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Potted plants can remove the pollutant nitrogen dioxide indoors

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Abstract
Nitrogen dioxide (NO_2) is a significant pollutant in both outdoor and indoor environments with exposure linked to serious respiratory illnesses, decreased lung function and airway inflammation. Here, we investigate whether potted plants can contribute as a simple and cost-effective indoor air pollution mitigation technique. Our study investigates the ability of the combination of the three plant species *Spathiphyllum wallisii* 'Verdi', *Dracaena fragrans* 'Golden Coast' and *Zamioculcas zamiifolia* with two different growing media to remove in situ concentrations (100 ppb) of NO_2 in real-time at two typical indoor light levels (0 and 500 lx) and in 'wet' and 'dry' growing media conditions. All studied 'growing medium–plant systems' were able to reduce NO_2 concentrations representative of a polluted urban environment, but to varying degrees. The greatest NO_2 removal measured inside a 150 L chamber over 1-h period in 'wet' growing media at ~ 500 lx was achieved by *D. fragrans*. When accounting for dilution, this would correspond to a removal of up to 3 ppb NO_2 per m^2 of leaf area over the 1-h test period and 0.62 ppb per potted plant over the same period when modelled for a small office (15 m^3) in a highly polluted environment. Depending on building ventilation rates and NO_2 concentration gradients at the indoor-outdoor interface that will vary massively between polluted urban and rural locations, potted plants offer clear potential to improve indoor air quality—in particular in confined indoor spaces that are poorly ventilated and/or located in highly polluted areas.

Keywords Indoor air quality · Indoor plants · Nitrogen dioxide · Pollutants · Potted plants

Introduction

Nitrogen oxides (NO_x) in urban environments

Nitrogen oxides (NO_x) have been shown to react to produce ground level ozone, increase susceptibility to ill health, particularly respiratory infections and also affect soil chemistry (DEFRA 2019). Within the UK, 34% of the NO_x is produced by road transport (DEFRA 2019). The most noxious component of NO_X is the pollutant nitrogen dioxide (NO_2) (WHO 2010). The UK government has set aside £255 million in the form of 'the NO_2 plan', specifically implementing mitigation measures to reduce roadside emissions such as bus retrofits, clean air zones, traffic signal improvements and the phase out of diesel cars by 2040 (DEFRA 2017, 2019); as a pollutant, NO_2 also infiltrates indoor environments (WHO 2010).

Nitrogen dioxide (NO_2) indoors and the associated health impacts

Indoor concentrations are a function of both indoor and outdoor sources, where elevated outdoor concentrations (e.g. in cities with a greater density of traffic) will inevitably produce elevated indoor concentrations (WHO 2010). Building's proximity to roads or the presence of an attached garage shown to be the largest factor influencing indoor concentrations (Nakai et al. 1995; Janssen et al. 2001; Kodama et al. 2002). Additionally, important indoor sources of NO_2 are combustion processes (i.e. from heating appliances, fireplaces and stoves). Indoor concentrations often exceed those

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outdoors because of the presence of these additional indoor sources (Kattan et al. 2007).

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 of 40 µg m^{-3} (21 ppb)—aiming to prevent respiratory illnesses and decreases in lung function, the main symptoms of long-term exposure (especially in children) (Hasselblad et al. 1992; Koistinen et al. 2008)—and an acute health guideline of 200 µg m^{-3} (105 ppb) appropriate for both indoor and outdoor environments. However, it has been suggested that the < 40 µg m^{-3} chronic guideline is unlikely to be achievable everywhere, especially in areas with a high density of traffic (Koistinen et al. 2008). Acute exposures to high concentrations of NO_2 significantly affect vulnerable groups, e.g. asthmatics, causing minor changes in pulmonary function (at 560 µg m^{-3} for two and a half hours) and increased airway reactivity (at 500 µg m^{-3}) (Tunnicliffe 1994; Strand et al. 1998; Niimi et al. 2003). Additionally, acute exposures have been associated with airway inflammation in both healthy and asthmatic study participants (DEFRA 2019; Ezratty et al. 2014).

The EU-commissioned INDEX report collected data on mean NO_2 concentrations across Europe pre-2004 and found indoor concentrations to be in the range of 13–62 µg m^{-3} but, in homes with gas cooking and heating equipment, the short-term peak concentrations were measured between 180 and 2500 µg m^{-3}. The study found that in up to 25% of homes NO_2 levels exceeded 60 µg m^{-3} (1-week average) (Koistinen et al. 2008).

Mitigation methods to reduce indoor NO_2 levels

Reducing the indoor NO_2 concentration indoors would likely reduce health issues alongside economic savings—one study estimated savings of £60,000 per school through a reduction in asthma flare-ups and associated medical costs (based on parents' willingness to pay model, Guerriero et al. 2016). Indoors, a variety of techniques can be utilised to reduce NO_2 concentrations; these include filtration, designing ventilation systems to provide sufficient fresh air and appropriate fans and indoor ventilation for combustion systems. These all require ongoing maintenance and often large initial costs for installation. It should be noted that out of these approaches only filtration can reduce the local indoor pollutant levels to below the outdoor concentrations: ventilation systems will simply lead to an equilibration of indoor and outdoor pollutant levels which only improves indoor air quality if there is a significant concentration gradient with initially higher indoor pollution. Established filtration systems for removal of NO_2 indoors include high-efficiency particulate air (HEPA) and carbon filters (e.g. Paulin et al. 2014). Our study investigates the feasibility of a simpler approach to remove NO_2 from the gas-phase similarly to a filtration system—low-cost potted indoor plants to remove the pollutant indoors and supplement already existing mitigation techniques.

NO_2 removal by vegetation

The ability of vegetation outdoors (i.e. trees/plants) to remove NO_2 has been extensively studied (Morikawa et al. 1998; Teklemariam and Sparks 2006; Jim and Chen 2008; Vallano and Sparks 2008; Nowak et al. 2014). Plants have been shown to remove NO_2 through the stomata, simultaneously with CO_2 or O_2, or through absorption by the water present in the leaves—it can therefore be hypothesised that potted plants would do the same, and the water content of plant and growing media would play an important role (Nowak et al. 2014; Gourdji 2018). Moreover, a clear variation between plant type ability to remove NO_2 has been previously measured in a study looking at 217 different plant taxa (including indoor plant species, albeit from dry leaf analysis post-fumigation not in situ, Morikawa et al. 1998). Additionally, it has been suggested that plants with elevated leaf ascorbate concentrations are able to remove more NO_2 (Teklemariam and Sparks 2006). It can therefore also be hypothesised that different types of cultivated potted plants will remove NO_2 at different rates.

The uptake of NO_2 by plants has previously shown to be concentration-dependent; thus, testing at an appropriate guideline concentration is important (Hu and Sun 2010). Additionally, as NO_2 is removed via the plant stomatal pathway, it can be assumed—as with CO_2 (Gubb et al. 2018, 2019)—that the light levels will influence NO_2 removal ability. It has been previously shown that if more UV radiation reaches the plants, a higher NO_2 removal is measured (Teklemariam and Sparks 2006; Gourdji 2018). This study will therefore investigate the impact of two light levels on a plants' ability to remove NO_2.

Morikawa et al. (1998) investigated the ability of 217 plant taxa to assimilate ^{15}N labelled NO_2 via leaf fumigation and dry leaf analysis. This included several indoor plant species such as *Spathiphyllum* spp. And *Dracaena sanderiana*—both possessing a removal ability at the lower end of their respective families. The study found uptake of NO_2-N content to differ as much as 657-fold between all the studied taxa, 62-fold within a particular family (*Theaceae*) and 26-fold within a species (*Solidago altissima*). Additionally, the authors suggest that the metabolic pathway of NO_2-N differs among different plant types (Morikawa et al. 1998).

Pettit et al. (2019) recently reported the removal of NO_2, NO_X and O_3 via an active green wall in a closed loop flow reactor. The authors tested *Spathiphyllum wallisii* and *Syngonium podophyllum* for their ability to remove NO_2 at ambient 70 ppb (134 µg m^{-3}) and elevated concentrations

6656 ppb (12,730 µg m^{-3}) at an average photosynthetic flux density of 9.95 µmol m^{-2} s^{-1} (~ 740 lx). The results suggested that at ambient NO_2 concentrations and high indoor light levels both plant types were able to remove NO_2, with a *Clean Air Delivery Rate* (*CADR*) of 79.92 and 87.84 m^3 h^{-1} m^{-3} of biofilter substrate, respectively. The authors, however, did not investigate how humidity inside the closed reactor—which would have risen sharply due to the presence of a plant—may have affected the sensors' ability to accurately measure concentrations. Additionally, the light level and 'elevated concentrations' for the indoor measurements were far exceeding what you would normally find indoors, likely elevating the removal ability of the plants above what could be observed in real indoor environments. Pettit et al. have recently applied the systems tested successfully for botanical biofiltration both for reduction of wildfire-induced NO_2, O_3 and $PM_{2.5}$ (Pettit et al. 2020), and most recently of roadside air pollution (Pettit et al. 2021).

Our research investigates the ability of three indoor potted plant species to remove, in real-time, an in situ concentration of 100 ppb NO_2 (chronic WHO guideline) on a whole plant/growing media scale with the substrate moisture content (SMC) being 'dry' (SMC < 20%, 0.2 m^3 m^{-3}) and 'wet' (SMC > 30%, 0.3 m^3 m^{-3}) and at 'typical' (~ 500 lx, photosynthetically active radiation, PAR, ~ 15 µmol m^{-2} s^{-1}) and 'no' (0 lx) indoor light. 0 lx was chosen to investigate taxa's NO_2 removal ability in the dark (measured at night), and ~ 500 lx was chosen to represent typical office conditions. The effect of the growing media was investigated in further detail once a potentially significant contribution was identified in initial tests.

Material and methods

Plant material

Three common houseplant taxa (*Dracaena fragrans* 'Golden Coast', *Spathiphyllum wallisii* 'Verdi' and *Zamioculcas zamiifolia*) were selected for this study. They represented a range of leaf types, physiology (succulent and herbaceous) and plant sizes (Table 1). Plants were maintained in a peat-free growing medium (Sylvamix, 6:2:2 sylvafibre: growbark pine: coir; Melcourt, Tetbury, Gloucestershire, UK) in 3 L containers (19 cm wide at the top and 15 cm tall, with 227 cm^2 of exposed substrate surface area), with a slow-release fertiliser feed (Osmocote, Marysville, OH, USA). Selected potted plants were purchased one year prior to the study. Within the taxon, plant height and stature were uniform (data not shown). Prior to experimentation (for > 160 days), plants were kept at room temperatures (21–22 °C) and 'typical' light levels (~ 500 lx) in an indoor office environment within the School of Geography, Earth and Environmental Sciences, at the University of Birmingham (UK).

Growing media-only experiments

For the growing media only experiments (the NO2 chamber experiments—comparison between two different growing media section), the growing media selected were Melcourt Sylvamix medium (6:2:2 sylvafibre: growbark pine: coir; Melcourt, Tetbury, Gloucestershire, UK) and Wyevale Multipurpose Compost (58% peat; 42% green compost/coir, exact ratios not disclosed, Wyevale, Brentford, Middlesex, UK). From now on, it is referred to as Sylvamix and Wyevale, respectively.

NO_2 chamber experiments

The experimental setup (Fig. 1A) consisted of a ~ 150 L (45 × 45 × 75 cm, 0.15 m^3) Perspex chamber (custom-built by The Plastic People, Leeds, West Yorkshire, UK) connected to a 1000 ppm NO_2 in air cylinder (> 99% purity; Speciality Gases, West Bromwich, West Midlands, U.K) with a combination of PTFE tubing (¼ inch outer diameter; Sigma Aldrich, UK) and Ultratorr fittings (Swagelok London, UK). Enclosed inside the Perspex chamber was an electrochemical NO_2 sensor (Alphasense, Great Notley, Essex, UK; Fig. 1B) connected via a Raspberry Pi stack with temperature and relative humidity sensor (South Coast Science, Brighton, East Sussex, UK) and a 12 V DC brushless fan (RS Components, Corby, Northants, UK). The chamber was placed in a ventilated laboratory (at the School of Biosciences, University of Birmingham) with a mixture of natural and room lights. The external RH/temperature surrounding the chamber was monitored with a calibrated (20–90% RH ± 3%, 0–40 °C ± 0.25 °C) Tinytag RH/temperature logger (Gemini Data Loggers, Chichester, West Sussex, UK).

Table 1 Characteristics of the indoor plant taxa chosen for experiments. Leaf area ($n = 5$) and plant height ($n = 5$) are means ± SEM. Latin (botanical) name is given in italic followed by cultivar, where applicable

Taxa	Family	Metabolism	Leaf area (cm^2)	Plant height (cm)
Dracaena fragrans 'Golden Coast'	*Asparagaceae*	C3	3081 ± 72	70 ± 1
Spathiphyllum wallisii 'Verdi'	*Araceae*	C3	5013 ± 220	43 ± 1
Zamioculcas zamiifolia	*Araceae*	CAM	2147 ± 249	77 ± 1

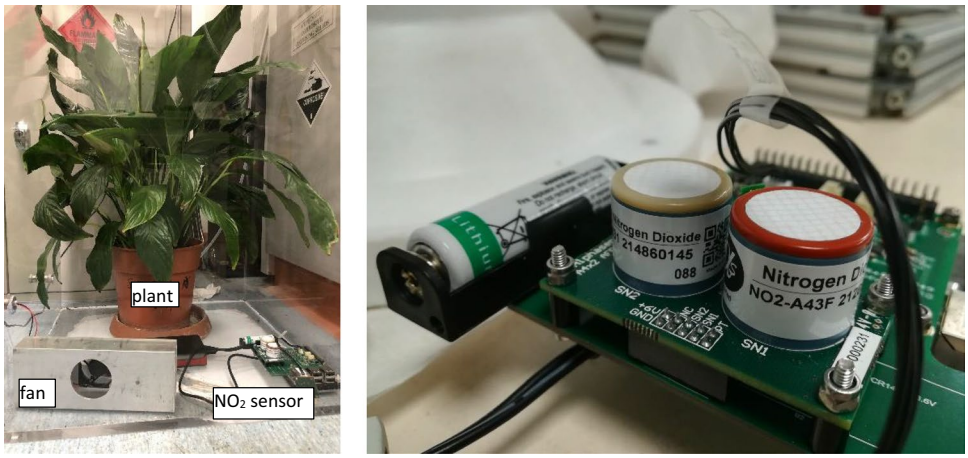

Fig. 1 Image of the experimental setup (**A**) and the electrochemical NO_2 sensor (**B**)

Inside the chamber, 'no' light (0 lx) was achieved by undertaking experiments at night; 'typical' light levels (~500 lx) were achieved in the usual lighting conditions of the experimental room—all light levels were measured prior to the experiment commencing with a calibrated light sensor (Professional Light Meter, Brannan, Cumbria, UK).

Measurements of the ability of different studied plant types to reduce NO_2 concentrations of 100 ppb (WHO acute 1-h guideline; WHO 2010) were undertaken on five plants per taxon, in 'typical' light levels and on 'wet' and 'dry' substrate, as well as in 'no light' for 'dry' (generating three experimental 'treatments', Table 2). The treatment 'no light'/'dry' was not introduced as it leads to leaf stomatal closure and thus would have been the least effective and impactful set of conditions. It was therefore decided, after preliminary tests and relatively low NO_2 removal rates even in the environmentally most favourable conditions there was no need to test this treatment for the current scope of works.

Plant taxa were prepared for experiments with growing media moisture at the container capacity (*substrate moisture content* (*SMC*) > 30%), and plants were thus considered optimally watered on the commencement of each experiment (Vaz Monteiro et al. 2016). To ascertain the growing media moisture, the SMC was measured prior to experimentation for each plant, in two locations per container using a SM300 capacitance-type probe connected to a HH2 Moisture Meter (Delta-T Devices, Cambridge, Cambridgeshire, UK; 0–100% range and an accuracy of ± 2.5%). Experiments were carried out on one whole 'plant–growing media system' (i.e. potted plant, with uncovered growing media) enclosed inside the Perspex chamber at an initial NO_2 concentration of 100 ppb (± 15%). Experiments were conducted for a duration of 1 h. Leaf area for each species was determined at the end of the experimental period on two representative plants per species using a WinDias Leaf image analysis system (Delta-T devices, Cambridge, UK).

Appropriate control measurements of the studied NO_2 concentration were run at both light levels on both the empty chamber and pot with growing media. The number of runs with only growing media and pot mirrored the replication of the number of experiments including plants ($n = 5$). Further control measurements were undertaken to assess the impact of increasing the humidity within the chamber on both the sensor functionality and the concentration of NO_2 measured. Any humidity increases (within an empty chamber) were found to have a negligible effect on the NO_2 concentration measured by the sensor (data not shown).

The chamber was also analysed for leakage prior, during and after experimentation; NO_2 background loss was found to be on average 4.5 ppb over the one-hour test period. All results were corrected for this loss. The NO_2 concentrations removed over the one-hour test period (ppb removed after

Table 2 Experimental and environmental parameters for each lighting treatment during experimentation

	'No' light		'Typical' light wet		'Typical' light dry	
	Ambient	Inside chamber	Ambient	Inside chamber	Ambient	Inside chamber
NO_2 (ppb)	< 50	-	< 50	-	< 50	-
Temperature (°C)	21–26	23–27	18–24	20–26	23–26	25–28
Relative humidity (%)	29–54	46–86	38–57	48–87	35–57	42–81

1 h; see Table 3) by each plant taxon were calculated with the data measured/logged directly every six seconds and divided by the leaf area in m^2 presented in Table 1 to enable us to calculate NO_2 in ppb removed after 1 h m^{-2} (Fig. 2). *Clean Air Delivery Rates per plant* ($CADR_p$) were calculated following Cummings and Waring (2020) and are also presented in Table 3.

Statistical analysis

The NO_2 concentrations were analysed using SPSS (26th Edition). An analysis of variance (ANOVA) was performed to compare means for each measured parameter between different taxa and/or over time. Variance levels were checked for homogeneity, and values were presented as means with associated standard error of the mean (SEM). Post hoc tests of Tukey's 95% confidence intervals were undertaken for multiple comparisons.

Results

NO_2 chamber experiments—per plant

Comparison between different plant types within treatment—per plant

No statistical differences were measured in NO_2 removal between different potted plant types in 'no' light, 'wet' growing media ($p = 0.174$) or 'typical' light 'dry' growing media ($p = 0.191$; Table 3). In 'typical' light under 'wet' growing media conditions however, a statistically significant difference in NO_2 removal was measured between *Dracaena fragrans* 'Golden Coast' and bare growing media (with *Dracaena* removing significantly more, 62 vs. 44 ppb removed after 1 h, respectively; $p = 0.03$; Table 3).

Comparison between treatments within the same plant type—per plant

Spathiphyllum wallisii removed similar concentrations of NO_2 in all three environments tested. This was also the case for bare growing media and *Dracaena fragrans* 'Golden Coast' ($p = 0.802$, 0.109, and 0.508, respectively; Table 3). However, statistical differences were measured for *Zamioculcas zamiifolia* between the treatments 'no' light 'wet' and 'typical' light 'wet' (where light significantly increased the removal of NO_2—from 47 to 58 ppb removed after 1 h, respectively; $p = 0.03$; Table 3).

Clean Air Delivery Rates—per plant ($CADR_p$)

We calculated *Clean Air Delivery Rates per plant* ($CADR_p$) following Cummings and Waring (2020) for all of the studied taxa. $CADR_p$ were found to range from 0.095 to 0.145 $m^3\ h^{-1}\ plant^{-1}$ (see Table 3) with the values for the bare growing media ranging from 0.082 to 0.101 $m^3\ h^{-1}$ per pot.

NO_2 chamber experiments—per m^2 of leaf area

'No' light, wet—per m^2 of leaf area

After one hour, statistical differences in NO_2 removal were measured between *Spathiphyllum wallisii* 'Verdi' (115 ppb removed after 1 h m^{-2}) and both, *Dracaena fragrans* 'Golden Coast' and *Zamioculcas zamiifolia* (185 and 218 ppb removed after 1 h m^{-2}, respectively; $p < 0.01$; Fig. 2). However, no statistical differences were measured between *Dracaena fragrans* 'Golden Coast' and *Zamioculcas zamiifolia* ($p = 0.08$; Fig. 2).

Table 3 Mean NO_2 removal per potted plant (ppb removed after 1 h), from inside the chamber containing 100 ppb at 'no' (0 lx) and 'typical' (~500 lx) indoor light in 'wet' (SMC > 30%, 0.3 $m^3\ m^{-3}$) and 'dry' (SMC < 20%, 0.2 $m^3\ m^{-3}$) conditions. Data are a mean of five plants per plant type ± SEM. *Clean Air Delivery Rates per plant* ($CADR_p$) calculated following Cummings and Waring (2020) are presented in square brackets. Different letters next to the means within a column indicate statistically significant differences

	NO_2 (ppb removed after 1 h) [$CADR_p$ ($m^3\ h^{-1}\ plant^{-1}$)]		
	'No' wet	'Typical' wet	'Typical' dry
Dracaena fragrans 'Golden Coast'	57 ± 1 a [0.127]	62 ± 6 a [0.145]	49 ± 4 a [0.101]
Spathiphyllum wallisii 'Verdi'	58 ± 6 a [0.130]	60 ± 3 ab [0.137]	55 ± 6 a [0.120]
Zamioculcas zamiifolia	47 ± 2 a [0.095]	58 ± 3 ab [0.130]	49 ± 3 a [0.101]
Bare growing media	49 ± 5 a [0.101]	44 ± 4 b [0.087]	42 ± 3 a [0.082]

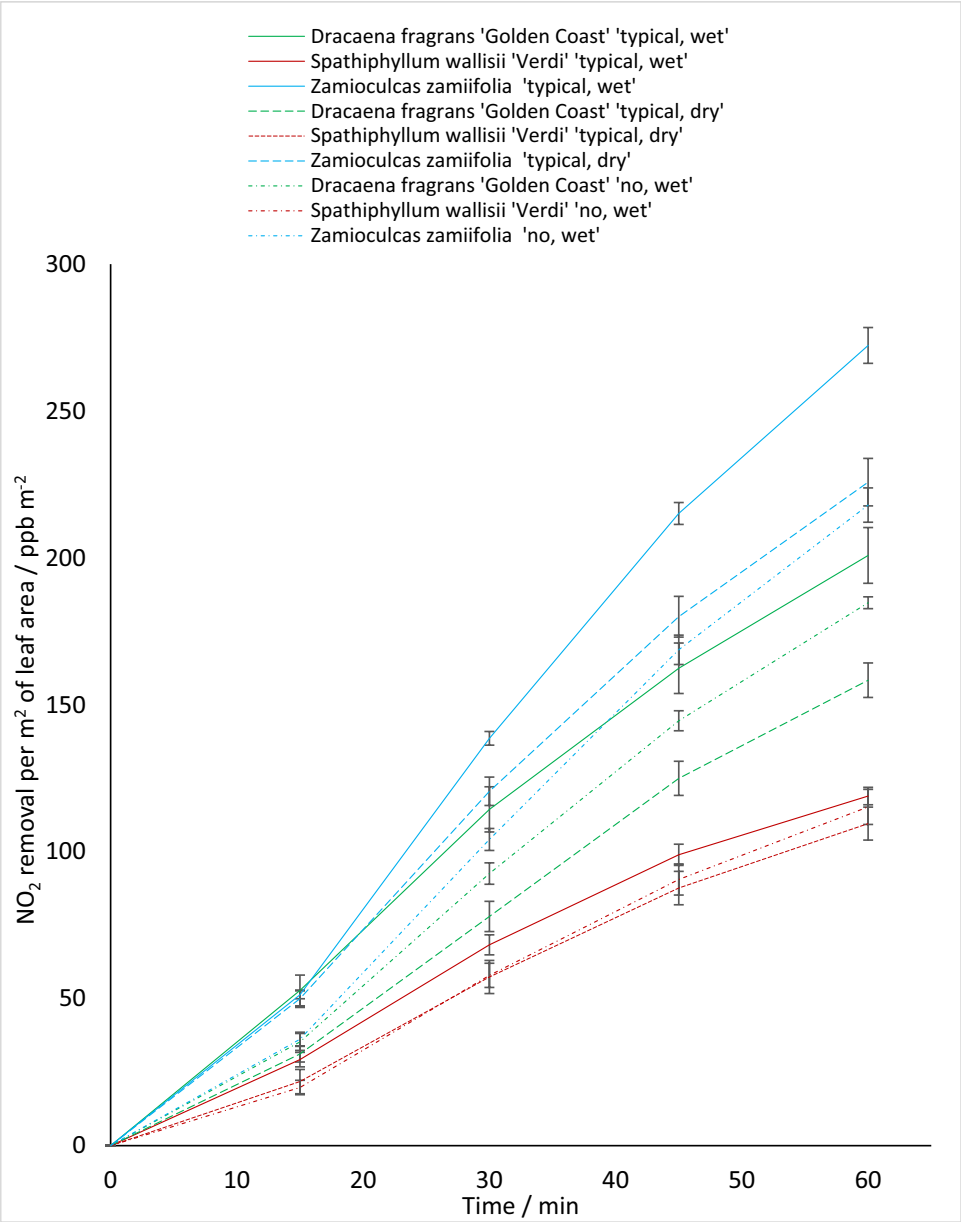

Fig. 2 Mean NO_2 removal per m^2 of leaf area as a function of time from a concentration of 100 ppb by each plant type under differing environmental conditions per m^2 of leaf area over a 1-h period (see legend). With light level defined as either 'no' (0 lx) or 'typical' (~ 500 lx) and substrate moisture content defined as 'wet' (SMC > 30%, 0.3 m^3 m^{-3}) or 'dry' (SMC < 20%, 0.2 m^3 m^{-3}). Data are a mean of five plants per plant type—error bars represent SEM

'Typical' indoor light level, dry—per m^2 of leaf area

After one hour, statistical differences in NO_2 were measured between *Zamioculcas zamiifolia* and both *Spathiphyllum wallisii* 'Verdi' and *Dracaena fragrans* 'Golden Coast' (226, 110 and 158 ppb removed after 1 h m^{-2}; $p < 0.01$). However, no statistical differences were measured between *Spathiphyllum wallisii* 'Verdi' and *Dracaena fragrans* 'Golden Coast' ($p = 0.06$; Fig. 2).

'Typical' indoor light level, wet—per m^2 of leaf area

After one hour, *Zamioculcas zamiifolia* removed more than *Dracaena fragrans* 'Golden Coast' and *Spathiphyllum wallisii* 'Verdi' (272, 201, and 119 ppb removed after 1 h m^{-2}, respectively; $p < 0.01$; Fig. 2).

Comparison between treatments within plant type—per m^2 of leaf area

After one hour, a statistical difference in NO_2 removal was measured between the treatments of 'typical' light wet and 'typical' light dry for *Zamioculcas zamiifolia* (272 and 226 ppb removed after 1 h m^{-2}; $p = 0.04$). No other statistical differences were measured between treatments for either *Spathiphyllum wallisii* 'Verdi' or *Dracaena fragrans* 'Golden Coast' ($p = 0.8$ and $p = 0.1$, respectively; Fig. 2).

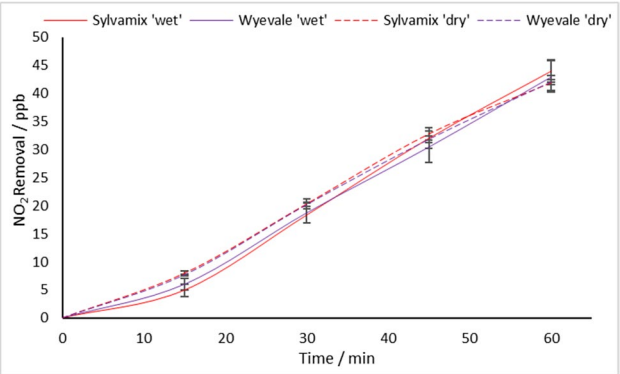

Fig. 3 Mean NO_2 removal as a function of time from a concentration of 100 ppb over a 1-h period by Sylvamix and Wyevale in 'wet' (SMC > 30%, 0.3 m^3 m^{-3}) and 'dry' (SMC < 20%, 0.2 m^3 m^{-3}) substrate moisture conditions at 'typical' (~ 500 lx) light levels. Data are a mean of five growing medias per growing media—error bars represent SEM

NO_2 chamber experiments—comparison between two different growing media

No statistical differences in NO_2 removal were measured between any treatments or growing media types at any timepoint (15 min, $p = 0.472$; 30 min, $p = 0.909$; 45 min, $p = 0.972$; 60 min, $p = 0.966$; Fig. 3).

Using chamber-based results to estimate room-level NO_2 exposure

From the experiments, taking into account volumetric considerations, we are able to estimate the amount of NO_2 each taxon may remove per plant and per m^2 in a sealed 15 m^3 room (the size of the PI's office) containing 100 ppb—assuming there are no additional sources within the room and the 100 ppb is uniformly distributed throughout. It should be noted that this estimation of the maximum impact is not considering natural or mechanical ventilation which is highly variable and may substantially alter the indoor NO_2 exposure in particular if there is a significant indoor–outdoor concentration gradient. In typical buildings, the outdoor-to-indoor air exchange provides approximately one air change per hour (~ 1 h^{-1}) (Cummings and Waring 2020).

For natural ventilation, air change rates are incredibly difficult to predict due to uncertainties around wind speed, pressure coefficient, air temperature and ventilation area (Clements-Croome 2005; HM Government 2015). With mechanical ventilation, various guidance bodies specify a minimum air supply criteria in litres per second per person with UK building regulations (Part F) suggesting a minimum of 10/L/s/per person (HM Government 2015).

Taking into account volumetric loading differences (Girman 1992) between the test chamber (0.15 m^3) and the small office (15 m^3), the rate of NO_2 removal is reduced by a factor of 100. Therefore, using measured removal rates (Fig. 2) and reducing by a factor of 100 allows us to derive the removal rate in a small office (Table 4). We therefore estimate that 1 m^2 of the highest NO_2 removing taxa per m^2—*Zamioculcas zamiifolia*—in optimal environmental conditions, namely 'typical' light and 'wet' growing medium, would reduce a concentration of 100 ppb by 3 ppb after 1 h (data not shown). Furthermore, the highest removing potted plant (not considering leaf area), namely *Dracaena fragrans* 'Golden Coast' potted in wet growing media under 'typical' light conditions, was able to reduce a concentration of 100 ppb by 0.62 ppb after 1 h. Results from all plant types under these presumed conditions are presented below, in Table 4.

Discussion

Interpretation of chamber-based experimental results

This work investigates the ability of three common indoor potted plants to remove—in real-time, over a period of 1 h—an in situ concentration of 100 ppb of NO_2 from a 150-L chamber. We demonstrate that the studied potted plants are able to remove significant amounts of NO_2 under common indoor conditions, i.e. 0 and 500 lx. As per the hypothesis, different taxa were able to remove NO_2 at differing rates—per m^2 of leaf area (Fig. 2), suggesting different inherent capacities for NO_2 removal. However, contrary to the initial hypothesis that water content of the growing media would influence NO_2 removal, only one plant type—*Zamioculcas zamiifolia*—was significantly influenced by this. Additionally, although the growing media significantly contributed to NO_2 removal—equal removal within error for the plant species *Spathiphyllum wallisii* 'Verdi' and *Dracaena fragrans* 'Golden Coast'—the type of growing medium used (peat or peat free) or its water content made no statistically significant difference to the NO_2 removal ability.

Table 4 The derived ability of each studied potted plant to reduce a concentration of 100 ppb inside a 15 m^3 room in 'wet' (SMC > 30%, 0.3 m^3 m^{-3}) substrate moisture conditions at 'typical' (~ 500 lx) light levels

	NO_2 (ppb removed after 1 h) 'Typical' wet
Dracaena fragrans 'Golden Coast'	0.62
Spathiphyllum wallisii 'Verdi'	0.60
Zamioculcas zamiifolia	0.58

In terms of removal per plant (ppb removed after 1 h), very few statistical differences were measured within or between treatments across all plant types and bare growing medium. This suggests that both the light level and growing media moisture had little effect on the NO_2 removal at single plant scale. Moreover, the similarity of removal between bare growing media and potted plants across all treatments suggests that most of the removal is achieved via the growing medium itself. Removal would likely be through breakdown by the microbial activity within the growing media or absorption through moisture contained within the soil—as NO_2 is absorbed by water (Dekker et al. 1959). Thus, further investigation and experiments were required (the NO2 chamber experiments—comparison between two different growing media section).

Investigating another growing medium for its NO_2 removal ability was hypothesized to clarify if microorganisms were breaking down/metabolising the pollutant. As different growing media support different microorganisms (Zhang et al. 2013) and possess differing adsorptive properties, it would be expected that variances in removal would be measured. However, no statistical differences in NO_2 removal were measured between 'wet', 'dry' or growing media types at any timepoint over the 1-h experiment (Fig. 3). This suggests that in the context of our experiment there either were no differences in microbial communities' composition, no differences in microbial activity or that the contribution of this pathway to NO_2 removal is insignificant. Moreover, the fact that no statistical differences were measured between growing media moisture content ('wet' and 'dry', Fig. 3) suggested that moisture absorption of NO_2 was also not the primary removal pathway. However, further experiments (data not shown) at very low moisture content (SMC < 10%) saw a reduction in removal rate, and it is therefore suggested that even in 'dry' growing media conditions (in a biological and practical horticultural sense, 15–20%), enough moisture was still present to remove NO_2.

In terms of removal per m^2 of leaf area, statistical differences were often measured between different plant types for the same light or substrate moisture treatment—confirming that there is an inherent difference between plant types to remove NO_2; this aligns with our hypothesis and is supported by previous work (Morikawa et al. 1998). However, when comparing between treatments within the same plant type, statistical differences were only measured for *Zamioculcas zamiifolia* in 'typical' light between 'wet' and 'dry' growing media. This suggests that neither light—up to 500 lx—nor water content (down to very low SMC, i.e. below 10%) had much of an effect on the NO_2 removal ability of each taxa, aligning with the per plant removal results. Furthermore, removal experiments investigating growing media alone showed a similar pattern of little change in NO_2 removal in response to the change in environmental conditions (Fig. 3). This lends further weight to the 'per plant result' conclusion that the growing medium (and its associated moisture content) is responsible for a large part of the NO_2 removal. Whilst the detailed mechanism could not be resolved in our experiments, it appears that even a very small amount of moisture within the substrate appears to be more important for NO_2 removal efficiency than any of the other parameters we have investigated here.

Potential implications for room-level NO_2 exposure

Based on our chamber experiments and taking into account volumetric considerations, we have estimated the amount of NO_2 each taxon may remove per plant and per m^2 of leaf area in a sealed 15 m^3 room (the size of the PI's office) containing 100 ppb—assuming there are no additional NO_2 sources within the room and the 100 ppb is uniformly distributed throughout. These estimates (see Table 4) suggest that five plants in such a small office could remove approximately 3 ppb of NO_2 after 1 h. At first sight, such a removal rate may look relatively low, but it should be noted that the measured NO_2 removal occurred in typical light and even dark conditions whilst NO_2 exposure peaks tend to appear over short, often rush-hour-related periods (Malley et al. 2018; Engström and Forsberg 2019). It can therefore be expected for any removal to be constant throughout the day or night, even when plants are under mild water deficit—unlike with CO_2 where supplementary lighting was required for CO_2 uptake to occur (Gubb et al. 2018, 2019). Therefore, plants are able to remove NO_2, without additional energy requirements. Furthermore, as plant type seems to have little effect (Table 4) on NO_2 removal at the office scale (considering the plant types in this study only), easier-to-maintain plants like *Zamioculcas zamiifolia* and other succulents would likely be just as effective.

Comparing to our earlier work on the potted plants' ability to remove carbon dioxide (CO_2) indoors (Gubb et al. 2018, 2019), the fact that removal of NO_2 occurs at typical indoor light levels is a significant advantage. Without the need for supplementary lighting, increasing both energy costs and integration difficulties for designers, passive NO_2 mitigation via potted plants is a much more viable technique—especially with the built environments push towards net-zero carbon buildings.

Our work is consistent with recent experiments that have suggested that the growing media and the microorganisms within are predominantly involved in the removal of pollutants and plants themselves are only utilised in-directly to maintain and support growing media microorganisms (Irga et al. 2018; Kim et al. 2018).

As both the concentration of NO_2 and light level—albeit, > 500 lx—affect the removal ability of plants (Teklemariam and Sparks 2006; Gourdji 2018; Hu and Sun 2010),

direct comparison to literature is difficult, unless removal with exactly the same conditions were investigated. However, numerous studies have tested outdoor vegetation for NO_2 removal, and this study aligns with those (Morikawa et al. 1998; Nowak et al. 2014; Petit et al. 2019) in the fact that all studied plant types were able to remove NO_2 to varying degrees at a wide variety of concentrations.

Comparison to alternative approaches to reduce NO_2 exposure

To put our small office estimate of an NO_2 removal of ~ 3 ppb after hour from five potted plants into context, it is useful to compare to alternative approaches that have been taken to reduce NO_2 exposure in urban areas. As an example, the Agglomeration of Lausanne-Morges (ALM) in Switzerland has a long-term record of introduction of successful clean air policies and a recent study by Castro et al. (2017) compared to the health benefits resulting from these policies over the decade 2005–2015. They suggested that the NO_2 exposure reduction by 2.8 ppb in the ALM region may have lowered the NO_2-related deaths by 51 and the life-years lost by 550 years in this 10-year period (Castro et al. 2017). Based on our estimate, five potted plants in each small office may be able to reduce the indoor NO_2 exposure for the occupant to a comparable extent (it is worth noting that Castro et al. based their findings on annual average NO_2 exposure, so the impact of potted plants in offices on life-years lost will not be as dramatic since most office occupants will not spend nearly 100% of their time annually in small plant-filled rooms). However, studies of mechanical and natural ventilation systems as well as investigations of the long-term ability of potted plants to retain NO_2 are needed to establish how significant the air quality services of potted plants are both in the long-term and in a wide range of real-life conditions. We would also expect that NO_2 removal efficiencies of the potted plants are not linear and that they will decrease with decreasing ambient NO_2 concentrations.

Potential impact on indoor NO_2 levels depending on Clean Air Delivery Rate (CADR), Air Changes per Hour (ACH) and room volume

The calculated *Clean Air Delivery Rates per plant* ($CADR_p$) presented in Table 3 (0.095 to 0.145 $m^3\ h^{-1}\ plant^{-1}$) are unsurprisingly much lower than the results from the active wall experiments by Pettit et al. (2019), where the CADR was two orders of magnitude higher. Our result was comparable to some of the studies summarised by Cummings and Waring (2020). This recent review paper calculated the CADR from 12 previously published potted plant VOC removal studies (but none investigating NO_2 removal). The study found that the distribution of single-plant CADR spanned orders of magnitude, with a median of 0.023 m^3/h (i.e. ~ 4–5 times lower than what we found). Their median CADR would require the placement of 10–1000 plants/m^2 of floor area for the combined VOC-removing ability by potted plants to achieve the same removal rate that outdoor-to-indoor air exchange already provides in typical buildings (~ 1 h^{-1}). However, the review fails to take into account differing pollutant toxicities across VOCs, whereby a smaller CADR may still be effective if the pollutant is highly toxic at a relatively low concentration, i.e. NO_2.

Additionally, it should be noted that outdoor-to-indoor air exchange for pollutants such as NO_2 may also increase the indoor NO_2 exposure especially since ventilation rates are likely to be higher during outdoor NO_2 peak periods (daytime, particularly during the morning rush-hour period when people tend to arrive at work and thus open doors and potentially windows) than during low NO_2 outdoor concentrations (night-time) unless a smart and active ventilation system is in place. In passively ventilated buildings which still represent the vast majority of buildings in the UK, a continuous NO_2 removal by potted plants can thus provide indoor air quality services. This can be in addition to exhaust fans or window opening, which remain the most effective way to reduce very high indoor NO_2 from indoor gas combustion (Clements-Croome 2005).

To illustrate the impact of varying ventilation rates and room sizes, we have calculated the reduction of indoor NO_2 in a range of conditions for *Air Changes per Hour* (*ACH*) of 0.2, 1 and 1 h^{-1} and room volumes (V) of 15 and 100 m^3. The outdoor NO_2 mixing ratios (C_{out}) were assumed to be either 100 ppb or 20 ppb. At steady state and ignoring potential NO_2 consumption by gas phase and surface chemistry, the NO_2 indoor concentration (C_{in}) is assumed to relate to C_{out}, by

$$C_{in} = ACH \times C_{out}/(ACH + CADR/V) \quad (1)$$

with *CADR* corresponding to $CADR_p$ multiplied by the number of plants in the room. For five plants of our most efficient NO_2 removing plant (*Dracaena fragrans* 'Golden Coast'; $CADR_p = 0.145$ in 'typical' wet conditions; see Table 3), we obtained the values presented in Table 5.

Table 5 clearly illustrates the importance of ACH: in poorly ventilated areas, the five potted plants show potential to remove significant amounts of NO_2 even in larger rooms, but their impact will be limited for areas with ACH of 2 h^{-1} or higher.

Further experiments measuring the effect of removal over a longer time period should be carried out allowing for determination of how the removal rate may alter. Another important area of future study ought to include the role of growing media/substrates or the use of hydroponic growing systems.

Table 5 Reduction of indoor NO_2 levels (C_{in}) by five potted plants of Dracaena fragrans 'Golden Coast' in a range of conditions calculated from Eq. (1) for two outdoor NO_2 levels (20 ppb and 100 ppb), two room volumes (15 m^3 and 100 m^3) and three rates of Air Changes per Hour (ACH) of 0.2, 1 or 2 h^{-1}

	C_{in} (ppb)		
	ACH: 0.2 h^{-1}	ACH: 1 h^{-1}	ACH: 2 h^{-1}
C_{out} = 100 ppb			
V = 15 m^3	80.5	95.4	97.6
V = 100 m^3	96.5	99.3	99.6
C_{out} = 20 ppb			
V = 15 m^3	16.1	19.1	19.5
V = 100 m^3	19.3	19.9	19.9

We do not dispute the notion that future work on green walls (especially 'active' walls) is urgently needed since these yield more effective removal due to an increased leaf area of taxa and increased growing media airflow (Irga et al. 2018). In their study, Pettit et al. (2019) found NO_2 removal, i.e. the CADR was measured at 79.92 and 87.84 m^3 h^{-1} m^{-3} of biofilter substrate, respectively—three orders of magnitude greater than the passive removal studies. Other active wall studies investigating VOCs have found similar CADRs (i.e. 28.3 and 18.9 m^3 h^{-1} m^{-2} green wall area, per different plant type) (Torpy et al. 2018). These however require a significantly increased amount of energy, irrigation considerations and thorough maintenance in comparison to simple potted plants and may not be suitable for all environments—albeit whilst providing greater removal (Cummings and Waring 2020). Thus, passive low-tech potted plant NO_2 removal should not be overlooked given the wide and immediate availability across the globe and a significant potential to improve indoor air quality (for a review of research on indoor pollutant removal services of houseplants, see Gubb et al. 2020), particularly, in small offices in urban environments without smart, active ventilation systems. For occupants of these offices, a realistic number of potted plants may have comparable health benefits to clean air policies that are obviously crucial to reduce NO_2 exposure outdoors.

Conclusion

This study investigated if a simple set up, with just a potted houseplant, could be effective at passively removing the harmful pollutant NO_2. This was carried out by investigating the ability of the combination of the plant species *Spathiphyllum wallisii* 'Verdi', *Dracaena fragrans* 'Golden Coast' and *Zamioculcas zamiifolia* with two different growing media to remove in situ concentrations of NO_2 in real-time at two typical indoor light levels and in 'wet' and 'dry' growing media conditions.

All studied growing medium–plant combinations were able to reduce the NO_2 concentrations representative of a polluted urban environment, but to varying degrees. Growing medium and/or moisture contained within emerged as a significant pathway of NO_2 removal.

The greatest NO_2 removal measured in a 150-L chamber over 1-h period corresponded to 272 ppb removed after 1 h per m^2 of leaf area and 58 to 62 ppb per plant over the 1-h period for each of the three plant types in 'wet' growing media at ~ 500 lx. This would correspond to a removal of up to 3 ppb per m^2 of leaf area after 1 h and 0.62 ppb per plant after 1 h in a small office when not considering natural or mechanical ventilation. The studied plant types remove clearly measurable amounts of NO_2 passively during the day and night without additional energy requirements (unlike mechanical ventilation or filtration systems), thus adding indoor air quality services and the associated health benefits to the other established building services potted plants provide at minimal cost.

This passive removal approach is unsurprisingly significantly less effective than the deployment of 'active' green walls, highlighting the need for further research in this area. However, these require a significantly increased amount of energy, irrigation considerations and maintenance compared to potted plants. This study demonstrates that simple potted plants will passively remove NO_2 under typical indoor conditions. The air quality 'services' delivered by potted plants will also strongly depend on room size and competing removal routes such as building ventilation, as well as on the success of clean air policies aiming to reduce outdoor NO_2 peak events that will in turn impact on indoor NO_2 exposure.

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