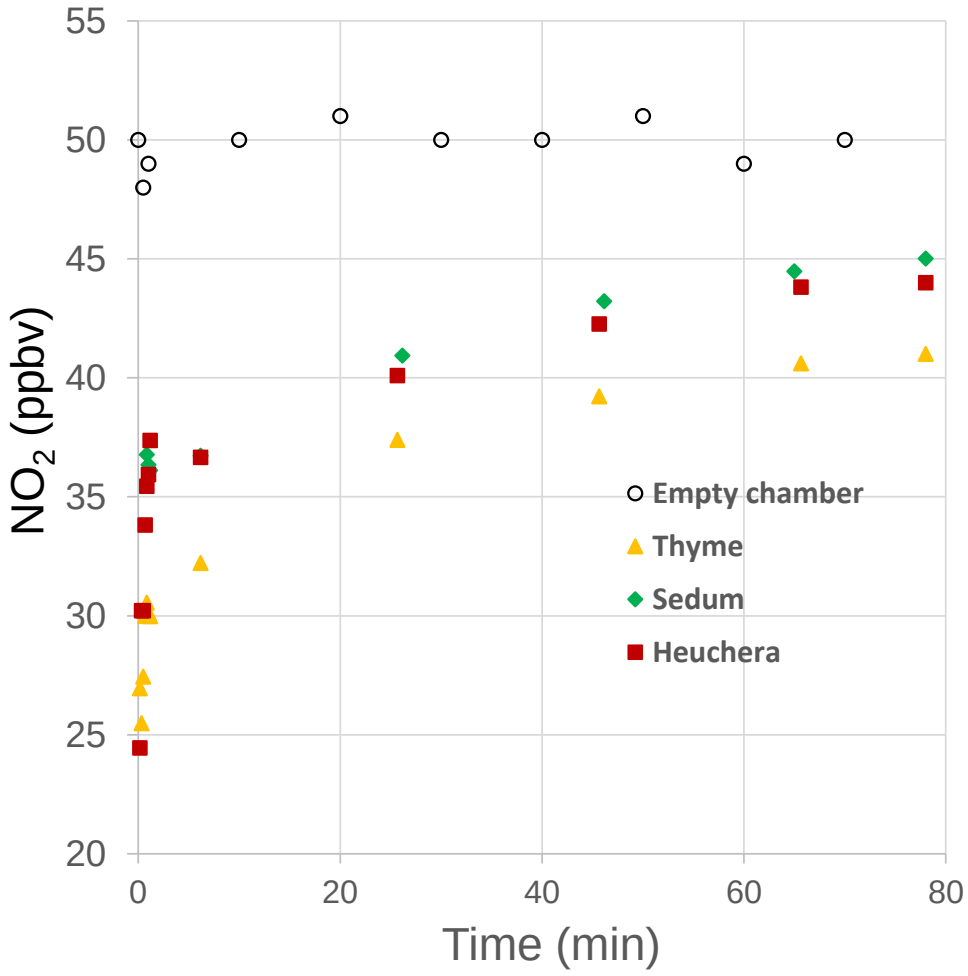
3. RESULTS AND DISCUSSION

3.1. Depollution capacity of detached leaves

3.1.1. NO_2 uptake

A maximum of 1 g of leaves was irradiated in the reactor for 1 hr while being ventilated with pure synthetic air at a flow rate of 0.8 L/min (green line in Fig. 2) under visible light allowing the plant to adapt to the conditions given before measuring the uptake. During this period, NO_2 generated by IMD was

directly monitored and its average concentration was found to be relatively stable around 50 ± 2 ppbv. Following the 1 h pre-conditioning of the plant, NO_2 gas flow was introduced into the reactor containing the detached leaves and the NO_2 concentration was monitored initially every 10 seconds and then regularly until reaching a steady-state to calculate the NO_2 uptake. In control experiment, NO_2 flow was passed through empty chamber (no leaves) and its concentration showed negligible drop suggesting a negligible background removal of NO_2 due to chamber walls (See Fig. 3). In the presence of detached leaves of green roof species, the chamber exit concentration of NO_2 concentration increases quickly in the first minute as the chamber is filled with constant level NO_2 followed by a slower and progressive increases until approaching a steady-state after 1h of exposure. At the end of the experiment, thyme showed the highest NO_2 uptake with a reduction of about 9 ppbv in NO_2 concentration followed by sedum and heuchera with a reduction of about 5-6 ppbv. The near steady-state deposition velocities for the three plants were calculated by averaging the last 15 min of the exposure.



211 **Fig.3.** Empty chamber and outlet NO_2 concentration for sedum, thyme, and heuchera.

212 **Table 1** shows the near steady-state NO_2 deposition velocities and corresponding uptake coefficients
213 for the three plant species tested. While Heuchera seems to perform as good as sedum according to Fig. 3,
214 the exposed surface of its leaves was twice higher than that for Sedum and Thyme due to its large leaves.
215 Yang et al [16] estimated the removal capacity of 71 green roofs using a big leaf dry deposition model and
216 reported an average uptake coefficient of 260 µg/m^2/h for NO_2 which is comparable to the values reported
217 in this study. In addition, the calculated $v_{d(p)}^{t}$ (1.70 – 5.56) fall also within the range of v_d in their model
218 (0.36 – 21.6 m/h). Our values are also in agreement with those reported by Currie and Bass [20] who used
219 the UFORE model (urban forest effects model) and grass as a proxy unit for green roofs and reported an
220 NO_2 uptake of 300 µg/m^2/h.

Table.1. Near steady-state NO_2 deposition velocities and plant uptake coefficients

Plant	$v_{d(p)}^{t}$ (m/h)	U_p^t (µg/m^2/h)
Sedum	2.99	282
Thyme	5.56	523
Heuchera	1.70	160

To better understand the uptake mechanisms and the difference between studied species, several experimental factors such as the stomata, water and chemical reactions were investigated.

- **Effect of stomata**

Leaf stomates are very important organs on the leaf surface as they control exchange of plants with the environment. In general, green plants affect air pollutants by taking up gaseous pollutants primarily through leaf stomates. The higher the density, the more CO_2 and gaseous pollutants can be absorbed or released [30].

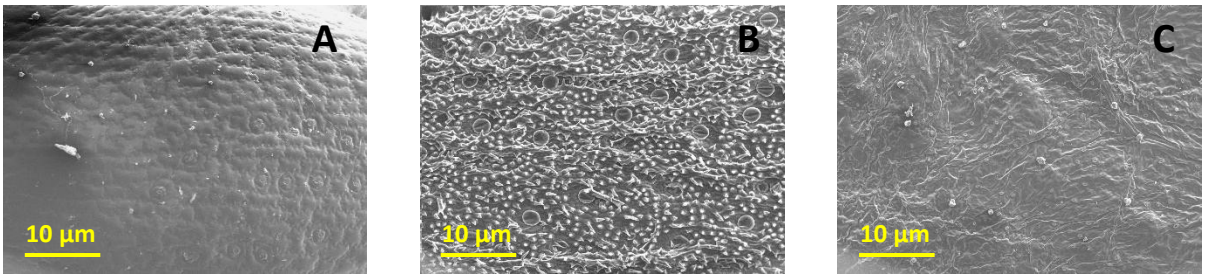


Fig.4. SEM Images of the three studied plants: sedum (A), thyme (B), and heuchera (C).

Using SEM, we observed the stomates on each leaf and estimated the stomatal density and average stomatal areas by taking into consideration abaxial and adaxial sides. Highest stomata density was seen with heuchera followed by thyme and sedum (40 mm^{-2} ± 2, 6 mm^{-2} ± 2, and 4 mm^{-2} ± 2 respectively). However, thyme exhibited the largest stomatal area (8400 ± 150 µm^2) while those of sedum and heuchera were equal to 5700 ± 150 µm^2 and 1400 ± 150 respectively. This finding suggests that the higher stomatal area for thyme could be responsible for its better performance in removing NO_2.

- **Effect of transpiration (surface reaction)**

A fraction of the consumption of NO_2 could be due to reactions with VOCs emitted by the plants. In general, NO_2 has a low reactivity towards VOCs. However, NOx might generate O_3 by photolysis under UV. As UV was not present, this pathway should be negligible. An alternative possibility is the decay of NO_2 through reaction with water leading to the formation of nitrous acid or HONO (process 1).

$$2NO_2 + H_2O \rightarrow HONO + HNO_3 \qquad \textbf{(process 1)}$$

Such reaction is possible in the case of sedum particularly as it is an evergreen plant with moist leaves and transpiration can occur. In our experiments, sedum might release moisture after being irradiated and its water might react with NO_2 to yield HONO. We checked this hypothesis by performing experiments aiming to monitor the formation of HONO. This was done by including Na_2CO_3 trap to sample HONO as described in the experimental section. In the same conditions as before, 1 g of leaves was irradiated under visible light for 1 h and the NO_2 uptake was monitored using sodium carbonate as a trap. The difference in the NO_2 uptake in the presence and absence of the trap reveals the uptake due to the reaction between NO_2 and water. Comparing the NO_2 values with and without the trap, we conclude that 55% of the uptake capacity was due to the reaction as shown in **process 1**. In the case of other species, no significant HONO production was observed, confirming that NO_2 uptake in the case of sedum is enhanced by surface water and its reaction with NO_2. This finding highlights the importance of chemical reaction in addition to stomatal uptake in the overall performance of plant species and could have implication on the photochemistry of air pollutants since HONO can undergo direct photolysis to produce hydroxyl radicals ($OH^{\bullet}$).

3.1.2. O_3 uptake

Fig.5. illustrates the time evolution of the outlet concentration of O_3 in the case of an empty chamber and in presence of the three studied plants. The same steps were followed as the ones in part 2.1 using

same plants, irradiation system, and duration (1 hour of pre-conditioning in the chamber). As for the experiment with NO_2, thyme showed the highest O_3 uptake with a reduction of about 10 ppbv followed by sedum and heuchera with a reduction of about 6-7 ppbv. **Table.2** shows the near steady-state O_3 deposition velocities and plant uptake coefficients for the three studied plants calculated by averaging the last 20 min of the exposure.

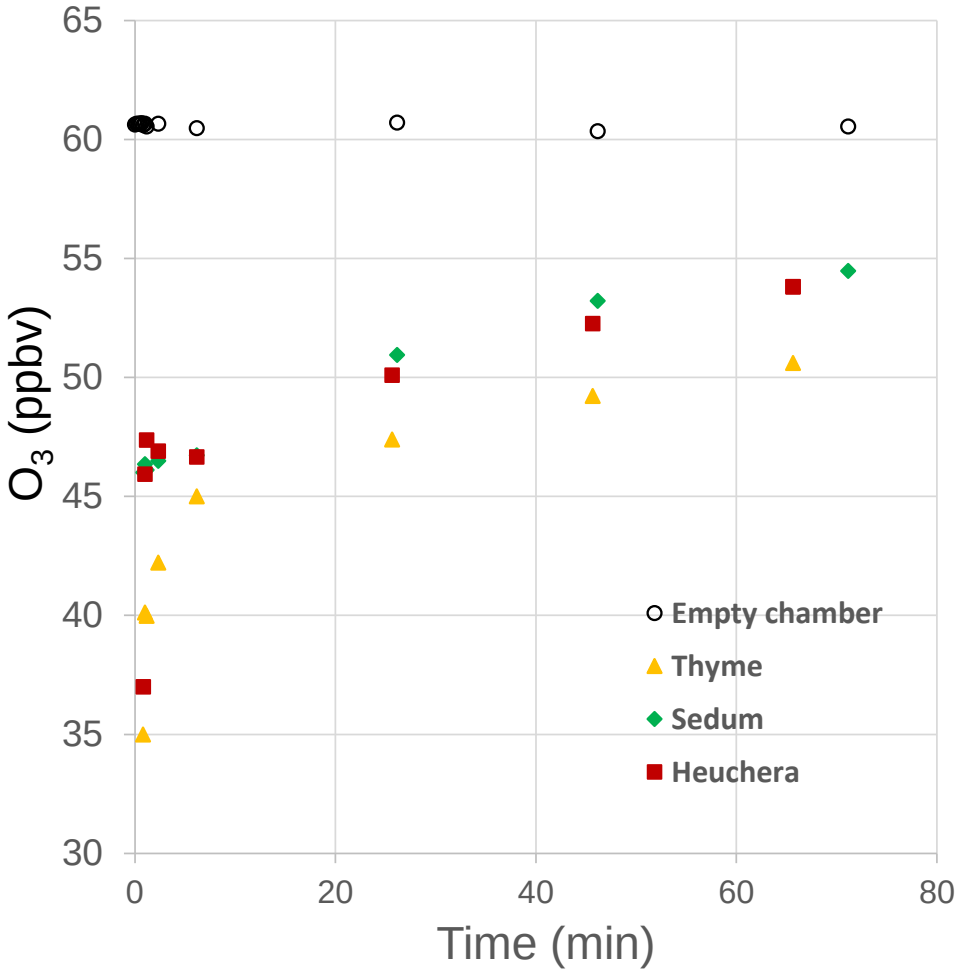


Fig.5. Empty chamber and outlet O_3 concentration for sedum, thyme, and heuchera.

Table.2. Near steady-state O_3 deposition velocities and plant uptake coefficients**.**

Plant	$v_{d(p)}^{t}$ (m/h)	U_p^t (µg/m^2/h)

Sedum	2.69	317
Thyme	4.82	569
Heuchera	1.60	189
Yang et.al [10]	1.8	100-6500
Curie et. Bass [11]	0.18	-

The calculated values in our study are in agreement with those reported by Yang et al. [16] whereas the study of Curie et Bass [20] showed lower values compared to those found here.

- **Effect of thyme volatile metabolites**

While the higher stomatal area can be responsible for the better performance of thyme in removing O_3, O_3 can potentially react with plant volatile metabolites particularly in the case of thyme which is known to release several terpenes in addition to thymol. For these reasons, thyme was selected as the main species to study in the following experiments. For a simpler approach, experiments were undertaken with one of the major emitted VOC, thymol (a phenolic derivative), first in solution to examine the feasibility of thymol degradation by O_3 and to facilitate the identification of by-products. O_3 reactions in solutions can be easier to perform and could provide a first indication of possible heterogeneous reactions between thymol and O_3 on leaves. Water can also be present on leaf surface and could participate in the reaction mechanisms. Following this feasibility test, additional experiments on thyme leaves were carried out to mimic realistic conditions and to investigate the heterogeneous reactivity of thyme volatiles with O_3.

Reaction of thymol with ozone in solution. We prepared a 20 ml solution of thymol ($2x10^{-4}$ M) in ACN and O_3 at a concentration of 4 ppm was bubbled into it for almost 6 h. Results were monitored by HPLC-DAD analysis that showed that 50 % of thymol was degraded. The percentage of degradation is related to ozone and thymol concentrations. According to a study on the catalytic ozonation of thymol, the simplified proposed degradation mechanism is the following: the *para* and *ortho* positions of the hydroxyl on thymol are attacked by O_3 and hydroxyl radical. This leads to diols with a backbone of cymene (**Fig.6.**). Several reactions then can take place prompting mineralization [25].

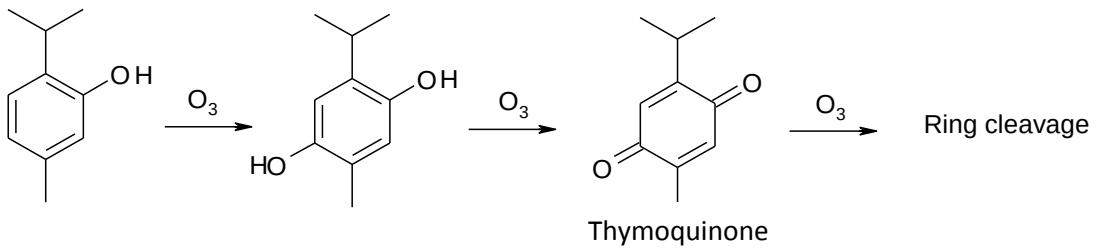


Fig.6. Thymol degradation pathway via the reaction with O_3.

The GC-MS analysis of an experiment conducted on thymol and O_3 revealed the production of Thymoquinone which corroborates the proposed mechanism.

Reaction of thyme VOCs with ozone. Two samples of detached thyme leaves (2 g) were introduced into Pyrex flow-reactors, under irradiation with visible light. To monitor the effect of O_3, the first sample (S1) was not exposed to O_3 while the second (S2) was exposed to O_3 (153 ppbv). In both cases, the production of VOC was monitored via sampling on sorbent tubes followed by ATD-GC-MS analysis.

Table.3. shows the four major terpenes emitted in addition to thymol. After 1 h of ozonation, their levels decreased drastically as expected since terpenes are known to undergo oxidation by O_3. This was associated with the identification of various oxidation products such as linalool-oxide, keto-limononaldehyde and thymoquinone. This finding confirms the role that plays thyme VOC metabolites in the observed good performance for the removal of O_3. However, while the uptake of ozone can be enhanced by the emission of terpenes, one should consider the consequences of O_3 reactions with terpenes since it can lead to the formation of secondary organic aerosols (SOA) [31]. Unfortunately, this was not confirmed here but future experiments are needed to measure the possible emission of ultrafine particles due to reaction of O_3 with thyme volatiles, and to estimate its impact on air pollution.

Table.3. Major VOC products identified in S1 and S2.

Sample	VOC collected mass (ng)				
	Cymene	***Limonene***	***Thymol***	***Eucalyptol***	***Linalool***
S1 (no O_3)	12.6	8.5	22.5	13.2	31.3
S2 (with O_3)	0.4	Non detected	Non detected	0.3	1.6

306 3.2. Depollution capacity of thyme full-size plant

307 3.2.1. NO_2/O_3 uptakes

308 These following experiments were conducted using a small thyme plant (with an estimated total leaf
309 area of 500 cm^2) which was pre-conditioned in the big reactor (12 L) with 1 h visible light irradiation
310 while soil was fully covered during experiments to ensure the least interference possible. After 1h of
311 exposure to NO_2 (50 ppbv) the NO_2 concentration dropped to reach a near-steady state around 10 ppbv.
312 Using eq.(1) and (2) we calculated a $v_{d(p)}^{t}$ of 3.84 m/h. In the case of O_3, same conditions were used as
313 with detached leaves with the exception of O_3 inlet concentration which was increased to 110 ± 3 ppbv to
314 reduce measurement uncertainty. Under these conditions, O_3 concentration dropped by around 91 ppbv to
315 reach 19 ppbv after 1h of exposure (Fig. SI-4). Assuming a near steady-state condition we obtained a
316 $v_{d(p)}^{t}$ of 4.65 m/h. These values are comparable with those obtained using detached leaves particularly
317 when considering the uncertainty in the estimation of total leaf area, presence of soil, emission of volatile
318 metabolites and the measurement uncertainty. It is noteworthy that a small production of NO was
319 observed when thyme plant was irradiated which was not detected with detached leaves.NO is a key
320 signaling molecule in plant physiology. However, its production in photosynthetic organisms remains
321 partially unresolved. The best characterized NO production route involves the reduction of nitrite (NO_2^-)
322 to NO via different non-enzymatic or enzymatic mechanisms. To better characterize the role of soil in the
323 production of NO and the uptake of pollutants, additional experiments using soil only were carried out.

324 - **Effect of soil on NOx production and uptake and of O_3 uptake**

Soil, as well, is used on green roofs so its uptake towards NO_2 and O_3 in addition to its NOx production were studied. In these experiments the same soil used for thyme was studied here.

NOx production. After 1 h of visible light irradiation, a mixture of N_2 and O_2 (pure synthetic air) was passed through the reactor containing the soil to monitor the NO/NO_2 production. Studied soil was either wet or dry, but the steps were the same in both cases. Only NO was produced at a level of ≈ 20 ppbv in the case of dry soil, and ≈ 10 ppbv in that of wet soil (**Fig.SI-5.**). Irrigation, N-fertilizers, and bacteria are known to be responsible for NO_2 production [32]. In our experiments, the adsorbed NO_2 is probably undergoing reactions producing $NO_{(g)}$ in case of both dry and wet soils; or reacting with water producing ions e.g. NO_2^- and NO_3^- (case of wet soil).

NO_2/O_3 uptake. The same experimental steps were followed as in section 3.2. In the case of O_3 (see Fig. SI-4), the reduction in concentration (Δ) for exposed soil ranged between 85 (dry) and 88 (wet) ppbv which is very close to that observed with thyme (91 ppbv). This suggests that soil can also be as effective in removing O_3 and could contribute to increase the overall performance of green roofs. On the other hand, soil contributed to the removal of 15 ppbv (wet) to 35 ppbv (dry) of NO_2 as compared with about 40 ppbv for thyme (Fig. SI-6) indicating that the thyme plant is more effective in removing NO_2. The higher NO_2 uptake by dry soil is likely associated with the higher surface area available for adsorption as compared with wet soil which can be partially saturated with water.

4. CONCLUSION

Natural air pollution mitigation approaches are needed to help improve air quality especially in urbanized areas. One promising recommended approach is the use of green roofs. In this study, we developed a new NO_2/O_3 bench-scale experimental system to measure the depollution performance of different green roofs species.

After the screening of several species, 3 species were found to be the most efficient for the NO_2/O_3 uptakes: *sedum sexangulare*, *thymus vulgaris*, and *heuchera americana L*. They offer a diversity

between being aesthetically pleasant, drought tolerant, climate resilient, and exhibiting good uptakes. NO_2 uptake coefficients ranged from 160 to 523µg/m^2/h while that of O_3 varied between 189 and 569 µg/m^2/h. These findings are in accordance with previously reported data using the big-leaf dry deposition models. Nevertheless, values were relatively higher in our experiments possibly due to other mechanisms than dry deposition (adsorption) such as the reactions between the VOCs and O_3 especially in the case of thyme, and between NO_2 and water in the case of the evergreen plant: sedum -which are not considered yet in models. If we apply our experimental results using the existing model [16] by taking the average deposition velocity in our experiments (0.095 m/h for NO_2 and 0.084 m/h for O_3), the total uptake by the 3 species (sedum, thyme, and heuchera) could reach 9 kg/ha/year of NO_2 and around 13.6 kg/ha/year of O_3. Assuming that Paris has around 76 ha of green roofs and walls (2016) [33], and if the three species investigated in this study were to be used, one can estimate that 683 kg/year of NO_2 and 1037 kg/year of O_3 can be mitigated.

While our study focused only on the uptake of two air pollutants, additional research should be carried to measure the performance of green roof species towards $PM_{2.5}$ and to investigate the potential formation of SOA. In addition, our experimental design does not consider some important variables such as the effects of humidity, lighting spectrum/intensity changes, nor the diurnal and seasonal cycles of the plant. In addition, field evaluation of laboratory results should be carried in order to better understand the effects of seasonality and weather conditions on the depollution performance of green roofs.

5. ASSOCIATED CONTENT

Supporting information (e-component) 6 figures

The Volatile Organic Compounds emitted by thyme obtained by headspace-GC-MS. The small and big reactors containing the detached leaves and the full-size plant/soil. The light spectrum of the lamps used in our experiments for irradiation. O_3 uptakes by Thyme and soil (wet and dry) after

irradiation. NO production by the soil (wet and dry) after being irradiated by visible light for 1 h. NO_2 uptakes by the soil (wet and dry) after 1 h of visible light irradiation.

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