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The Biofiltration Ability of Asparagus densiflorus to Remove Sulfur Dioxide from the Indoor Atmosphere

Rhiannon de la Rosa
University of Arkansas, Fayetteville

The Biofiltration Ability of *Asparagus densiflorus* to Remove Sulfur Dioxide from the Indoor

Atmosphere

An Honors Thesis submitted in partial fulfillment of the requirements of Honors Studies in

Horticulture, Landscape, and Turf Sciences

by

Rhiannon de la Rosa

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Abstract

Sulfur dioxide is an inorganic compound (IC) and air pollutant that causes health risks in humans at concentrations as small as 6 ppm. The buildup of sulfur dioxide in enclosed indoor spaces is therefore a concern to human health, especially since the average person spends 90% of his/her time indoors. This study focused on decreasing a sulfur dioxide concentration in a cost-effective and simple way—by using botanical biofiltration, or the uptake of pollutants by plants. Research in biofiltration has focused mostly on the remediation of volatile organic compounds (VOCs) and which plant species are most proficient at VOC uptake. However, research has also shown that species that remediate VOCs efficiently also have the potential for superior IC remediation. *Asparagus densiflorus*, which has a large capacity for VOC uptake, has been researched very little concerning ICs, and has not yet been tested for the uptake of sulfur dioxide. Therefore, this study sought to fill that research gap by testing the remediation of *Asparagus densiflorus* of sulfur dioxide in an airtight container. This was accomplished by measuring the amount of sulfur dioxide removed during 3 hours in an airtight container in the presence of an *Asparagus densiflorus* plant divided by the amount of sulfur dioxide in the absence of the plant. This result was considered the fraction of sulfur dioxide remediated by the plant. The final results in this experiment, although showing significant fraction of sulfur dioxide removal, were too variable to be conclusive about the amount of sulfur dioxide removed from an enclosed atmosphere and therefore of the biofiltration ability of *A. densiflorus*. Nonetheless, further research using a different research design is recommended to investigate whether *A. densiflorus* is more efficient than other plants at removing sulfur dioxide from the atmosphere and therefore could be used in larger-scale biofilters that must utilize space effectively.

Introduction

According to surveys conducted in 1989 and 2001, the average American spends about 90% (or 22 hours a day) of his or her time indoors (U.S. Environmental Protection Agency, 1989; Klepeis et al., 2001). For urban residents, from 58 to 78% of their time is in a building with air that is considered contaminated to some extent (Compton, 2011). Therefore, indoor air quality should be a priority concern for all individuals who spend this much time within buildings and sealed structures.

Two main chemical categories contribute to indoor air pollution: volatile organic compounds (VOCs) such as benzene and toluene, as well as inorganic compounds (ICs) including sulfur dioxide (SO$_2$). Both contribute to many health risks and are regulated in order to protect individuals. If a limit of one of these compounds were to be exceeded, the options for remediation can be very expensive: repairing ventilation systems, replacing faulty appliances, or even remodeling structures. A more cost-effective way to reduce pollutants is botanical biofiltration—the removal of contaminants from the environment using green plants (Soreanu et al., 2013).

Previous research has focused mostly on VOCs, though it is evident in the literature that plants efficient in the uptake of VOCs may also be efficient in the uptake of ICs (Esguerra et al., 1982; Wolverton et al., 1985; Yang et al., 2009). One plant that has been categorized as superior in VOC remediation is *Asparagus densiflorus* (Yang et al., 2009). However, it has not been used widely in IC remediation studies, and has not been investigated for the uptake of SO$_2$. Therefore, this study was established to determine *A. densiflorus*' capacity for SO$_2$ remediation.

Literature Review

Indoor Air Pollution

The most common source of indoor air pollution results from the combustion of fossil

fuels by improperly vented gas appliances, worsened by buildings, which are sealed in order to

conserve energy (Wolverton et al., 1985). These pollutants include carbon monoxide, sulfur

oxides, nitrogen oxides, and various VOCs, especially hydrocarbons (Solá, 1998) and are present

both indoors and outdoors. Indoor air pollution can be considered of greater immediate concern

to human health as pollutant concentration indoors can be 2-4 times greater than that outdoors

(Jafari et al., 2015).

Sulfur Dioxide

The IC sulfur dioxide is a gas with a density more than twice that of air and a molecular

mass of 64 g/mol. Sulfur dioxide originates primarily from the combustion of fossil fuels, and

becomes a problem in the indoor environment when household appliances such as gas heaters

and stoves are not functioning properly (Solá, 1998). Another source of SO$_2$ is pollution from

out-of-doors entering the building either by passive (openings in the structure) or active means

(ventilation systems with improper filtration) (Solá, 1998).

Sulfur dioxide is a pollutant of priority concern for air quality, along with carbon

monoxide, lead, nitrogen dioxide, ozone, and particle pollution, as outlined in the Clean Air Act

(U.S. Environmental Protection Agency, 1990). In the outdoor atmosphere, the Clean Air Act

sets a maximum limit of 75 ppb (parts per billion) of SO$_2$ (U.S. Environmental Protection

Agency, 1990).

Indoors, concentrations of SO$_2$ as small as 6 parts per million (ppm) can be irritating to the nose and throat, with larger concentrations progressing from eye irritation to irritation of moist skin at 12 ppm (Compton, 2011). Prolonged exposure can be harmful to the respiratory tract, with possible lung damage, chronic bronchitis, as well as worsening preexisting heart disease (Compton, 2011).

Due to these health risks, the Occupational Safety and Health Administration (2017) has set workplace environment limits at 5 ppm SO$_2$. While it is common to use electric SO$_2$ meters that directly measure ambient concentrations in parts per million, another method for analyzing SO$_2$ levels was proposed by Hochheiser (1964) using an absorbent solution and titration to find the amount of SO$_2$ captured. This method relies on the reaction of SO$_2$ and hydrogen peroxide to form sulfuric acid, which is then neutralized by the titrant sodium hydroxide solution (Hochheiser, 1964).

Botanical Biofiltration

Botanical biofiltration, as defined by Soreanu et al. (2013), is a hybrid term incorporating both phytoremediation, the remediation of contaminants by green plants, and biofiltration, the remediation of contaminants by biological activity. Pollutant uptake in botanical biofiltration has been predicted to occur by any combination of the following mechanisms: rhizosphere degradation via soil microorganisms, phytoextraction (plant-liquid extraction), stomatal uptake (plant-gas extraction), phytodegradation via the enzymes within plant tissue, and/or phytovolatilization by means of evaporation from leaves or plant transpiration (Soreanu et al., 2013). The activity in the rhizosphere is the main mechanism of pollutant remediation.

Regardless of mechanism(s) involved, optimization of large biofilter systems calls for the identification of the most efficiently remediating plants.

The mechanism of pollutant uptake by plants in phytoextraction, stomatal uptake, and phytodegradation is via concentration gradient, in which the concentration of pollutant is greater in the air than it is in plant cells; however, the flow of the pollutant into plant cells is limited by the resistances of the stomata and mesophyll (Esguerra, et al. 1982). Due to the differences in structure of both pollutant and plant, Hörmann et al. (2018) suggested that remediation capabilities are both plant species and contaminant dependent. Not only does botanical biofiltration offer a cost-effective method of remediating indoor air pollution, but the presence of green plants can be a décor and morale boost to the inhabitants of the building.

Sulfur as a Plant Nutrient

Sulfur is an element required for plants to grow, considered a secondary macronutrient after nitrogen, phosphorus, and potassium (Acquaah, 2009). Plants use sulfur from the environment in the synthesis of amino acids cysteine and methionine and in protein synthesis (Ernst, 1998). Furrer (1967) found that not only do plants obtain their sulfur requirements from the soil, but also from atmospheric sulfur in the form of SO_2. In this, phytoremediation of indoor SO_2 pollution may not only benefit inhabitants' health but may alleviate sulfur deficiency in plants.

It is important to remember, however, that the plant may be exposed to a level of SO_2 that could become excessive and hurt the plant. Injury may appear up to four days after exposure (Esguerra et al., 1982) and includes leaf rolling, drooping, appearance of dark brown or ashen

spots (Chung et al., 2011). The occurrence and severity of the reaction are dependent on species resistance to SO₂, exposure time, and exposure concentration (Soreanu et al., 2013).

Asparagus densiflorus

   Asparagus densiflorus is a common house plant known as an "Asparagus Fern". It has vibrant green, needle-like foliage and mounded growing habit. Furthermore, *A. densiflorus* takes up the VOCs benzene, toluene, octane, trichloroethylene, and α-pinene designated at a superior rating of total uptake of all pollutants by square meter of leaf surface (Yang et al., 2009). Yang et al. (2009) reported VOC uptake rates by *A. densiflorus* of 2.65, 7.44, 3.76, 6.69, and 11.40 μg pollutant • m^{-3} (container volume) • m^{-2} (leaf area) per hour, respectively, for each of the previously listed compounds. Hörmann et al. (2018) investigated *A. densiflorus*' capacity to take up the VOCs 2-ethylhexanol and toluene under light and dark conditions and did not detect a significant difference in remediation between light and dark treatments. In light, *A. densiflorus* had an hourly uptake rate of 2 L 2-ethylhexanol • m^{-2} leaf area and 4 L toluene • m^{-2} leaf area (Hörmann et al., 2018). In the dark, *A. densiflorus* had an hourly uptake of 1.7 L 2-ethylhexanol • m^{-2} leaf area and 3.4 L toluene • m^{-2} leaf area (Hörmann et al., 2018).

Objectives & Hypothesis

Objectives

   The goal of this research was to determine the amount of SO₂ *A. densiflorus* could absorb. The objective of this study was to determine the amount of SO₂ a single *A. densiflorus* plant could absorb from a closed system in three hours.

Hypothesis

The null hypothesis was that SO_2 measured in a defined empty volume (i.e. in the absence of *A. densiflorus*) after 3 hours of exposure to a source of 10 ppm SO_2 would be the same as the SO_2 measured in the presence of an *A. densiflorus* plant in the same defined volume after 3 hours of exposure to the same source of 10 ppm SO_2.

Experimental Approach

This experiment was modeled after Hochheiser's (1964) gas sampling train, with modifications to incorporate a 0.3 x 0.3 x 0.3 meter, 28 liter airtight box that contained the *A. densiflorus* plant and a fan to ensure uniform mixing of the air (**Figure 1**). In addition, a safety trap was added in line to ensure that all SO_2 was captured. The SO_2 at an original concentration of 10 ppm from a tank was pulled through the box and into an impinger filled with 0.3 N hydrogen peroxide absorbing solution. The impinger (**Figure 2**) bubbled the incoming air through 75 mL of the 0.3 N hydrogen peroxide solution, which captured all SO_2 before the cleaned air breaking the surface of the 0.3 N hydrogen peroxide solution. This absorption is based on the chemical reaction of sulfur dioxide and hydrogen peroxide to form sulfuric acid. Air with any remaining SO_2 was pulled from the impinger through the side port into a safety trap filled with approximately 200 mL of 0.3 N hydrogen peroxide, which acted much like a large impinger, in order to ensure there was no remaining SO_2 in the air before it was pulled through the vacuum pump and released into the hood and subsequently the atmosphere.

The modified gas sampling train was assembled and smoke tested for airtightness before beginning the experiments testing four treatments: 1) ambient air with no plant present, 2)

ambient air with a plant, 3) SO_2 with no plant exposed to a source of 10 ppm SO_2 in a defined

volume for three hours, and 4) SO_2 with the plant present exposed to a source of 10 ppm SO_2 in a

defined volume for three hours.

Materials & Methods

Materials

The source of SO_2 (10 ppm SO_2, balance air) was obtained from AirGas USA, LLC

(Durham, NC) and the tank was secured to a lab bench with a chain and had a safety duct system

placed above it in case of leaks. The airtight box was constructed with five 0.3 x 0.3 meter

acrylic sheets of half centimeter thickness and silicone caulk. Hinges and latches were glued onto

the outside, and a rubber gasket was fastened to the top edge. A sixth acrylic sheet was then

glued to the hinges to form a lid that sealed with the gasket when the box was closed. The box

was then tested for airtightness by burning incense in the latched box. If any scent or smoke

escaped, the leak was sealed. To protect from the outflow of SO_2 in the case of any damage to

the box, it was placed in a sealed glove bag during the experiment (**Figure 3**). These components

were attached to the flow control, impinger, safety trap, and vacuum pump with Tygon tubing

and plastic connectors.

The absorbing solution was 3% hydrogen peroxide solution while the sodium hydroxide

titrant was 0.002 N sodium hydroxide. The mixed indicator was comprised of bromocresol green

and methyl red in methanol. A standard 50 mL burette was used for the titration.

Four *A. densiflorus* plants (Lowe's, Fayetteville, AR) were purchased and kept in the

Horticulture Department greenhouse to acclimate for four months before being divided into 12

plants in total in potting soil. After dividing, plants were maintained in the Horticulture

Department greenhouse with regular watering for four additional months to regulate

physiological processes before the experiment (**Figure 4**).

Methods

First, the airtight box was latched with the fan, and plant if applicable, inside. The bag

was sealed around the box, and the connections were checked to ensure attachment to the rest of

the sampling train. The impinger was filled with 75 mL of the 0.3 N hydrogen peroxide solution

and connected via Tygon tubing to a valve, which controlled outflow from the airtight box. The

safety trap was filled with approximately 200 mL of the 0.3 N hydrogen peroxide solution. Once

all components were confirmed in the sampling train, the SO₂ tank (if applicable) was set to have

an output of 5 psi while the vacuum was set at a suction of 10 inches Hg. The treatment was run

for 3 hours. The SO₂ tank was then detached, the vacuum was shut off, and the 75 mL of 0.3 N

hydrogen peroxide solution in the impinger was collected and transferred to a beaker. The 0.3 N

hydrogen peroxide solution in the safety trap was checked regularly for the presence of SO₂ from

possible overflow and none was ever detected.

To determine the amount of SO₂ collected during each run, 4 drops of the mixed indicator

were added to the 0.3 hydrogen peroxide solution from the impinger (or safety trap) that was

stirred continuously with a magnetic stir bar. The sodium hydroxide titrant was added dropwise

via the burette until the titer turned green. Amount of SO₂ (mg) was found by multiplying the

total sodium hydroxide titrant used by 64.07, as calculated based on the equation below.

$$\frac{x\ L\ NaOH}{1} \times \frac{0.002\ mol\ NaOH}{1\ L} \times \frac{1\ mol\ H_2SO_4}{2\ mol\ NaOH} \times \frac{1\ mol\ SO_2}{1\ mol\ H_2SO_4} \times \frac{64.07\ g\ SO_2}{1\ mol\ SO_2} \times \frac{1,000\ mg\ SO_2}{1\ g\ SO_2}$$

Data Analysis

Treatments 1 (ambient air with no plant present) and 2 (ambient air with a plant) were replicated four times. Treatment 3 (SO$_2$ with no plant exposed to a source of 10 ppm SO$_2$ in a defined volume for three hours) was replicated six times. To evaluate replicability in treatment 3, treatment 3b consisted of six additional replicates (another 6 replications). Treatment 4 (SO$_2$ with the plant present exposed to a source of 10 ppm SO$_2$ in a defined volume for three hours) was replicated six times.

The first two treatments measured SO$_2$ content in ambient air. Any measured amount of SO$_2$ in treatment 1 would need to be subtracted from treatment 3, and any measured amount of SO$_2$ in treatment 2 would need to be subtracted from treatment 4.

The descriptive statistics, including the mean, median, first and third quartiles, minimum, maximum were calculated for the SO$_2$-no plant (treatment 3) and SO$_2$-plant treatment (treatment 4) and are displayed in a box plot. Percent relative difference was calculated for a pair of SO$_2$-no plant runs. Standard deviation and relative standard deviation were calculated for the SO$_2$-no plant (treatment 3 and 3b) and SO$_2$-plant treatments (treatment 4).

The SO$_2$-no plant (treatment 3b) and SO$_2$-plant treatments (treatment 4) were run in pairs (n = 5) and used to determine SO$_2$ uptake for the purposes of the study. To find percentage uptake (or fraction removed), each pair of treatments (SO$_2$-plant and SO$_2$-no plant) was analyzed. The SO$_2$-plant (SO$_2^P$) value was subtracted from the SO$_2$-no plant (SO$_2^N$) value. The difference was divided by the SO$_2$-no plant value and multiplied by 100, shown in the equation below.

$$\text{Percentage uptake} = \frac{SO_2^N - SO_2^P}{SO_2^N} \times 100$$

The distribution of the total of 12 replications of SO_2-no plant (treatment 3 and 3b) is displayed in a histogram. After a log transformation in order to normalize the distribution of samples, a paired t-test was run to evaluate significance of SO_2 removal.

Results

The SO_2 content of treatment 1 and 2 was expected to be 0 mg. For four replications of treatment 1 (ambient air, no plant) and treatment 2 (ambient air, plant), all runs had 0 mg SO_2. Repeated sampling is generally expected to follow a normal distribution and statistical analyses are often based on that normal distribution and those tests are parametric tests. A histogram was created of the 12 samples of SO_2 in the absence of the plant to determine if samples followed a normal distribution. Sample distribution is shown in **Figure 5**, displaying a non-normal, right skewed distribution.

Regardless, of sample distribution, results demonstrate that amounts of SO_2 are variable **(Figure 6)**. The mean of the first six replications of SO_2 in the absence of the plant (i.e. treatment 3) is less the mean of the second six replications within the same treatment (i.e. treatment 3b). The median is a robust measure of central tendency; however, the median is also much larger (2.6 times larger) in the second six replicates (i.e. treatment 3b) compared to the first six of the same treatment (i.e. treatment 3). The range of values is more than 4 times greater in the second six replicates compared to the first six. Even in the presence of plants, treatment 4, the range of values is 1.8 times greater than in the absence of plants. To analyze the data despite variability among the means, coefficient of variation (CV) or relative standard deviation was used **(Table 1)**. The CVs varied between the first six and second six replicates in the SO_2 treatment in the absence of a plant, treatments 3 and 3b, respectively, and compared to the presence of a plant, or

in treatment 4. However, a repeated run of SO$_2$ in the absence of the plant yielded a percent

relative difference between duplicates of 17.3 % (data not shown), which is within generally

accepted values of less than 20%. Due to these facts, the first six replicates (treatment 3) were

disregarded and the second six (treatment 3b) were paired with each replicate of treatment 4. The

fifth replicate was discarded due to a failure in data collection and a total of five paired

replications were used to analyze percent removal.

Percent of SO$_2$ removal from the atmosphere ranged from 35 to 84%, with a mean

removal rate of 53% and median of 46% (**Figure 7**). A paired t-test indicated significant percent

removal of SO$_2$ from the enclosed atmosphere under these defined conditions for 3 hours (P =

0.011).

Discussion

While there was a significant difference in SO$_2$ removal with the presence of the plant,

the data are too widely variable to make a definitive statement about the removal capacity of

Asparagus densiflorus. The original treatment 3 with six replicates was varied, and so an

additional 6 replicates were tested (treatment 3b). However, instead of shrinking the variability

as was expected, the additional 6 replicates increased variability. Thus, while the pairs of

treatment 3b and treatment 4 each indicated a certain percentage of removal, up to 84%, the

inherent variability of the data creates an issue in claiming to what extent the plant may

remediate SO$_2$.

The gas regulator itself provided a possible source of error, as the output was not

consistent across treatments involving SO$_2$. To circumnavigate this potential source of error,

SO$_2$-no plant and SO$_2$-plant runs were conducted consecutively in pairs without turning the gas

regulator on or off; however, given the variability within and between runs, it is difficult to determine if this error was minimized.

In relation to the inconsistent gas regulator, the original concentration of 10 ppm SO_2 could not be confirmed as being the same concentration in the airtight box. The amount of liters of air flowing through the system could not be measured, and thus a concentration within the system could not be determined. Ideally, at any given time there would have been 280 mg of SO_2 in the 28 L box, yielding a concentration of 10 ppm. However, this could not be confirmed and thus remains as a possible source of error.

If the data had not been so variable as to not be reliable, the mean removal capacity of *A. densiflorus* would have been 296 mg SO_2 in three hours, or 99 mg SO_2 per hour. The results here are difficult to compare to other studies where remediation capacity was reported in other, more inclusive units. Yang et al. (2009) found *A. densiflorus* to take up VOCs at 2.65 to 11.40 μg of pollutant • m^{-3} container volume • m^{-2} leaf area per hour, and Hörmann et al. (2018) measured *A. densiflorus* to take up VOCs at 1.7 to 4 L pollutant • m^{-2} leaf area per hour. Esguerra et al. (1982) found an uptake range from 0.15 to 2.77 μg SO_2 • m^{-2} leaf area • s^{-1} for three hours. All these measurements were taken in relation to exposed leaf area, and all experiments covered the soil surface in order to isolate effect on pollutant concentration by aboveground plant tissue.

In the case of a standard houseplant that had the soil exposed to the atmosphere, the uptake measured in this study would increase, though it should not be attributed to the actual remediation of *A. densiflorus* but instead remediation by the soil and related microbes performing rhizosphere degradation of SO_2 (Soreanu et al., 2013). Soreanu et al. (2013) also summarized research that suggested that phytoremediation is a collective effort between plants and microorganisms, which depends on interactions with each other.

It also must be accepted that in experiments such as this, the closed, modified environment used to measure uptake cannot be compared to uptake in a normal indoor condition. Similarly, the closed box increased concentration of SO$_2$ around the plant, and therefore created a greater concentration gradient. A concentration gradient will eventually cause sulfur levels in both plant tissue and air to equalize, stopping uptake until the sulfur is metabolized and transported elsewhere (Hörmann et al., 2018). This greater concentration would therefore create the appearance of greater or faster uptake in comparison to within a large room in which the amount of SO$_2$ may be the same, but the concentration itself would be substantially lower.

However, hypothetically speaking, if the mean 99 mg SO$_2$ per hour rate found in this study was to be used as a calculation, a standard 4 by 4 by 4 cubic meter room at 5 ppm SO$_2$ would require 20 plants to remediate all SO$_2$ in a week. Calculations such as these are difficult to substantiate when the remediation rate is not only determined from variable data, but also from an experiment lasting only three hours in a closed system with conditions unlike that of a larger room. These challenges also compound when scaling up remediation rates to incorporate into a larger biofilter system.

Conclusion

It was determined that the experimental design resulted in data that was too variable to assess confidently *Asparagus densiflorus'* uptake of sulfur dioxide. Any repetitions of the experiment would require a more constant and reliable method of delivery of SO$_2$ and measurement of plant uptake of SO$_2$.

Further Research

With further resources, this experiment could be expanded in multiple directions. The priority would be to utilize a more consistent method of pollutant delivery to deliver and be able to measure the same output of gas across runs. A calibrated SO$_2$ meter is expensive but is needed to be able to measure concentration accurately in real time, as well as a meter in order to measure flow rate to determine units of output.

Another source of data that would better detail uptake would be to measure sulfur in the plant biomass and compare sulfur in plants in the absence of SO$_2$ to sulfur in plants in the presence of SO$_2$. With improved logistical operations in place, investigation of exposure times ranging from 3 hours to 3 days would be beneficial. Additional research may include different contaminants or different species of plants that have been shown to be efficient in remediation, including *Hemigraphis alternata*, *Hedera helix*, *Tradescantia pallida*, and *Hoya carnosa* (Yang et al., 2009).

References

Acquaah, G. 2009. Horticulture: Principles and practices. Pearson Education. Upper Saddle
River, New Jersey.

Chung, CY., PL. Chung, and SW. Liao. 2011. Carbon fixation efficiency of plants influenced by
SO2. Environmental Monitoring and Assessment. 173:701-707.

Compton, B.W. (Ed.). 2011. SO2: Properties, applications and hazards. Nova Science
Publishers, Inc., Hauppauge, New York.

Ernst, W. H. O. 1998. Sulfur metabolism in higher plants: potential for phytoremediation.
Biodegradation. 9:311-318.

Esguerra, C. J., E. C. Santiago, N. R. Aquino, and M. L. Ramos. 1982. The uptake of SO₂ and
NO₂ by plants. Science Diliman. 2:44-56.

Furrer, O. J. 1967. The amount of sulphur dioxide absorbed by plants from the atmosphere.
Symposium on the use isotopes in plant nutrition and physiology studies. Vienna,
Austria.

Hochheiser, S. 1964. Methods of measuring and monitoring atmospheric sulfur dioxide. U.S.
Department of Health, Education, and Welfare. Cincinnati, Ohio.

Hörmann, V., KR. Brenske, and C. Ulrichs. 2018. Assessment of filtration efficiency and
physiological responses of selected plant species to indoor air pollutants (toluene and 2-
ethylhexanol) under chamber conditions. Environmental Science and Pollution Research.
25(1):447-458.

Jafari, J. M., A. A. Khajevandi, S. A. M. Najarkola, M. S. Yekaninejad, M. A. Pourhoseingholi,
L. Omidi, and S. Kalantary. 2015. Association of sick building syndrome with indoor air
parameters. Tanaffos. 14(1):55-62.

Klepeis, N., W. C. Nelson, W. R. Ott, J. P. Robinson, A. M. Tsang, P. Switzer, J. V. Behar, S. C.

    Hern, and W. H. Engelmann. 2001. The national human activity pattern survey

    (NHAPS): A resource for assessing exposure to environmental pollutants. Journal of

    Exposure Science & Environmental Epidemiology. 11:231-252.

Solá, X. G. 1998. Chapter 44: Indoor air quality. In J. M. Stellman (Ed.), Encyclopaedia of

    occupational health and safety (44.2-44.26). International Labour Organization. Geneva,

    Switzerland.

Soreanu, G., M. Dixon, and A. Darlington. 2013. Botanical biofiltration of indoor gaseous

    pollutants—A mini-review. Chemical Engineering Journal. 229:585-594.

U.S. Environmental Protection Agency. 1989. Report to Congress on indoor air quality: Volume

    2. EPA/400/1-89/001C. Accessed 20 February 2020. Available at

    https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=9100LMBU.TXT

U.S. Environmental Protection Agency. 1990. NAAQS table. Accessed 17 March 2020.

    Available at https://www.epa.gov/criteria-air-pollutants/naaqs-table

U.S. Occupational Safety and Health Administration. 2017. Table Z-1-limits for air

    contaminants. Code of Federal Regulations. Accessed 20 February 2020. Available at

    https://www.osha.gov/laws-regs/regulations/standardnumber/1910/

Wolverton, B. C., R. C. McDonald, and H. H. Mesick. 1985. Foliage plants for indoor removal

    of the primary combustion gases carbon monoxide and nitrogen dioxide. Journal of the

    Mississippi Academy of Sciences. 30:1-8.

Yang, D. S., S. V. Pennisi, KC. Son, and S. J. Kays. 2009. Screening indoor plants for volatile

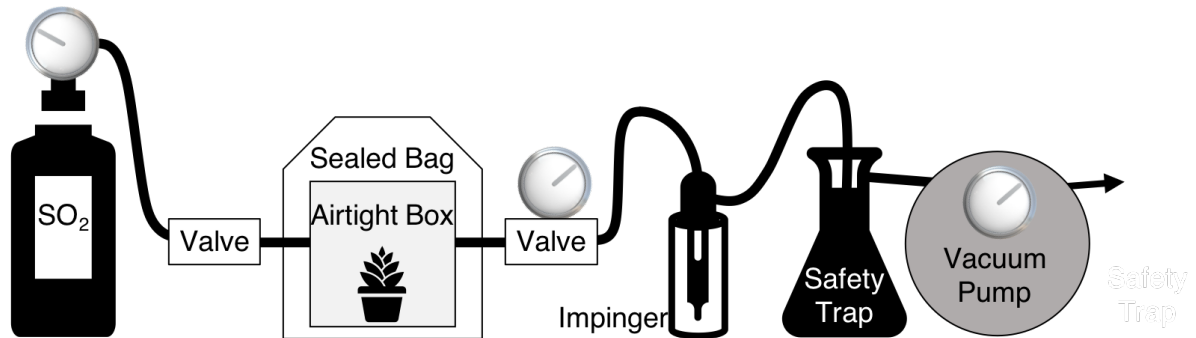   organic pollutant removal efficiency. HortScience. 44(5):1377-1381.

Figures

Figure 1. The experimental setup that was used to evaluate *A. densiflorus'* ability to take up SO$_2$ from the atmosphere in a defined volume. The air-tight system was attached first to a safety trap in order to absorb any overflow of SO$_2$, then to a vacuum pump in order to control the flow through the system. (fig. by de la Rosa)
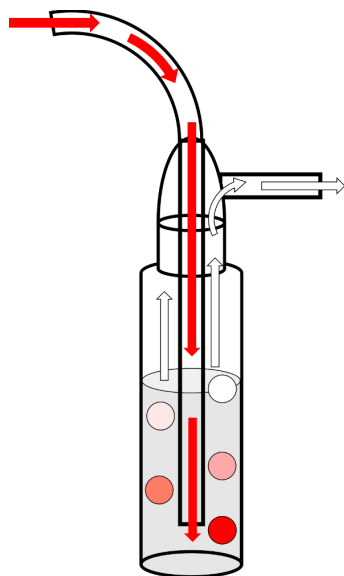
Figure 2. A schematic of how the hydrogen peroxide solution-filled impinger collects SO$_2$. Air containing SO$_2$ (shown as red arrows) flows down the impinger tube and to the bottom of the hydrogen peroxide solution. As bubbles of SO$_2$-contaminated air are formed in the solution (red circles), they react with the hydrogen peroxide in order to form sulfuric acid and remove all SO$_2$ from the bubbles until there is none within them (white circles) before they break the surface of the solution and the cleaned air is pulled through the outer port.
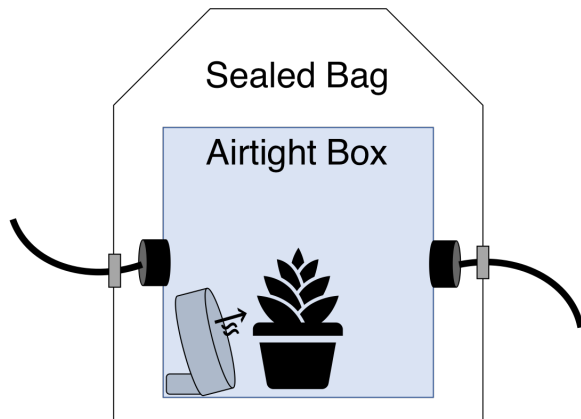
Figure 3. The airtight box used in the experiment to test the presence or absence of atmospheric

SO$_2$ is surrounded by the sealed bag, with tape-reinforced inlets and outlets for the Tygon tubing.

Box contains either no plant or one plant and a fan regardless of the presence or absence of the

plant.

Figure 4. One of the divided *A. densiflorus* plants used in the experiment prior to exposure to sulfur dioxide. Shown with plastic wrap used to prevent contact of rhizosphere with atmosphere.
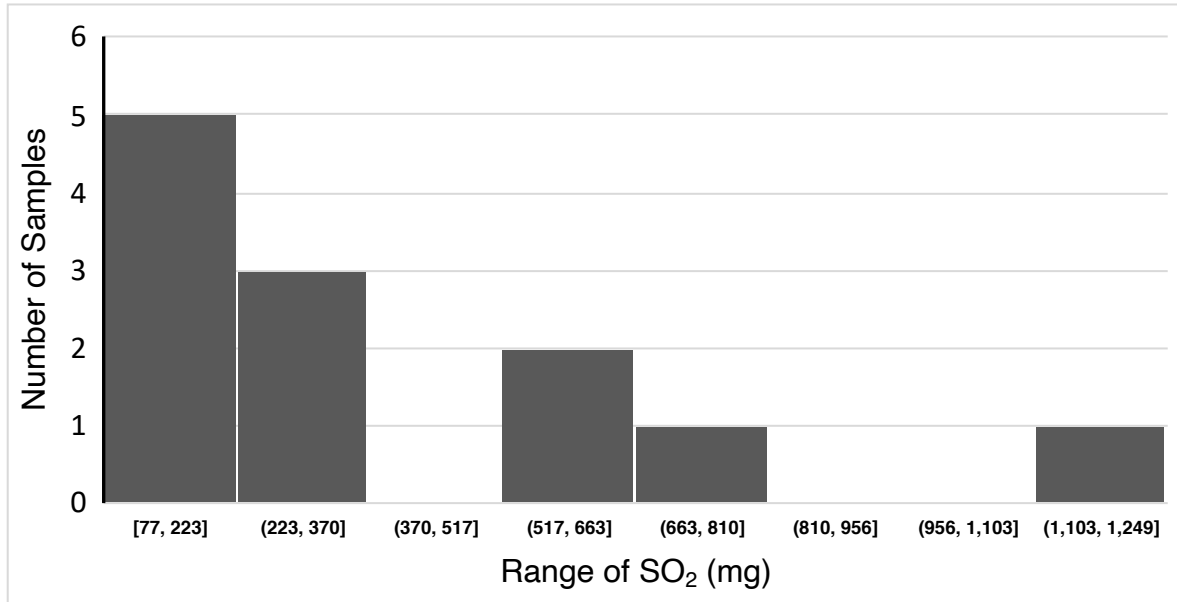
Figure 5. A histogram showing the distribution of the data collected in the presence of an original source of 10 ppm SO$_2$ but in the absence of *Asparagus densiflorus* for 3 hours in a space of 28 liters (n = 12).
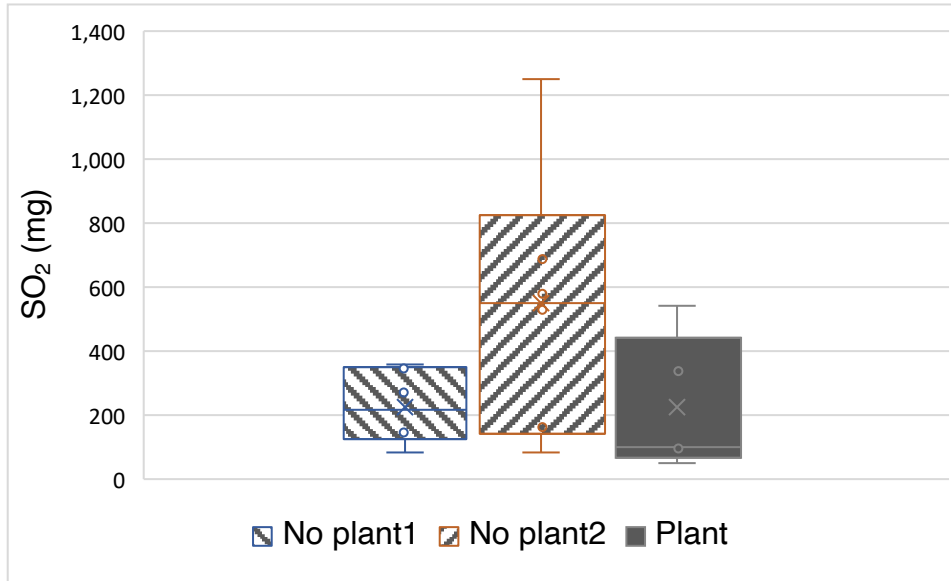
Figure 6. The amount of SO_2 in mg when pulled at an original concentration of 10 ppm at 10 inches of Hg negative pressure for 3 hours in a space of 28 liters in the absence of *Asparagus densiflorus*, evaluated twice (treatment 3 is No plant1 and treatment 3b is No plant2, n = 6), and in the presence of *Asparagus densiflorus* (treatment 4 is Plant, n = 5).
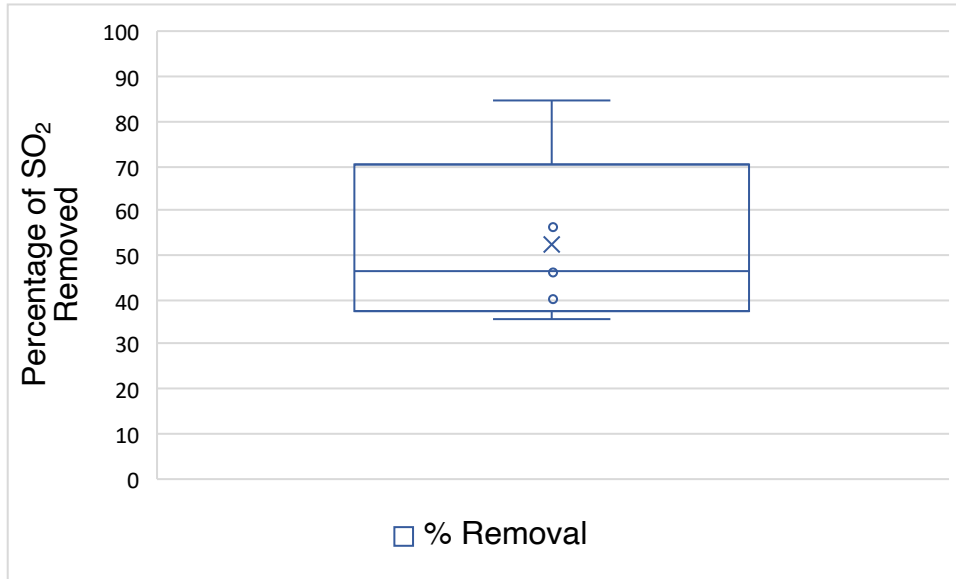
Figure 7. Percent removal of SO$_2$ from paired treatments in which SO$_2$ at a source concentration of 10 ppm was pulled through a 28-liter space at 10 inches Hg negative pressure for 3 hours in the absence of *Asparagus densiflorus* (e.g. treatment 3b) and in the presence of *Asparagus densiflorus* (treatment 4 as described in the methods text, n = 5).

Tables

Table 1. Mean, standard deviation, and coefficient of variation (or relative standard deviation

expressed as a fraction of mean divided by the standard deviation) of mg SO$_2$ in the absence or

presence of *Asparagus densiflorus,* and given the percent removal attributed to *Asparagus*

densiflorus within a defined volume after 3 hours exposure to a source of 10 ppm SO$_2$.

Property	Mean Value	Standard Deviation	CV
SO$_2$ (mg) absence of *Asparagus densiflorus* – 1st 6 reps	223.2	115.6	51.8
SO$_2$ (mg) absence of *Asparagus densiflorus* - 2nd 6 reps	546.7	419.2	76.7
SO$_2$ (mg) presence of *Asparagus densiflorus* (n = 5)	223.0	213.7	95.8
% Removal of SO$_2$ (n = 5)	52.5	19.5	37.2