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Effectiveness of Indoor Plants for Passive Removal of Indoor Ozone

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Effectiveness of indoor plants for passive removal of indoor ozone

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ABSTRACT

Indoor vegetation is often proposed as a passive approach for improving indoor air quality. While studies of outdoor environments indicate that vegetation can be an important sink of outdoor ozone, there is scant data in the literature concerning the dynamics of ozone uptake by indoor plants. This study determined ozone deposition velocities (v_d) for five common indoor plants (Peace Lily, Ficus, Calathia, Dieffenbachia, Golden Pothos). The transient v_d was calculated, using measured leaf areas for each plant, for exposures mimicking three diurnal cycles where ozone concentrations in chamber tests were elevated for 8 h followed by 16 h in the absence of ozone. Estimates of v_d at the end of the first exposures ranged from 5.6 m h^{-1} for Golden Pothos to 0.9 m h^{-1} for Peace Lily. Values of v_d were approximately 50% and 66% lower at the end of a second exposure and third exposure, respectively. Estimates of v_d were also made for a range of photosynthetic active radiation (PAR) levels typically observed indoors. An increase in PAR from 0.6 to 41.2 μmol m^{-2} sec^{-1} resulted in increases in v_d ranging from a factor of 1.7 (Diffenbachia) to 4.7 (Peace Lily). For deposition velocities measured in this study, the ozone removal effectiveness ranges from 0.9% to 9% for leaf surface area to room volume ratio of 0.06 m^{-1} (approximately one plant for every 1.8 m^2 of floor area) when accounting for values of air exchange and background loss typical of a residential environment.

1. Introduction

Ozone is a strong oxidant gas with known adverse health effects. The predominant source of indoor ozone is outdoor air, where ozone is formed through photochemistry. The EPA regulates outdoor ozone levels to be no higher than 70 ppb averaged for an 8-h period [1]. Although ozone may be generated indoors by, e.g., photocopiers or air-cleaners using UV light or corona discharge, the transport of outdoor ozone to indoor spaces through ventilation and infiltration is the predominant indoor source. Once indoors, ozone can react with different surfaces indoor such as flooring, paints, and metals [2]. While these reactions suppress indoor concentrations of ozone, they may also result in the production of byproducts that may be more harmful than ozone itself [3].

While indoor levels are typically lower than outdoors due to indoor surface reactions [4], indoor ozone concentrations, in certain circumstances, may exceed 50 ppb. Ratios of the indoor levels of ozone range from <10% to 90% of outdoor levels for buildings with negligible sources of indoor ozone, depending on a number of factors including air exchange rates and ventilation type [5]. For example, in a study of eight schools in France, Blondeau et al. [6] reported indoor ozone concentrations of up to 60 ppb. In addition to outdoor air as a source of indoor ozone, high-tension electrical equipment is another source of indoor ozone. Allen et al. [7] found that ozone emissions from electrostatic air cleaners and unmaintained photocopiers led to ozone levels up to 202 ppb in small spaces with low ventilation rates. Elevated ozone levels indoors can be expected to have negative health effects on building occupants, based on a body of literature investigating health effects in the context of outdoor ozone levels for which more extensive reporting has historically been available. Lippmann [8] states that studies suggest long-term exposure to outdoor ozone will cause premature aging of lungs. Brauer and Brook [9] report a reduction in lung function associated with ozone exposure for people working outdoors subjected to ozone levels of around 50 ppb. This adverse effect was still noticeable even a day after exposure, indicating that the health effect of ozone exposure, even below its permissible limits, can be serious. This statement is supported by Refs. [10,11] which suggest that ozone levels above 10 ppb are

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associated with some health risk. Given the predominance of indoor environments in human activity patterns [12], reducing exposure to ozone requires addressing indoor ozone levels.

In the absence of indoor sources of ozone, two general approaches can be employed to achieve reductions in indoor ozone levels. The first is to remove ozone in air entering the building. The second approach is to reduce the concentration of ozone once present indoors. Previous research suggests that some indoor materials may serve as "passive" (i.e., no direct energy input) air cleaners. For instance Cros et al. [13], studied the performance of three building materials (activated carbon mat, painted gypsum board, and ceiling tiles) as passive ozone removing surfaces and found that both activated carbon mat and ceiling tiles are capable of removing ozone from the indoor environment. Gall et al. [14] performed a Monte Carlo simulation to characterize passive removal materials (PRMs) such as activated carbon cloth and gypsum wallboard, employing statistical distributions for model inputs such as uptake to materials and indoor-outdoor air exchange rates. The simulation results show that there are some challenges in achieving a threshold of 50% removal of indoor ozone. These challenges include the need for using a large area of passive materials, a requirement that the air speed indoors be increased to enhance transport to surfaces, and aesthetic challenges associated with installing such materials.

One indoor ozone removal strategy with limited quantitative research is the use indoor plants. Research about plants, especially outdoor vegetation, shows their ability to remove pollutants including ozone. For instance Hill [15], stated that a 16" height of alfalfa canopy in chamber tests conducted at ~ 5 ppm showed removal of ozone in addition to removing other pollutants. Calfapietra [16] show that nine urban tree species remove ozone, noting that removal increases from 0.5 to 6.5 nmol m^{-2} s^{-1} when ozone concentrations increased from 100 to 300 ppb.

With regard to indoor plants, much of the existing research on air cleaning effects of plants focuses on volatile organic compounds (VOCs). For instance Kim et al. [17], studied the removal efficiency of formaldehyde at initial concentration of (2.0 μl L^{-1}) due to 68 different species of plants in an air tight chamber. They report results categorizing plants based on formaldehyde removal as excellent (>1.2 mg m^{-3} cm^{-2} of leaf area in a 5 h period of time), intermediate (1.2–0.6), and poor (<0.6). Orwell et al. [18]; studied the benzene removal by seven potted plants when initial doses of 25 ppm benzene were injected, reporting removal rates of 12–27 ppm d^{-1}. Wolverton et al. [19] studied the efficiency of 12 indoor plants with activated carbon aerated roots in removing benzene, trichloroethylene, and formaldehyde injected separately into test chambers. The total leaf areas of the plants ranged from ~1000 cm^2 to ~15,000 cm^2. The results showed removal ratios of 5–70% for the chemicals under investigation, although the authors attributed most of removal effectiveness to the activated carbon root area. Root-associated microbes may also play a role in affecting removal pathways of indoor air pollutants [20].

Investigations of ozone uptake by indoor plants, including estimations of deposition velocities, are scarce in the literature. We are aware of one paper that investigated the ozone removal due to three indoor plants via decay tests of ozone in a sealed continuously stirred tank reactor [21]. The results show that the time required for the ozone to decay from 200 ppb to less than 5 ppb ranged from 38 to 120 min per evaluation. The depletion rate of ozone was greater when plants were present in the chamber than for an empty chamber, with variation in the decay rate of ozone noted for different species of indoor plants. Deposition velocities are not reported and the implications for realistic indoor environments are not discussed. Furthermore, studies have not addressed potentially important indoor environmental factors that may influence pollutant removal by plants, such as indoor lighting levels. This information is crucial to evaluate the effectiveness of indoor plants as passive ozone removal strategies. The current research aims to investigate and calculate the ozone deposition velocity and ozone removal effectiveness of five common indoor plants, and to explore the effect of indoor light level on the ozone deposition velocities.

2. Methodology

2.1. Materials

Five types of indoor plants were chosen based on their popularity and availability. Plants were purchased from a local nursery in Portland, OR, USA in standard 6" (15.24 cm) pots. The top surface area of every leaf of every plant was measured individually using KLONK image measurement software (Image Measurement Corporation), then summed to determine the leaf surface area of each tested plant. The relative uncertainty associated with consequent measurements of known areas using the software was found to be 0.63%. Table 1 shows a list of the popular and scientific names of the plants and the measured leaf surface areas. The loading factor, the leaf area of the tested plant divided by the volume of the test chamber, was approximately 1.9 m^2/m^3.

To minimize the effect of the interaction of ozone with materials other than plants, such as the pot itself and soil, plants were placed in a 600 mL glass beaker two days prior to an ozone uptake test. The glass beaker was chosen as an alternative to the standard plastic pot provided by the nursery because glass is an inert material with respect to ozone [22]. During tests with plants, the soil was covered by placing aluminum foil around the plant stem to cover the soil surface and minimize the interaction with ozone. Fig. S1 in the Supporting Information shows a photo of one tested plant in the glass beaker and with aluminum sheet cover. In addition, to characterize the contribution of the soil itself to ozone uptake, one test of a glass beaker was conducted with only soil exposed in the beaker (i.e. no plant present). The exposed soil was found to have a negligible effect on overall ozone removal.

2.2. Experimental apparatus

A diagram for the experimental apparatus is shown in Fig. 1. Also, Fig. S2 in the Supporting Information shows a photograph of the apparatus. The apparatus consists of an air supply system, two 52 L glass chambers, ozone generation, and ozone monitoring equipment. Compressed air was supplied from the laboratory air supply, which then passed through two stage air filters to remove suspended oil and particulate matter. Air was then dehumidified using a granular drying media (Indicating Drierite, W.A. Hammond Drierite Co. Ltd.) placed in a laboratory gas-drying column. The air stream then passed through an activated carbon air filter to purify the air stream of any VOCs in supply air. Air then was humidified using a bypass controlled impinger filled with distilled water to the required relative humidity. The temperature and relative humidity of the air stream were measured and recorded in 1-min interval using a HOBO 12Bit sensor (Onset, model S-THB-M002) of range

Table 1
List of indoor plants used in tests of ozone removal rate.

Name	Scientific name	Leaf top surface area (cm^2)
Peace Lily	Spathiphyllum	998.1
Ficus species	Ficus Decora Burgundy	1022
Calathia	Calathia Species	1047
Dieffenbachia	Dieffenbachia Species	969.1
Golden Pothos	Epipremnum aureum	1011

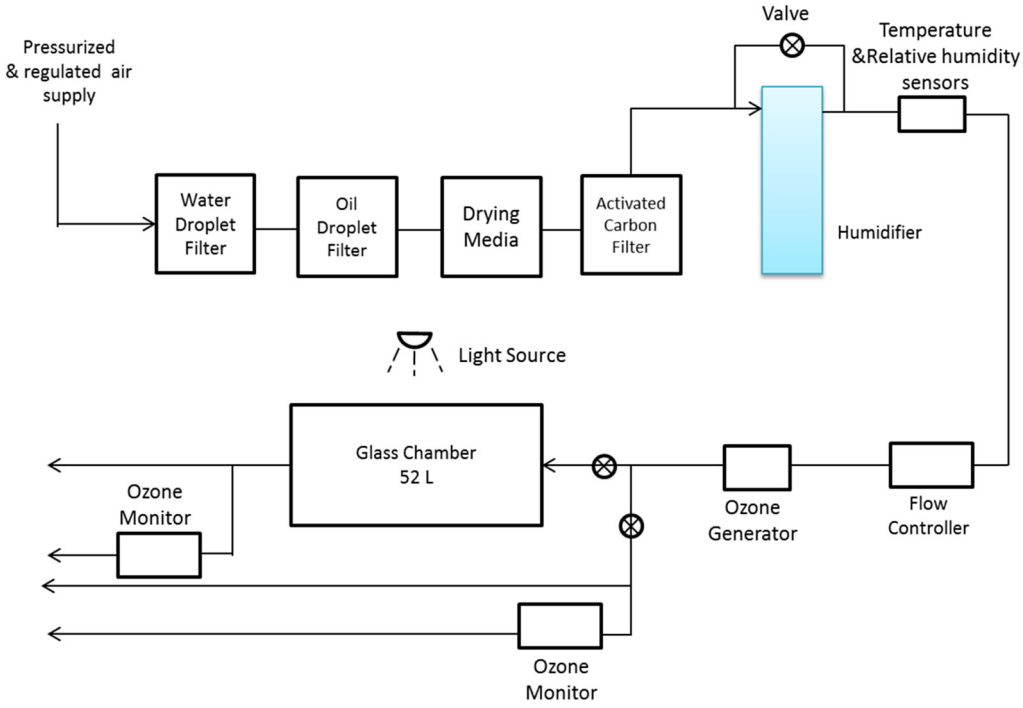

Fig. 1. Schematic diagram of the experimental apparatus.

of −40 °C to 75 °C with accuracy of 0.2 °C, and 0–100% relative humidity range with 2.5% accuracy that was connected to an HOBO data logger (Onset, model H21-002). A mass flow controller of range of 0–15 LPM with accuracy of 1.5% (OMEGA, model FMA 5523) was used to stabilize the airflow rate before supplying the air to a stable UV ozone generator (UVP, model SOG-2). The ozonated air stream was then divided into two lines. One was supplied to the glass chamber and the other served as a reference line to measure the inlet ozone concentration. Two UV portable photometric ozone analyzers (2B Technologies, model 106-L) were used to record the ozone concentrations in 1-min interval upstream and downstream the chamber in the range of 0–60 ppb with accuracy of 2% of the reading. All tubing, connections, and valves were PTFE or stainless steel to minimize their reactivity with ozone. The air pressure inside the chamber was maintained at slightly positive pressure above atmospheric pressure to prevent intrusion of air into the chamber.

2.3. Experimental procedure

The experimental chamber was supplied with ozonated air with an air exchange rate of 3.0 ± 0.045 h^{-1}. The monitored values for temperature were in the range of 21 ± 1 °C, and the relative humidity was 50 ± 2%. The ozone concentration at the inlet to the chamber was 60 ± 1.2 ppb, which was selected to represent an elevated indoor level, but in the range observed in prior field studies [6].

Prior to conducting an experiment, the chamber was thoroughly wiped with distilled water, dried with a heat gun, then quenched with a stream of air containing elevated ozone (350 ppb) for 3 h (similar to Coleman et al. [23]. To characterize background ozone removal, two separate tests were performed to calculate the ozone consumption by an empty chamber and a chamber with a soil-filled glass beaker covered with aluminum foil. From these tests, ozone deposition velocity for the glass chamber material and background materials were calculated. It was found that the soil-filled glass beaker with aluminum cover had a statistically insignificant effect on ozone deposition velocity values compared to the glass chamber alone.

For plant tests, each plant was exposed to 8 h of ozonated air (at 60 ppb) followed by 16 h of a non-ozonated air stream. The 8-h exposure time was chosen based on an EPA report for ozone exposure analysis in urban areas and prior experimental studies [1,24]. This 24-h cycle was repeated two more times to observe the ozone deposition change with three repeated cycles of ozone exposure. Thus, each test lasted for a total of three days.

A separate series of tests was conducted to study the effect of light on ozone removal. This test was conducted by exposing the plants to an ozonated stream of air until the ozone concentration at the test chamber exit reached a steady-state condition (defined as changing by no more than 2 ppb in 20 min). After reaching steady-state, a light source was sequentially turned on for 2.5 h and then turned off for 2.5 h to monitor the change in ozone concentration as a result of plants' photosynthetic activity. A control test was also performed to confirm that the light did not affect ozone removal for an empty chamber. Fig. 2 shows the timeline of the sequence of both ozone re-exposure and light tests.

To quantify the light intensity in the indoor environment in the spectrum that is most relevant for plant activity, a short field study of indoor lighting conditions in a Portland State University building and residential apartment was conducted. A photosynthetically active radiation (PAR) sensor (Onset, model S-LIA-M003) with measurement range of 0–2500 μmol m^{-2} sec^{-1} and accuracy of ±5%, and solar radiation sensor (Onset model S-LIB-M003) with measurement range of 0–1280 W m^{-2} and accuracy of ±5%, and combined temperature and relative humidity sensor (Onset, model S-THB-M002) were used to record the PAR, solar intensity, temperature and relative humidity for different indoor conditions. These sensors were connected to portable data logger (Onset, model S-THB-M002). This test was performed to ensure that PAR and solar radiation levels were consistent with levels that may be reasonably anticipated to be present in an indoor environment. The peak PAR and solar intensity values recorded in different indoor locations are shown in Table 2. The values recorded in the shade of

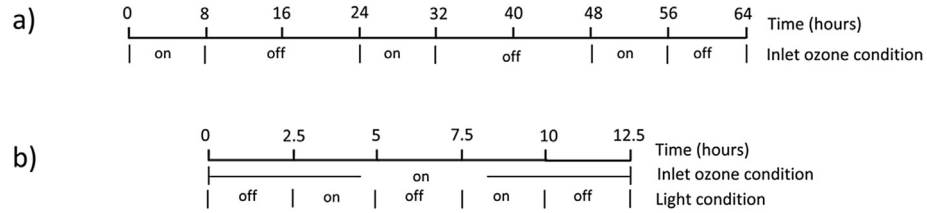

Fig. 2. Experimental timeline for tests of ozone uptake to each type of plant. a) Ozone re-exposure test b) Light exposure test.

Table 2
Peak photosynthetic active radiation (PAR) and solar radiation intensity values recorded in different indoor locations.

Location[a]	PAR (μmol m^{-2} sec^{-1})	Solar radiation intensity (W m^{-2})
Inside laboratory, no windows (ceiling lamps on)	1.2	0.6
In residential apartment at night	1.2	0.6
South facing hallway, cloudy day	18.7	3.1
North facing office, cloudy day (in shade)	10.5	1.9
South facing hallway, sunny day (in shade)	39.7	6.9
Inside lab with lamps projected to plants	41.2	6.9

[a] All values of PAR and solar radiation intensity are maximum values observed in each location. All values except the residential apartment were collected in the Portland State University Engineering Building. All data collection occurred in September 2016, on days for which outdoor conditions were as noted.

an indoor south facing hallway under clear sky conditions were chosen to adjust the lighting condition of light exposure tests described in Fig. 2b. This condition was chosen as outdoor ozone levels typically reach their peak values in late morning or early afternoon [25].

Two fluorescent lamps (Bright Green, model UL#E170906) with power of 23 W/1600 lumens each were used to provide a PAR radiation value of 41.2 μmol m^{-2} sec^{-1} for the plants during the test period. Both lamps were mounted on a tripod, adjusting the vertical distance from the plant to achieve the required PAR value. The power was supplied to the lamps using a timer switch to control the periods of on and off as shown in Fig. 2b.

3. Data analysis

3.1. Ozone deposition velocity

For the plants tested in this research, a transient ozone deposition velocity was calculated, similar to Poppendieck et al. [26]. To calculate the ozone deposition velocity for the empty chamber material, which is glass in our experiments, a test of an empty chamber was conducted. The background test ran until the steady-state condition was achieved, i.e., where empty chamber exit concentration change was less than 2 ppb over 20 min [23], and the loss rate to background chamber surfaces was solved for as described in Abbass et al. [27]. A mass balance on ozone balance for the test chamber is shown in equation (1), which is solved for the transient ozone deposition velocity shown in equation (2):

$$\frac{dC_{outlet}}{dt} = AER \times C_{inlet} - AER \times C_{outlet} - k_g C_{outlet}\frac{Ag}{V} - k_s C_{outlet}\frac{As}{V} \quad (1)$$

$$k_s^t = \frac{V}{A_S}\frac{1}{C_{outlet}^t}\left[AER \times \left(C_{inlet}^t - C_{outlet}^t\right) - k_g C_{outlet}^t \frac{A_g}{V} - \frac{C_{outlet}^t - C_{outlet}^{t+1}}{\Delta t}\right] \quad (2)$$

where C_{inlet} and C_{outlet} are the concentration of ozone in the inlet and outlet of the chamber (ppb) respectively, $\frac{dC_{outlet}}{dt}$ represents the change in the outlet ozone concentration (ppb h^{-1}), AER is the air exchange rate (h^{-1}), V is the net volume of chamber minus the volume of soil container (m^3), A_g, A_s are the internal surface areas of the glass chamber, and the sample area respectively (m^2), k_g and k_s are ozone deposition velocities for the glass chamber material and the plant (m h^{-1}), respectively.

For every plant test, the ozone deposition velocity of glass is used in equation (2) to calculate the transient deposition velocity of the plant sample, k_s. The presence of the glass beaker inside the chamber was found to have a negligible effect on ozone deposition velocity for the glass chamber. To facilitate comparison across plants, the steady-state ozone deposition velocity was calculated for each test when the rate of change in exit ozone concentration was less than 2 ppb over 20 min, as in Coleman et al. [23].

The experimental uncertainty was calculated using a propagation of error analysis for the instruments used: an uncertainty of 2% of readings from ozone monitors, 1.5% of reading for the flow controller, and 0.63% for the estimated surface area of the plants. The resulting uncertainty in the calculated ozone deposition velocity for the empty chamber was found to be a maximum of ±0.009 m h^{-1}. For deposition velocity in the plant experiments, the uncertainty varied between ±0.14 and ±0.27 m h^{-1} depending on the type of plant and the exposure test.

3.2. Plant ozone removal effectiveness

To simulate the ozone removal effectiveness of indoor plants in realistic, hypothetical indoor spaces, an analysis similar to that of Kunkel et al. [28] was performed. The effectiveness metric, *H*, was employed in this analysis and is defined as shown in equation (3):

$$H = 1 - \frac{C^*}{C^{**}} \quad (3)$$

where C* and C** are the simulated indoor/outdoor ozone concentration ratios (−) for the case of an indoor environment with and without the presence of the plants, respectively.

The effectiveness metric represents the percent removal of indoor ozone due to the presence of an air cleaning strategy. The effectiveness is 1 if the all ozone is removed and 0 if the strategy has no effect on indoor ozone levels. The effectiveness is calculated as

shown in equation (4), for time-averaged conditions, with C* and C** as shown in equations (4) and (5):

$$C^{*} = \frac{C_{indoor,p}}{C_{outdoor}} = \frac{1}{1 + \frac{L_b}{AER} + k_s \frac{A_s}{V \times AER}} \quad (4)$$

$$C^{**} = \frac{C_{indoor}}{C_{outdoor}} = \frac{1}{1 + \frac{L_b}{AER}} \quad (5)$$

where $C_{indoor,p}$ is the concentration of ozone in the hypothetical indoor space with plants present (ppb), $C_{outdoor}$ is the outdoor level of ozone (ppb), L_b is the loss rate (h^{-1}) due to background ozone removal, and C_{indoor} is the concentration of ozone in the hypothetical indoor space in the absence of plants (ppb).

Equations (4) and (5), therefore enable calculation of time-averaged indoor/outdoor ratios of ozone by defining typical values of air exchange rate (AER, h^{-1}), background ozone loss rate (L_b, h^{-1}), and plant leaf surface area (A_s, m^2) to zone volume (V, m^3) ratio. Air exchange rate was input as 0.5 h^{-1} based on the median value of 164 homes in Texas, reported by Yamamoto et al. [29]. Background ozone loss rate was set to a value of 2.8 h^{-1} based on the mean value from a study of 43 homes in California [30]. The values of k_s are taken from calculations of steady state ozone deposition velocity for plants determined in this investigation. In this analysis, the value of the ratio of plant surface area to the space volume is varied in the range of (0.01–0.1) m^{-1} to calculate the ozone removal effectiveness H. This approach enables a better understanding of the potential for ozone removal by indoor plants in realistic indoor environments.

4. Results and discussion

4.1. Exit ozone concentration

Fig. 3 shows the chamber exit ozone concentration of the multiple exposure tests for the Peace Lily plant as an example. The results for the other four plants are shown in Fig. S3 of the Supporting Information. Fig. 3 shows that the exit ozone concentration for the 1st exposure increases, nearly linearly, from approximately t = 20 min until the end of the test. In contrast, for the second and third exposures, the exit ozone concentration reaches a steady state value after approximately 200 min. Also, the maximum value at the end of test for the first exposure is reduced by about 7 ppb than in the subsequent exposures. Similar behavior, but with different reductions in ozone exit values (7–17) ppb, was observed for the other four tested plants. This suggests that the plants were more effective at removing ozone in the first exposure. For the subsequent exposures, ozone removal is still present but to a lesser extent than for the first exposure. This behavior could be explained as a result of unexposed plant leaves having higher reactivity with the ozone when exposed for the first time. This exposure will subsequently lead to a change in the composition or structure of the leaf surface that will lead to a reduction in ozone removal activity. This explanation is in-line with the results of Szinyei [31] and Kozlowski [32], both of whom showed images of damage to plant leaves as a result of ozone exposure. Lambers et al. [33] also states that ozone will enter the leaf through stomata causing direct damage to photosynthetic cells.

4.2. Ozone deposition velocity

The background ozone deposition velocity for the empty chamber is calculated first by passing an ozonated air stream through an empty, thoroughly cleaned chamber. By applying steady state values of inlet and outlet ozone concentrations, and air exchange rate to equation (1), the background ozone deposition velocity was found to be 0.019 m h^{-1}. This value is of similar order of magnitude to values reported by Grøntoft and Raychaudhuri [2] for cleaned glass. For the plants, Fig. 4 shows the transient ozone deposition velocity for the five plant species tested. The figure shows that for all plants, the values of deposition velocity are generally high at the first hour of the test, consistent with the findings of Kersiens and Lendzian [34] who conducted experiments of ozone uptake to outdoor plants. In the case of second and third exposures, the deposition velocity then converges to steady state values for nearly all cases. Elevated initial ozone deposition velocities may partly be attributed to low initial ozone concentrations at the beginning of each test as the chamber ozone concentrations increase from ~0 ppb to steady-state values as a constant level of ozone is injected into the well-mixed flow reactor. It is plausible that during initial periods of ozone exposure (when well-mixed chamber ozone levels are low), replenishment of reactive sites on plant surfaces more effectively compete with ozone uptake, leading to higher values of ozone deposition velocity. As time elapses, the ozone concentration increases inside the chamber until

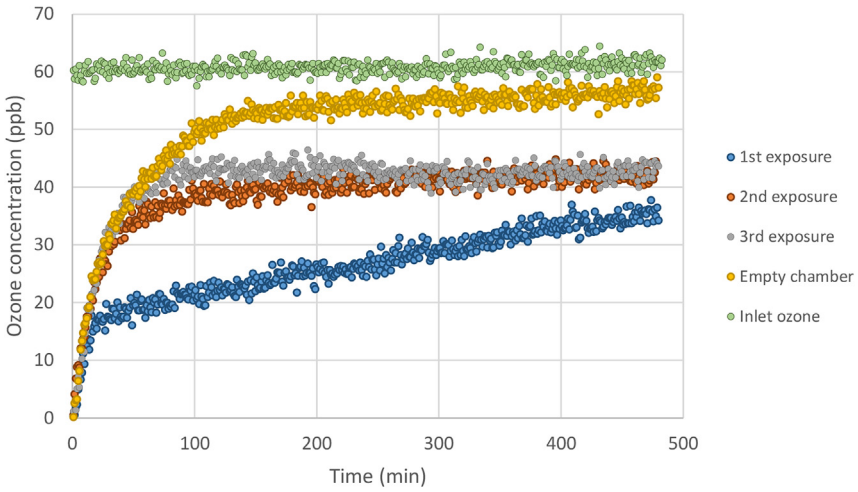

Fig. 3. Empty chamber, inlet, and outlet ozone concentration for Peace Lily plant. The ozone was on for 8 h and off for 16 h. This pattern of ozone exposure was repeated three times and reported as first, second, and third exposures.

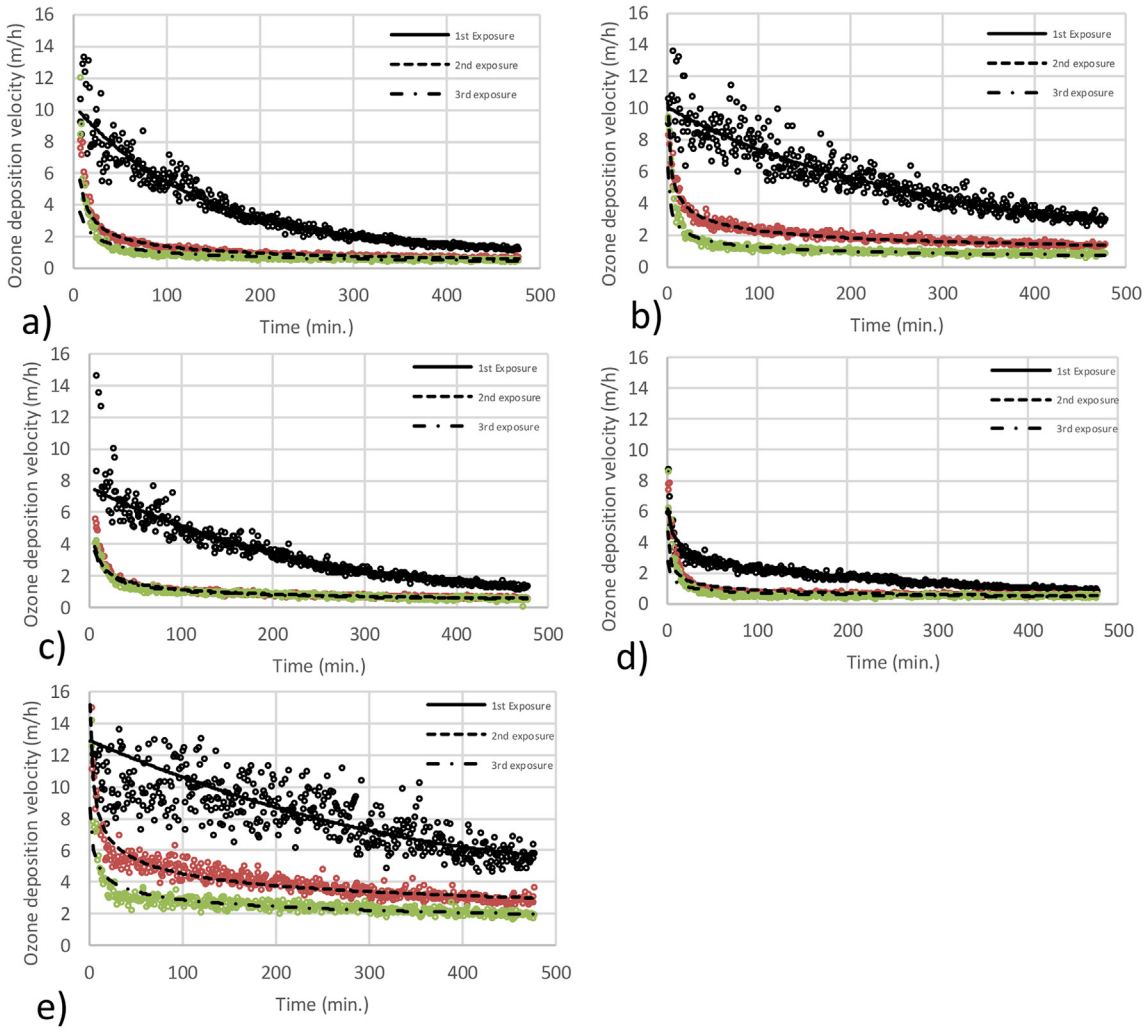

Fig. 4. Change of transient ozone deposition velocity for all plants across three ozone exposures for a) Ficus species, b) Diffenbachia, c) Calathia, d) Peace Lily, e) Golden Pothos. Lines of best fit are the best polynomial fit.

approaching a steady-state value (see the example in Fig. 3 for Peace Lily). Then, deposition velocity curves appear to flatten, reaching an asymptotic value after about 2 h. These differences in ozone deposition velocity may be attributed to the leaf composition and structure including leaf surface roughness that varies from one plant to another.

The near steady-state values of deposition velocity for all plants for the three exposures were calculated by averaging the last 20 min of each 8 h test; results of these calculations are reported in Fig. 5. The figure shows that the Golden Pothos is the plant with the highest ozone deposition velocity values across all plants for all three exposures. Conversely, the Peace Lily had the lowest values. Also, the ozone deposition velocities for the first exposure for all plants are the highest in value, while for the second exposures are about half the value of the first exposure, and the third exposure values are about one third of those from the first exposure. From Fig. 5, it can also be concluded that the Golden Pothos has high ozone deposition values to a degree that it is in-line with other indoor surfaces including, for example, carpets as reported by Abbass et al. [27]. To compare the average value of the Golden Pothos with other researchers' findings, the equivalent ozone deposition velocity was calculated from the decay curve for Golden Pothos provided by Papinchak et al. [21]; assuming a first order decay after subtracting the background losses. The calculated equivalent ozone deposition velocity was ~3.5 m h^{-1}. This value matches the average value of steady-state ozone deposition velocity from the three 8-h exposures, found to be 3.5 m h^{-1} as well.

Fig. 6 shows the results of experiments testing the effect of light on ozone deposition velocities to the five plants. The PAR lighting levels for the experiments in Fig. 6 were 1.2 μmol m^{-2} sec^{-1} for the first 180 min when the chamber lights were off and laboratory lighting was on. It is worth noting that results presented in Figs. 3–5 were conducted at this level (1.2 μmol m^{-2} sec^{-1}) of PAR. This value increased to 41.7 μmol m^{-2} sec^{-1} when the chamber overhead lamps were on. For every plant, the light test was performed 8 h subsequent to the three exposure tests except for the Ficus plant where the test was performed a week later. The data reported in Fig. 6 shows that all plants have reached steady state values at about 1 h after the initial ozone exposure, and the steady state ozone deposition values for all plants are very similar across all exposures except for the Ficus plant which is substantially higher for the first exposure than the third exposure. This effect for the Ficus plant could be explained by the fact that this plant was left unexposed to ozone for seven days, providing additional time for biological mechanisms to repair damage to the plant, with the likely outcome of regenerating ozone reaction sizes and increasing

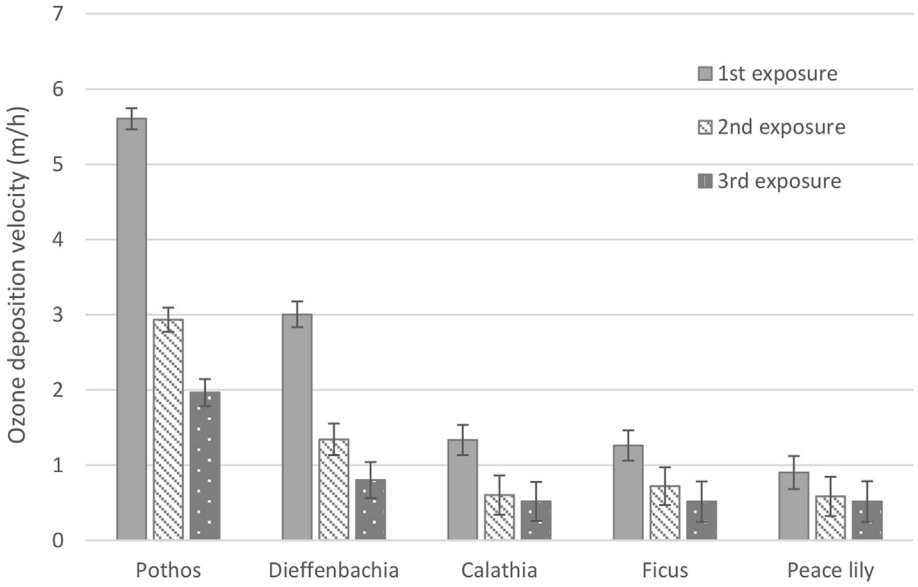

Fig. 5. Comparison of change of steady state ozone deposition velocity for the plants with number of exposure. The steady state value represents the average of last 20 values in transient data. Error bars are calculated based on error propagation. The PAR light intensity was 1.2 μmol m^{-2} sec^{-1} as only typical overhead laboratory lights were on.

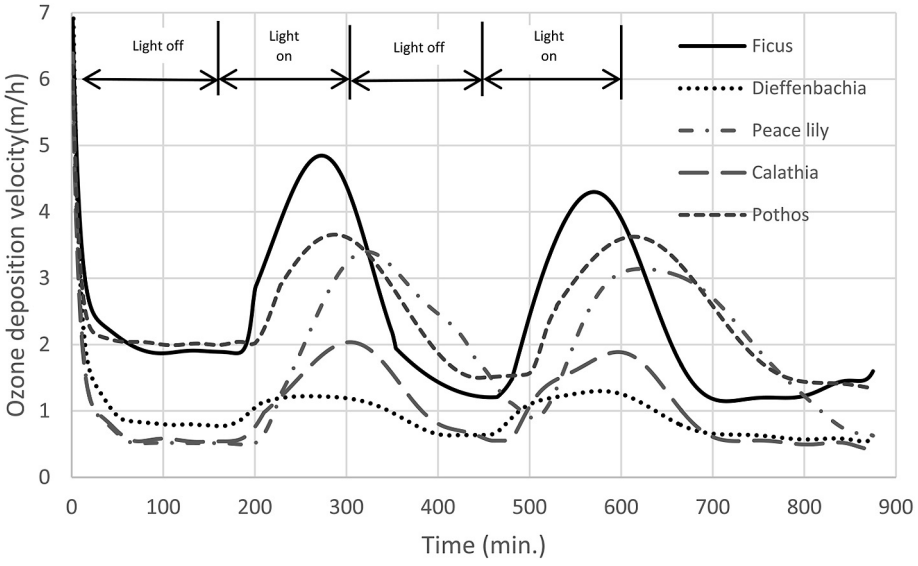

Fig. 6. Ozone deposition velocity change of the five plants with exposure to light. Inlet ozone concentration was 60 ppb. A light with PAR value of 41.2 μmol m^{-2} sec^{-1} was used to replicate indoor lighting conditions of a southern facing indoor environment shaded from direct insolation on a sunny day. The light was off at minute 600 and later.

the plant's ability to remove ozone.

The graph also shows that when the lights were on, the ozone deposition velocity for all plants increased meaningfully. The increment varies between a factor of 1.7 for Dieffenbachia (or an absolute increase of 0.45 m h^{-1}) to a factor 4.7 (an increase of 2.7 m h^{-1}) for Peace lily. One plausible explanation for the observed dependence of ozone removal on light level is that higher light levels will result in stomatal openings on the leaves. This permits greater flux of chamber air to penetrate to the leaf. As a result, ozone can either be consumed by the photosynthetic process or react with interior leaf components [35], resulting in an increase in ozone flux to the surface of leaf. This proposed mechanism, however, will vary from one plant to the next. Another observation of the plants' behavior is the speed with which they respond to changes in levels of lighting. To evaluate this effect, the rate of change of ozone deposition velocity was calculated for the 20 min after discrete changes in light levels. The slope values show that the Ficus Species had the fastest response, with a slope value of 0.079 m h^{-1} min^{-1}, and Dieffenbachia was the slowest with a slope value of 0.01 m h^{-1} $min.^{-1}$.

4.3. Ozone removal effectiveness

The ozone removal effectiveness of indoor plants is shown in Fig. 7, calculated as a function of the ratio of plant leaf area to volume of a hypothetical indoor environment as described in Section 3.2. Values of calculated effectiveness are determined for the range of the highest and lowest determined values of steady state ozone deposition velocities; the highest value being for Golden Pothos for the first exposure to ozone (5.61 m h^{-1}) and the lowest

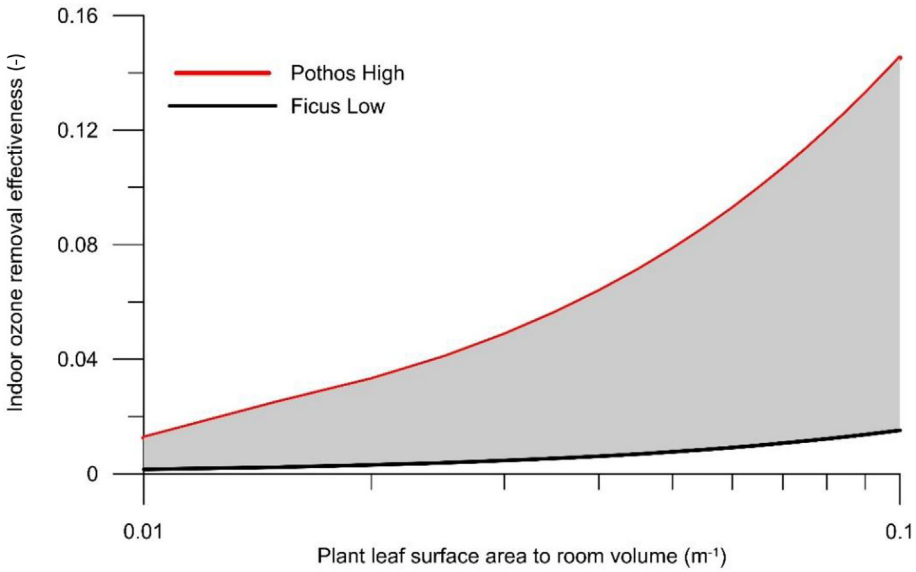

Fig. 7. Effectiveness of ozone removal versus the ratio of plant leaf area to space volume. The upper line shows the calculated value based on maximum steady state ozone deposition velocity of Golden Pothos with value of 5.61 m h^{-1}, and the lower line is calculated based on the lower value of ozone deposition velocity of Ficus with value of 0.51 m h^{-1}.

value being for Ficus Species for the third exposure (0.51 m h^{-1}). The values of effectiveness of other plants will be within the zone between the two lines. Note that the selection of this range of values was chosen to be illustrative; several plants exhibited higher v_d than 5.6 m h^{-1} during early portions of their first exposure to elevated ozone which would result in higher values of effectiveness for those time periods. However, experiments summarized by Figs. 4 and 5 show uniformly lower v_d during second and third exposures to elevated ozone across all tested plants. Therefore, since 5.6 m h^{-1} represented the highest near steady-state v_d across the five studied plants, it was deemed a reasonable upper-limit for this effectiveness screening analysis.

Calculated values of effectiveness are shown in Fig. 7 for ranges of plant leaf area to room volume ratio of 0.01–0.1 m^{-1}; a similar calculation across a larger (less realistic) range of leaf area to volume ratios is provided in Fig. S4 of the Supporting Information. Fig. 7 also shows that ozone removal effectiveness will be in the range of 0.1–2% across the plants studied here for a 0.01 m^{-1} leaf surface area to volume ratio, and between 2 and 15% for a 0.1 m^{-1} leaf surface area to volume ratio.

The number of plants necessary to provide a given leaf surface area is dependent on the size of the plant. Papinchak et al. [21] report that five Golden Pothos plants provided ~13,000 cm^2 of leaf surface area, or 2600 cm^2/plant. Using this leaf area per plant to provide an illustrative example, the range reported in Fig. 7 (0.01 m^{-1}–0.1 m^{-1}) would be achieved by placing from 2 to 23 plants in a 60 m^3 room. It is worth noting that different plants will have varying leaf surface areas provided per plant. The data presented in Fig. 7 can also be interpreted based on the floor area density necessary to achieve a given effectiveness. For example, achieving a leaf surface area to volume ratio of 0.06 m^{-1} would require, assuming a ceiling height of 2.5 m and the previously determined leaf area of 2600 cm^2/plant, one plant per 1.8 m^2 of floor area. This leaf surface area would result in ozone removal effectiveness from 0.9 to 9% across the range of low to high values of near steady-state v_d.

The range of ozone removal effectiveness values associated with plant leaf area in the range of 0.01–0.1 m^{-1} are modest in the context of indoor air cleaning applications, generally because the feasible amount of plant surface area is small in comparison with the total volume of an indoor space. However, it is possible that, if no harmful byproducts are formed as a result of ozone removal by plants, such modest contributions to indoor ozone removal may complement other indoor ozone control strategies.

5. Conclusions

In this research, five different popular indoor plants have been tested for their ability to passively remove indoor ozone. Also, the effect of indoor lighting on ozone removal of plants was investigated. The indoor plants tested had moderate ozone deposition velocity values ranging from about 0.5 to 5.5 m/h depending on period of time exposed to ozone, and number of exposures to ozone. Also, the results show that the ozone deposition velocity may increase substantially, between a factor of 1.7 for Dieffenbachia (or an absolute increase of 0.45 m h^{-1}) to a factor 4.7 (an increase of 2.7 m h^{-1}) for Peace lily, by exposing plants to light representative of levels typically encountered in indoor environments. However, calculations of effectiveness in a hypothetical indoor environment show, at best, modest contributions of about 0.9–9% to indoor ozone removal effectiveness for generally reasonable indoor loading factors of plant leaf surface area. Further research is necessary to quantify the combined effect of plant volatile organic compound emissions, ozone removal, and secondary byproducts that may result from ozone interactions with plant surfaces and/or emitted volatile organic compounds to provide further insight into the implications of indoor plants on indoor air quality.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2017.04.007.

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