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Quantifying the potential of façade climbing plants in reducing air pollution: a novel investigation into the absorption capabilities of three climbers for CO_2, NO_2, and O_3 in urban environments

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Abstract

Air pollution and climate change will require the advancement of suitable green technologies and mitigation measures in the future, especially in cities. However, the possibilities for this are limited, partly due to the heavily built-up and thus restricted urban open space and sealed surfaces. Incorporating vertical surfaces, abundant in cities, as a valuable space for climbing plants is an ideal opportunity and means of improving air quality. Unfortunately, there are hardly any reliable quantitative facts on the improvement of air quality brought about by these climbing plants. In this study, we analysed and compared typical climbing plants with regard to their absorption potential of gaseous air pollutants. This revealed pronounced differences between *Hedera helix*, (ivy) *Lonicera henryi* (honeysuckle) and *Clematis montana* (anemone clematis) regarding their absorption/filtering capacity of CO_2, NO_2 and O_3, the last two of which are hazardous to health.

Keywords Green facades · Urban climate · Air pollution · Air phytoremediation · NO_2 · Ozone · Carbon dioxide

Introduction

One unique and innovative approach to urban greening is the use of climbing plants in facade greening. Their ability to grow vertically and to cover large surfaces not only presents a distinct solution to the limited horizontal space in densely populated urban areas but also enhances buildings` aesthetic appeal and energy efficiency (Aduse-Poku et al. 2024a, b; Hoelscher et al. 2016). More importantly, these plants reduce urban heat island effects through shading of building surfaces, transpiration and reduction of the overall thermal load of buildings, lowering the overall temperature in urban areas during summer and also improving air quality; one of the ultimate goals of city planners and managers striving to create climate-sensitive urban environments (Baumgardner et al. 2012; Buchin et al. 2016).

Urban air quality is a critical determinant of public health, especially in densely populated neighbourhoods where pollution levels tend to be high (European Environment Agency 2022). Poor air quality in cities is primarily caused by vehicle emissions, industrial activities, and other human activities that release pollutants such as carbon dioxide (CO_2), nitrogen dioxide (NO_2), and ozone (O_3) into the atmosphere (European Environment Agency 2022). These pollutants have been linked to various adverse health effects; improving urban air quality therefore is a vital public health concern. Exposure to high CO_2 -, NO_2 -, and O_3- levels can lead to respiratory and cardiovascular problems (Nowak et al. 2014; Tang et al. 2024). Globally air pollution accounted for a staggering 8.1 million deaths in 2021; an estimation of great concern, as 709,000 were children under 5 years old.

Worldwide, ozone was reported to have contributed to nearly 490,000 deaths, while exposure to NO_2 contributed to the loss of 177,000 healthy years for children and adolescents in the same year (Health Effects Institute 2024).

By understanding and addressing the impacts of air pollutants, cities can create healthier environments for their inhabitants, fostering better public health and well-being.

Various studies have shown that plants have the potential to absorb greenhouse gases and pollutants (Buchin et al. 2016; Jones et al. 2019). Cities increasingly aim to adopt this practical and multi-purpose solution for improving air quality. Yet, the nature and structure of cities (prevalent sealing with concrete, asphalt, underground

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infrastructure like communication cables, etc.) make implementing trees very difficult. On the other hand, façade climbing plants have been identified as an excellent option for utilising vertical spaces on city buildings due to their adaptive nature.

Façade greening has recently gained attention due to its numerous benefits, of which air quality improvement is a general main feature. Unfortunately, research into their contribution to reducing gas pollutants is limited, making it necessary for this knowledge gap to be filled for a scientifically based holistic view of their contributions to air quality improvement.

In this study, the absorption potential of three typical façade climbing plants—*Hedera helix* "Plattensee," (Araliaceae) *Clematis montana* (Ranunculaceae) and *Lonicera henryi* (Caprifoliaceae)—with respect to carbon dioxide (CO_2), nitrogen dioxide (NO_2) and ozone (O_3) is analysed to comprehend and assess their phytoremediation potentials. The results presented for the three typical climbing plants provide a scientific basis for evaluating and appraising the phytoremediation potential rarely found for climbing plants.

Materials and methods

Plant preparation and experimental setup

For measurements, pot plants previously grown in the field were transferred and placed in special glass chambers, designed for the flow-through experiments. The plants were maintained at room temperature and well-watered before the experiments. Five (5) individuals of each plant species except for *C. montana* (consisting of 4 individuals) were separately investigated in a 90-L volume glass chamber, as principally illustrated in Fig. 1. The experiments were conducted in a laboratory setting using a photosynthetic lamp with photosynthetic active radiation (PAR) = 950 µm/s/m^2, following the protocols detailed in (Aduse-Poku et al. 2024a, b).

Principal experimental setup

Gas administration and measurement

The experiments involved injecting NO_2, and CO_2 from gas cylinders and O_3 from an ozone generator using a pen-ray UV lamp. Additionally, N_2O was introduced into the reaction chamber through ambient air and in the case of $H_2O_{(g)}$, due to the transpiration of the plants. This created a gas mixture that mimics the external environment with the corresponding pollutant load. High-resolution measuring devices, namely: mid-infrared direct laser absorption spectrometer (MIRO Analytical AG, Wallisellen CH-8304, Switzerland; type MGA10—GP +) and a cavity-ring-down spectrometer (Picarro Inc. Santa Clara, CA 95054, USA; type G2307) recorded peak concentration values after gas injections.

The concentrations of these gases were measured over time as they passed through the chamber's outlet. Since the gases of interest (CO_2, NO_2, and O_3) were known to be absorbed by plants, there was the need to use nitrous oxide (N_2O), a stable greenhouse gas with an atmospheric lifetime of 123 years (Prather et al. 2015); in the troposphere N_2O is regarded as an inert noble gas. Thus, N_2O will not be absorbed by plants and pass through the reaction chamber with unchanged concentrations. Due to its inert nature in the troposphere, it was used as the control in this experiment, providing a base/reference line for comparison.

Leaf surface area measurement

After the gas absorption experiments, the leaves of each plant were detached from the plants to quantify their surface area. A gravimetric method was employed in the estimation directly after detachment. This data was essential in calculating the gas absorption rates/deposition velocity per unit leaf area (Aduse-Poku et al. 2024a, b).

Data analysis

The decrease in the concentration of the injected gases (NO_2, O_3, and CO_2) was analysed and compared to that

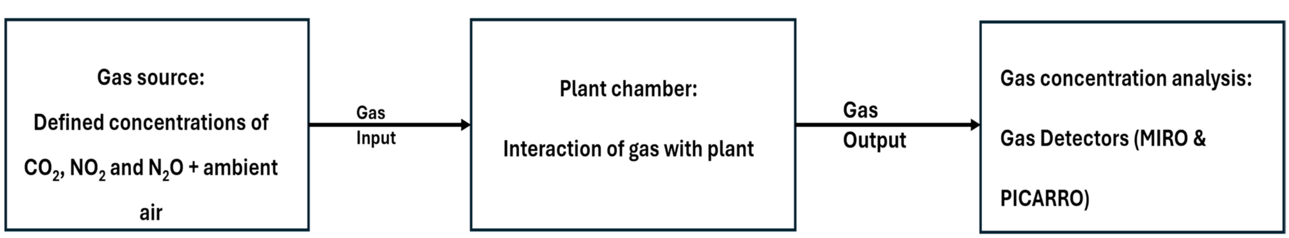

Fig. 1 Diagram depicting the principal experimental setup to analyse the gas absorption potentials of different climbers

of N_2O. This allowed for the calculation of net decreases in concentration over time. The absorption rate for each gas was then determined by considering/referring to each plant's total leaf surface area. Total amounts (mass) absorbed were then calculated according to the prevailing concentration at each point in time. All experiments under each species were analysed using descriptive statistics and ANOVA.

Results

Generally, the plants showed preferences in the type of gases absorbed; NO_2, CO_2, and O_3 were significantly reduced. In contrast, N_2O showed no significant change within the experimental period of about 1 h per each experiment carried out. Also, in additional experiments, i.e. the flow-through tests without plants, no gas absorption was observed (see online resource 4), so that an interaction of the gases with the reaction chamber can be excluded.

One conspicuous finding was the general diurnal absorptive behaviour of the plants. This effect is reflected in the plants' almost insignificant absorptive behaviour during the dark phase and a profound effect under light conditions (representing a clear indication of stomata-controlled absorption). The decrease in gas pollutants in the chamber followed an exponential decay curve, as shown in Fig. 2, highlighting an example of the absorptive trend of concentration reduction in the chamber under light conditions. In Fig. 2, one can observe both gases decreasing exponentially at very different rates. Denoted as 1/e (Euler number e ≈ 2.718) a standard measure to describe the point at which a quantity has reduced to approximately 36.8% of its initial value and mostly used as a measure of decay rates, the absorption of NO_2 depicted in orange was shown to have reached the 1/e = 0.37 on the y-axis within 100 s while the unperturbed N_2O, represented by the blue curve, reached the same 1/e at 600 s. These two values represent the decay time scale for both gases, which is used in the estimation process. Each single value shown in Fig. 3 is based /originates from decay curve analysis as illustrated in Fig. 2.

This decay (rate of reduction) trend resulted in the derivation of the following parameters:

$$\frac{\partial X(t)}{\partial t} = (P\_Inj + P\_plant) - (D\_plants + D\_surface + D\_DIL) \cdot X(t) \quad (1)$$

X	compound of interest
t	time
P_Inj	production rate by dedicated injection of X
P_plant	production rate of X by the plants
D_plants	loss rate coefficient due to removal by the plants
D_surf	loss rate coefficient for removal at the surfaces of the chamber
D_DIL	loss rate coefficient for dilution inside the chamber due to inflow of synthetic air

$$A(t) = A0 \cdot e^{-t/\tau} + offset \quad (2)$$

Where $A0 = (X(t = 0) - P\_plant/D)$, $\tau = 1/D$, and $offset = P\_plant / D$. (Aduse-Poku et al. 2024a, b) The parameter τ signifies the time a gas molecule spends in the plant chamber. The parameters A0, τ, and offset were

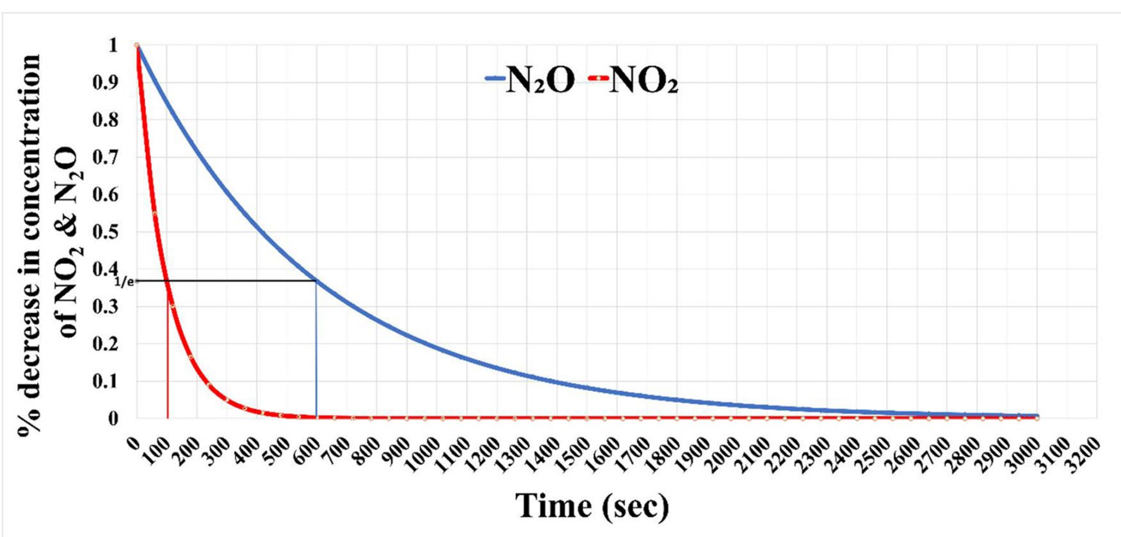

Fig. 2 Decay (time scale) of NO_2 & N_2O as measured in the plant chamber output under light conditions

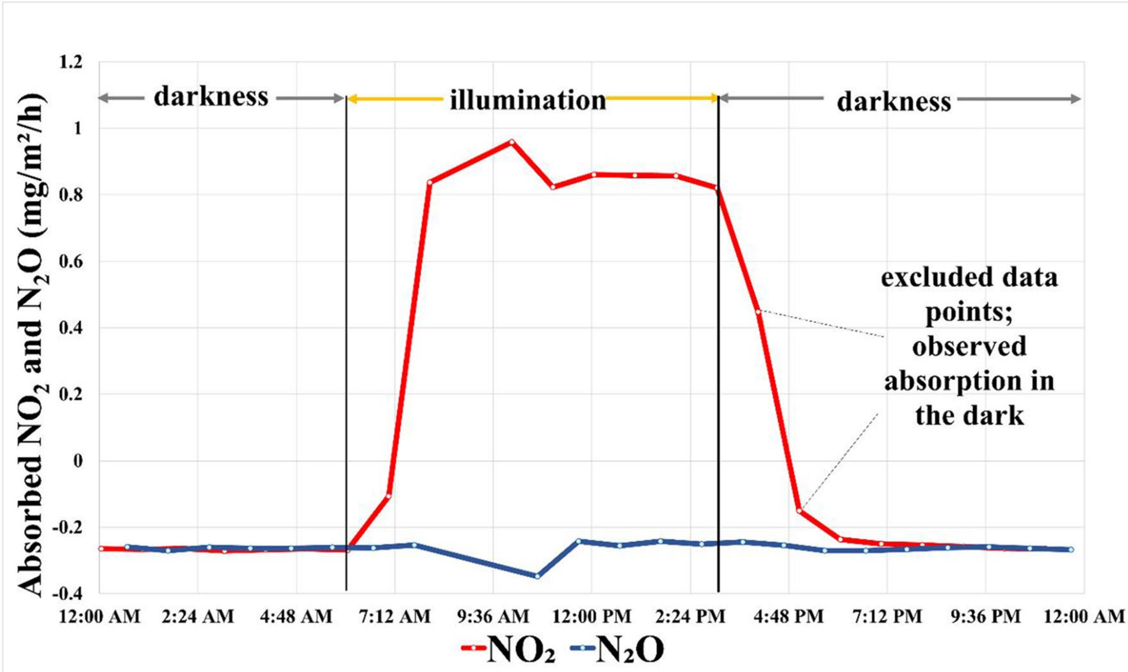

Fig. 3 Diurnal absorption trend of NO_2 (blue line) and N_2O (red line) in *Hedera helix*, derived from the results of decay curves (Fig. 1), as the origin of each point, plotted in this curve as a function of light- and dark conditions

established through iterative processes using a Levenberg–Marquardt algorithm (Gavin 2019) upon visual examination, it was noted that the decrease in gas concentrations (CO_2, NO_2, O_3, and NO_2) following injection closely adhered to the specified pattern given in Eq. 2 most of the time, except for instances where the lighting changed within the timeframe being analysed, leading to pronounced shifts between light and dark. This was because the parameter D_plant was not consistent during that period due to the opening or closing of the stomata in response to light. These specific time points were omitted from the analysis, as the fitting process could not account for these complex decay trends.

Each experiment was analysed following the processes described in detail in (Aduse-Poku et al. 2024a, b) and Fig. 2 above, at concentrations of about 400 ppm for CO_2, 40 ppb for NO_2, and 80 ppb for ozone (in other words, each point in Fig. 3 originates from an independent experiment). These differences were computed for each point during the light and dark phases, as shown in Fig. 3 below. Experimental observations do not start from 0 due to the emission of gases in the dark phase of plant metabolism. Observations of gas absorption in an empty chamber resulted in no absorption of gases (see online resource 4).

Further data analysis will concentrate on the amount of each gas (CO_2, NO_2, and O_3) absorbed in the light phase of the experiment due to the light-dependent absorption trend observed in the example (Fig. 3) above, which can be attributed to stomatal closure during the dark- and opening during the light phase of the experiment.

Absorption of carbon dioxide (CO_2)

H. helix "Plattensee" exhibited an average absorption rate of 0.06 mg/m^2/s, while *C. montana* showed a higher average absorption rate of 0.09 mg/m^2/s. *L. henryi* had an average absorption rate of 0.07 mg/m^2/s, as depicted in Fig. 4. These values indicate that *C. montana* absorbed gases more effectively than the other two species in this study. Given that the *P*-value (0.24) exceeds the alpha level of 0.05 (see online resource 1), we fail to reject the null hypothesis. This indicates that based on the data collected in this study, there are no statistically significant differences in the carbon dioxide absorption rates among *H. helix* "Plattensee," *C. montana*, and *L. henryi*. Therefore, the observed variations in average absorption rates are likely due to random chance rather than actual differences between the species.

Absorption of nitrogen dioxide (NO_2)

A comparative analysis delivered significant differences in absorptive capabilities among the plant species *H. helix* "Plattensee," *C. montana*, and *L. henryi*. The mean measurement values of 0.07 µg/m^2/s, 0.06 µg/m^2/s, and 0.03 µg/m^2/s, along with their respective 95% confidence

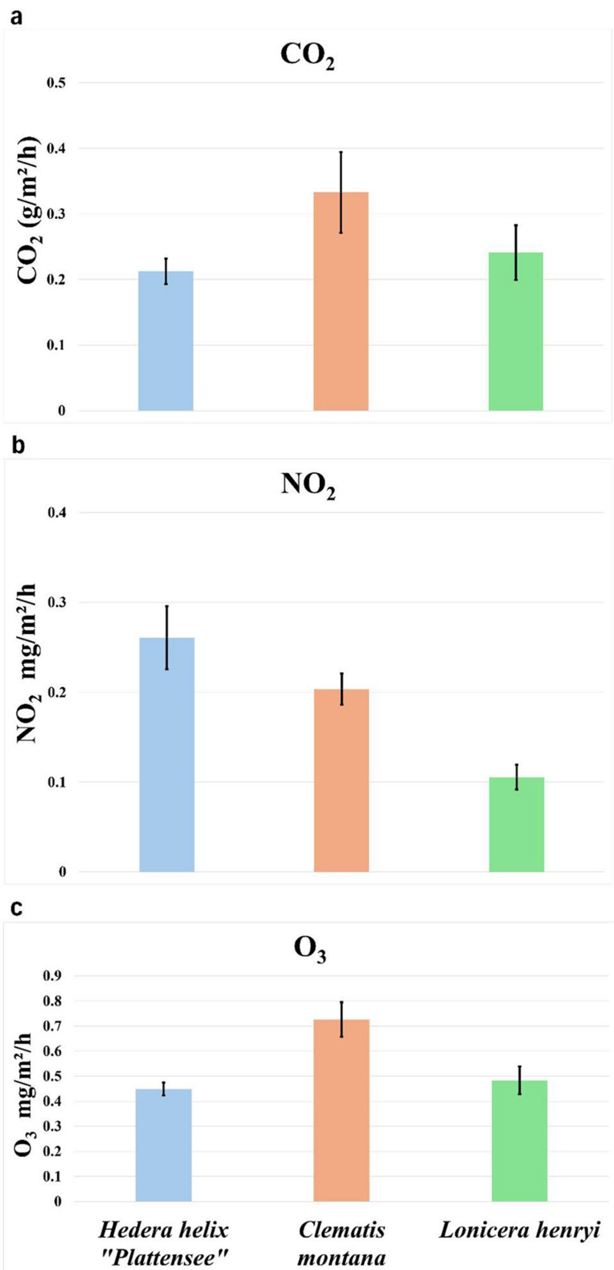

Fig. 4 Absorption potentials of 3 climbers used in façade greening with standard error bars. **a** – carbon dioxide/CO_2 ($n=81,34,109$). **b** – nitrogen dioxide/NO_2 ($n=64,34$ and 67), **c** – Ozone/O_3 ($n=53$, 29 and 63), by *H.helix*, *C.montana*, and *L. henryi*, respectively, under light conditions

intervals, provided valuable insights. ANOVA analysis showed significant group differences (P-value 4.54686E-05), and post hoc comparisons indicated most (2/3) group differences were statistically significant ($P<0.017$) (see online resource 2).

Absorption of ozone (O_3)

The experiment yielded average absorption rates of 0.12, 0.20, and 0.13 µg/m^2/s for *Hedera helix, C. montana,* and *L. henryi*, respectively. All values obtained for each species satisfied the 95% confidence interval, indicating reliable measurements. An ANOVA analysis yielded a P-value of 0.002 (supplementary data), demonstrating significant differences among the groups. Subsequently, a post hoc pairwise comparison using the Bonferroni correction, with an adjusted significance level of 0.017, revealed substantial differences in all pairings except for the comparison between *H. helix* and *L. henryi*. This suggests that while most group differences were statistically significant, the difference between *H. helix* and *L. henryi* was insignificant under the adjusted threshold.

Discussion

In recently growing discussions about the many urgent measures resulting from climate change, more and more voices are being raised in favour of green architecture. However, the specific benefits of the various plants used for this purpose are hardly known. The results of our analysis on three species typically used for façade greening reveal detailed, specific characteristics with regard to their capacity to purify various air pollutants. To facilitate meaningful comparisons with other data and to provide a comprehensive understanding of the plant's capacity for pollutant absorption over a more extended period, the observed absorption rates were converted to annual rates (g or µg/m^2/s to kg/ha/a) by multiplying the average annual sun hours in Germany (1764 h in 2023).

Contribution of climbing plants to carbon sequestration

There is a net positive effect concerning carbon absorption and its storage by climbing plants. Climbing plants are characterised by a positive net performance in terms of carbon uptake and storage. This is evident in Fig. 5b, which depicts well-formed woody vines of the plant *Parthenocissus tricuspidata.*

However, the detailed intricacies of the absorbed CO_2 fixed in the form of biomass in the long term cannot be determined within the framework of the study presented here; yet, it can be assumed that a certain proportion is released again through respiration processes (Hartmann et al. 2020; Wang et al. 2016; Zelitch 1969). It would require a longer-term *in-situ* study with many

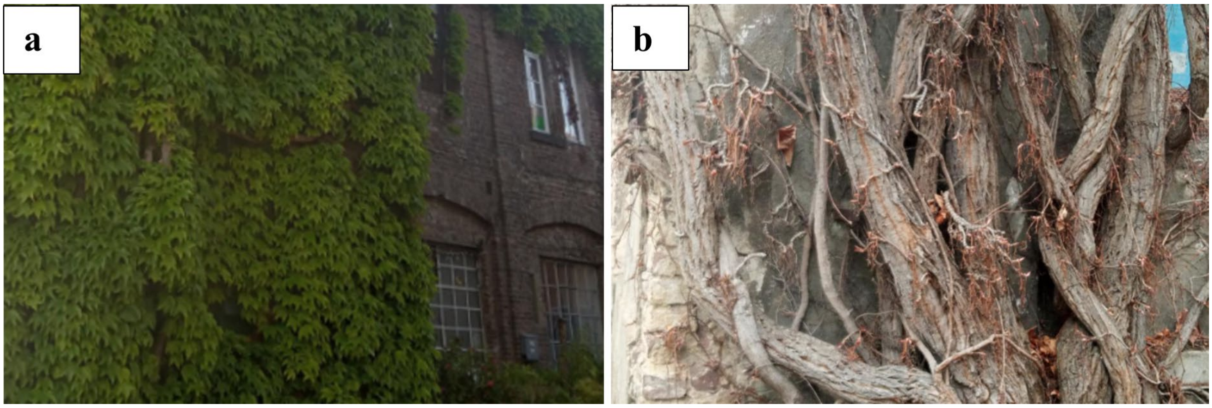

Fig. 5 **a** – Images of foliage-covered vines of *P. tricuspidata*, **b** – Exposed (enlarged) basal vines during deciduousness (illustrating carbon storage)

imponderable aspects, which could only yield operationally defined approximations.

Furthermore, climbers in cities are mainly cultivated for other ecosystem services they provide, such as heat reduction (improving building energy efficiency) (Aduse-Poku et al. 2024a, b; Hunter et al. 2014), aesthetics, biodiversity, besides air quality improvements, which we seek to quantify in this paper.

Climbers generally necessitate a strict management regime that involves regular pruning of their vegetation to control their extent of growth, encourage new shoots, and, as a precautionary measure, regulate the load-bearing capacity of the walls and climbing aides on which they grow. While the reasons mentioned above present challenges, they do not entirely preclude the potential of climbing plants as carbon storage systems in cities. These plants still offer unique advantages that warrant further exploration.

Relevance of CO_2 absorption by urban climbing plants

Urban areas are significantly responsible and contribute to global CO_2 emissions due to transportation, industry, heating, and energy consumption. Addressing these anthropogenic emissions is crucial for mitigating climate change and improving urban air quality. Our results indicate that climbing plants in cities can absorb up to 0.09 mg/m^2/s (0.33 g/m^2/h.) or approximately 6000 kg of CO_2 per hectare per year (see Fig. 4a). The absorption rate per leaf area found in our study is in the range reported for trees (Jo and Mcpherson 1995; Strohbach et al. 2012).

To understand and evaluate the significance of these absorption rates, it is, for example, helpful to compare it with the emissions of CO_2 from private cars, prevalent in urban settings.

Private cars in Europe emit an average of 145 to 153 g of CO_2 per km for petrol and diesel cars, respectively (using the real-world dataset) (Marrero et al. 2020). To put the absorption capacity of urban plants into context, we can estimate the distance that would correspond to the emission of 6000 kg of CO_2 by a private car. This means that one hectare of urban plant leaf surface area absorbing 6000 kg of CO_2 per year offsets the emissions from a car traveling approximately 40,000 km annually. The average annual car distance is estimated at around 18000 km (Marrero et al. 2020). This could account for about 2.2 years of carbon emissions compensation or at least a year, if half of the carbon absorbed is devoted to another loss process in the plant, such as respiration, etc.

Our findings may be useful for urban planners to advocate for the expansion of urban green vertical walls, as their unique climbing abilities fit seamlessly into the efficient use of building vertical spaces.

Contribution of climbing plants to NO_2 reduction

Nitrogen dioxide (NO_2) is a significant air pollutant, primarily emitted from industrial processes, vehicle exhausts, and power generation. It poses severe risks to human health and the environment (Tang et al. 2024). NO_2 is known to cause a range of respiratory problems, including asthma, bronchitis, and other lung diseases. Chronic exposure can lead to diminished lung function and increased susceptibility to respiratory infections (Mele et al. 2021; Tang et al. 2024). By absorbing NO_2, plants help to reduce the concentration of this harmful pollutant in the air, thereby lowering the incidence and severity of these health issues among urban populations.

In the city context, climbing plants' ability to absorb NO_2 is a critical ecological service. Hedera helix's measured maximum absorption rate of 0.07 μg/m^2/s (0.26 mg/m^2/h), or approximately 5 kg per hectare per year (see Fig. 4 b), substantially benefits urban environments. This significant reduction in NO_2 levels can reassure urban residents about potential health benefits from façade greening.

The obtained results support the deduction that plants inherent affinity for absorption can be considered; this observation can, in turn, be leveraged towards targeted pollution control in cities, where high NO_2-polluted areas can be selected and targeted with *H. helix* and *C. montana*, for example.

NO_2 is crucial in forming ground-level ozone, a harmful pollutant that exacerbates respiratory conditions and damages crops. By absorbing NO_2, plants can help limit ground-level ozone production. This role of climbing plants in reducing ground-level ozone can bring optimism about potential improvements in air quality and healthier ecosystems (Nguyen et al. 2022), contributing to better air quality and healthier ecosystems.

NO_2 also contributes to the formation of acid rain (Menezes and Popowicz 2022), which can harm water bodies, soil, and plant life. By increasing the use of vertical spaces on buildings for façade greening, the potential for plants to absorb NO_2 can increase, helping mitigate the impact of acid rain. With their high absorption rates, climbing plants can significantly reduce the concentration of NO_2 in the air, thereby reducing the formation of acid rain. This protects aquatic and terrestrial environments and helps maintain biodiversity, making climbing plants valuable to urban air quality control strategies.

The investigated plants' absorption of 5 kg of NO_2 per hectare per year is well within the range of other studies involving other tree species. This is a significant ecological service that offers multiple benefits for urban areas (Jones et al. 2019; Nowak et al. 2018). With the ongoing prioritization of air quality and public health in cities, greening existing vertical spaces on buildings should be a key component of urban planning and environmental management efforts.

Significance of ozone absorption by climbing plants in urban air quality control

Ground-level ozone (O_3) is a significant pollutant concern affecting cities today. (Låg and Schwarze 1997). It is formed by the reaction of sunlight with pollutants such as volatile organic compounds (VOCs) and nitrogen oxides (NOx) (Tiwari and Agrawal 2018). High ozone levels can cause respiratory problems, exacerbate asthma, and reduce lung function, posing significant health risks to urban populations (Bell et al. 2007).

In this study, climbing plants absorbed up to 0.2 µg/m^2/s (ca. 0.73 mg/m^2/h) or an approximated 13 kg/ha/a. of ozone (see Fig. 4c). This finding is well in the range of similar studies conducted on trees (Baumgardner et al. 2012; Guidolotti et al. 2016).

Ozone is a major component of smog and is known for its adverse effects on human health and vegetation (Fiscus et al. 2005).

Lowering ozone levels can lead to fewer respiratory problems among urban residents. This may help reduce hospital admissions, improve public health, and lower healthcare costs. Reducing ozone exposure can significantly improve the quality of life for individuals with pre-existing respiratory conditions (Fiscus et al. 2005).

When implemented on a large scale, the cumulative effect of ozone absorption by climbing plants across multiple hectares can be substantial. For instance, greening initiatives that cover hundreds of hectares of leaf area can absorb significant amounts of ozone, leading to measurable improvements in air quality.

Conclusion

This study highlights the significant potential role of climbing plants in urban air quality management. With the capacity to absorb approximately 13 kg of ozone (O_3), 5 kg of nitrogen dioxide (NO_2), and substantial amounts of carbon dioxide (CO_2) per hectare per year, these plants provide crucial ecological services. Depending on the building density and building structure, cities offer a multiple of potential vertical green spaces relative to the built-up area, which in the case of city centres alone extends to many square kilometres. This means that, in addition to the potentially greenable roof areas, the existing vertical façade area offers many-fold potential for greening.

The calculation of pollutant absorption per hectare provides a useful standardized metric; however, it is important to note that the actual absorption capacity largely depends on the vegetation's leaf area index (LAI) and other factors including light availability, which in many cases could be a factor of 3 – 5 and more, depending on species, age, etc. (Hoelscher et al. 2016). This translates to a very significant absorption capacity when viewed from the point that a few climbing plants do not necessarily have to cover a whole acre of land to possess a hectare of leaf area.

Though quantified in an operationally defined environment in order to allow for reproducibility, the presented values may be subject to change depending on prevailing conditions in-situ in nature. These facts, however, apply to almost all ecophysiological studies.

In general, large-scale implementation of green walls and facades covered with climbing plants can significantly improve air quality, contribute to public health, and urban climate resilience at a relatively cheaper cost. By integrating such green façade infrastructure into urban planning, cities can effectively reduce harmful pollutants. The use of climbing plants can therefore contribute to compliance with the air pollution limits set by the relevant authorities, to the enhancement of biodiversity, to urban aesthetics and to the promotion of long-term health and sustainability.

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Author contributions M. A.-P. an the experiments and prepared the figures and also contributed to the text also written by H.G.E.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

References

Aduse-Poku M, Niels W, Pacini A, Großschedl J, Edelmann HG, Schlüter K (2024a) Façade greening – from science to school. At-Automatisierungstechnik 72:694–703. https://doi.org/10.1515/auto-2024-0022

Aduse-Poku M, Rohrer F, Winter B, Edelmann HG (2024b) Methodology for the quantification of the absorption potential of greenhouse- and pollutant gases by climbing plants used in façade greening; a case study on ivy (*Hedera helix*). Environ Adv 17:100568. https://doi.org/10.1016/j.envadv.2024.100568

Baumgardner D, Varela S, Escobedo FJ, Chacalo A, Ochoa C (2012) The role of a peri-urban forest on air quality improvement in the Mexico City megalopolis. Environ Pollut 163:174–183. https://doi.org/10.1016/j.envpol.2011.12.016

Bell ML, Goldberg R, Hogrefe C, Kinney PL, Knowlton K, Lynn B, Rosenthal J, Rosenzweig C, Patz JA (2007) Climate change, ambient ozone, and health in 50 US cities. Clim Change 82:61–76. https://doi.org/10.1007/s10584-006-9166-7

Buchin O, Hoelscher MT, Meier F, Nehls T, Ziegler F (2016) Evaluation of the health-risk reduction potential of countermeasures to urban heat islands. Energy Build 114:27–37. https://doi.org/10.1016/j.enbuild.2015.06.038

European Environment Agency (2022) Air quality in Europe 2022 — European environment agency. https://www.eea.europa.eu/publications/air-quality-in-europe-2022. Accessed 06.02.2025

Fiscus EL, Booker FL, Burkey KO (2005) Crop responses to ozone: Uptake, modes of action, carbon assimilation and partitioning. Plant Cell Environ 28:997–1011. https://doi.org/10.1111/j.1365-3040.2005.01349.x

Gavin HP (2019) The levenberg-marquardt algorithm for nonlinear least squares curve-fitting problems. Duke University. https://api.semanticscholar.org/CorpusID:113404737

Guidolotti G, Salviato M, Calfapietra C (2016) Comparing estimates of EMEP MSC-W and UFORE models in air pollutant reduction by urban trees. Environ Sci Pollut Res 23:19541–19550. https://doi.org/10.1007/s11356-016-7135-x

Hartmann H, Bahn M, Carbone M, Richardson AD (2020) Plant carbon allocation in a changing world – challenges and progress: introduction to a Virtual Issue on carbon allocation: Introduction to a virtual issue on carbon allocation. New Phytol 227:981–988. https://doi.org/10.1111/nph.16757

Health Effects Institute (2024) State of global air 2024. Special report. Boston, MA:Health Effects Institute

Hoelscher MT, Nehls T, Jänicke B, Wessolek G (2016) Quantifying cooling effects of facade greening: Shading, transpiration and insulation. Energy Build 114:283–290. https://doi.org/10.1016/j.enbuild.2015.06.047

Hunter AM, Williams NSG, Rayner JP, Aye L, Hes D, Livesley SJ (2014) Quantifying the thermal performance of green façades: a critical review. Ecol Eng 63:102–113. https://doi.org/10.1016/j.ecoleng.2013.12.021

Jo H-K, Mcpherson EG (1995) Carbon storage and flux in urban residential greenspace. J Environ Manage 45(2):109–133. https://doi.org/10.1006/jema.1995.0062

Jones L, Vieno M, Fitch A, Carnell E, Steadman C, Cryle P, Holland M, Nemitz E, Morton D, Hall J, Mills G, Dickie I, Reis S (2019) Urban natural capital accounts: developing a novel approach to quantify air pollution removal by vegetation. J Environ Econ Policy 8:413–428. https://doi.org/10.1080/21606544.2019.1597772

Låg M, Schwarze PE (1997) Helseeffekter av bakkenaert ozon [Health effects of ozone in the environment]. Tidsskr Nor Laegeforen 10;117(1):57–60

Marrero GA, Rodríguez-López J, González RM (2020) Car usage, CO2 emissions and fuel taxes in Europe. Series 11:203–241. https://doi.org/10.1007/s13209-019-00210-3

Mele M, Magazzino C, Schneider N, Strezov V (2021) NO2 levels as a contributing factor to COVID-19 deaths: The first empirical estimate of threshold values. Environ Res 194:110663. https://doi.org/10.1016/J.ENVRES.2020.110663

Menezes F, Popowicz GM (2022) Acid rain and flue gas: quantum chemical hydrolysis of NO2. ChemPhysChem 23:1–6. https://doi.org/10.1002/cphc.202200395

Nguyen DH, Lin C, Vu CT, Cheruiyot NK, Nguyen MK, Le TH, Lukkhasorn W, Vo TDH, Bui XT (2022) Tropospheric ozone and NOx: A review of worldwide variation and meteorological influences. Environ Technol Innov 28:1–13. https://doi.org/10.1016/j.eti.2022.102809

Nowak DJ, Hirabayashi S, Bodine A, Greenfield E (2014) Tree and forest effects on air quality and human health in the United States. Environ Pollut 193:119–129. https://doi.org/10.1016/j.envpol.2014.05.028

Nowak DJ, Hirabayashi S, Doyle M, McGovern M, Pasher J (2018) Air pollution removal by urban forests in Canada and its effect on air

quality and human health. Urban Forestry Urban Green 29:40–48. https://doi.org/10.1016/j.ufug.2017.10.019
Prather MJ, Hsu J, DeLuca NM, Jackman CH, Oman LD, Douglass AR, Fleming EL, Strahan SE, Steenrod SD, Søvde OA, Isaksen ISA, Froidevaux L, Funke B (2015) Measuring and modeling the lifetime of nitrous oxide including its variability. J Geophys Res 120:5693–5705. https://doi.org/10.1002/2015JD023267
Strohbach MW, Arnold E, Haase D (2012) The carbon footprint of urban green space-A life cycle approach. Landsc Urban Plan 104:220–229. https://doi.org/10.1016/j.landurbplan.2011.10.013
Tang Z, Guo J, Zhou J, Yu H, Wang Y, Lian X, Ye J, He X, Han R, Li J, Huang S (2024) The impact of short-term exposures to ambient NO2, O3, and their combined oxidative potential on daily mortality. Environ Res 241. https://doi.org/10.1016/j.envres.2023.117634
Tiwari S, Agrawal M (2018) Tropospheric Ozone Budget: Formation, Depletion and Climate Change. In: Tropospheric Ozone and its Impacts on Crop Plants. Springer International Publishing 31–64. https://doi.org/10.1007/978-3-319-71873-6_2
Wang B, Shugart HH, Shuman JK, Lerdau MT (2016) Forests and ozone: Productivity, carbon storage, and feedbacks. Sci Rep 6. https://doi.org/10.1038/srep22133
Zelitch I (1969) Mechanisms of carbon fixation and associated physiological responses. In: Eastin JD, Haskins HA, Sullivan CY, van Bavel CHM (eds.) Physiological Aspects of Crop Yield 206–226 https://doi.org/10.2135/1969.physiologicalaspects