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1. Foliage Plants for Indoor Removal of the Primary Combustion Gases
Carbon Monoxide and Nitrogen Dioxide.

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Abstract. Foliage plants were evaluated for their ability to sorb carbon monoxide and nitrogen dioxide, the two primary gases produced during the combustion of fossil fuels and tobacco. The spider plant (*Chlorophytum elatum* var. *vittatum*) could sorb $2.86 \mu\text{g CO/cm}^2$ leaf surface in a 6 h photoperiod. The golden pothos (*Scindapsus aureus*) sorbed $0.98 \mu\text{g CO/cm}^2$ leaf surface in the same time period.

In a system with the spider plant, $\geq 99\%$ of an initial concentration of 47 ppm NO_2 could be removed in 6 h from a void volume of approximately 0.35 m^3 .

One spider plant potted in a 3.8ℓ (1 gal) container can sorb $3300 \mu\text{g CO}$ and effect the removal of $8500 \mu\text{g NO}_2$ per hour, recognizing the fact that a significant fraction of NO_2 at high concentrations will be lost by surface sorption, dissolving in moisture, etc.

Additional Index Words: foliage plants, carbon dioxide, nitrogen dioxide, combustion gases, spider plants, golden pothos, *Chlorophytum elatum* var. *vittatum*, *Scindapsus aureus*.

Introduction. Two primary sources of indoor air pollution are tobacco smoking and the combustion of fossil fuels in heaters, gas stoves, water heaters, etc. Combustion products are becoming an even greater threat to our health due to increased sealing of homes, offices, and other structures for energy conservation. Reduced ventilation contributes to a buildup of such gaseous combustion products as carbon monoxide (CO) and nitrogen dioxide (NO_2).

Carbon monoxide is a product formed during incomplete combustion. Hemoglobin has 210 times the affinity for CO than it has for oxygen; consequently, very low concentrations of carbon monoxide in the air can substantially elevate the carboxyhemoglobin concentration in the blood. Three to five percent saturation of hemoglobin with CO may adversely affect one's ability to detect small, unpredictable environmental changes. At 4 to 5% saturation, patients with cardiovascular disease can exacerbate their symptoms (National Research Council, 1977).

During cooking with a gas range, carbon monoxide levels can increase up to 500 ppm (National Research Council, 1981). Carbon monoxide levels of 2.5-15 ppm have been measured in restaurants. The main source was attributed to tobacco smoking (Seppänen and Uusitalo, 1977). Other measurements of CO in confined areas have indicated buildups of 30-90 ppm (Russel et al., 1973; Seppänen, 1977; and Srch, 1967).

The current EPA standards for carbon monoxide are 9 and 35 ppm for 8 and 1 h average exposures, respectively. At 9 ppm CO and 8 h, 1.4% saturation of hemoglobin with CO will occur during heavy activity. At 35 ppm and 1 h, 2.9% saturation will occur during heavy activity (National Research Council, 1977).

Indoor combustion can also contribute to the buildup of nitrogen dioxide. Nitrogen dioxide concentrations equal to or greater than the current ambient air quality standard of 0.05 ppm are not unusual in kitchens where gas is used for cooking. At these concentrations, nitrogen dioxide may affect sensory perception, especially dark adaptation, and produce eye irritation (National Research Council, 1976; Goldsmith and Friberg, 1977). Nitrogen dioxide can produce transient and long-term damage to both small bronchial airways and alveolar tissue. Exposure of rats to a minimum of 2 ppm nitrogen dioxide for 4 hours stimulated the differentiation of nonciliated cells into mature clara cells and ciliated cells in the bronchial airways (Evans and G. Freeman, 1980). This effect raises the possibility that chronic exposure could lead to chronic bronchitis.

The National Aeronautics and Space Administration (NASA) at the National Space Technology Laboratories (NSTL) has conducted research for many years on the use of natural systems for wastewater treatment and water reclamation. This research has been expanded to include the evaluation of foliage plants for air filtration and purification in closed systems such as space stations and energy-efficient homes. The first studies concentrated on formaldehyde removal and found that the spider plant (*Chlorophytum elatum* var. *vittatum*) is particularly efficient in removing this organic from contaminated air (Wolverton et al., 1984).

This paper contains data from experiments where foliage plants were tested for their ability to remove the two primary combustion gases, carbon monoxide and nitrogen dioxide.

Materials and Methods. A. Experimental Apparatus. The system shown in Fig. 1 consists of a Plexiglas cubical chamber, 73.7 cm on each inside edge. The removable top was fitted with a rubber gasket and clamps. To this top was

attached a copper coil which was used to control temperature and humidity by continuously circulating water at 20°C through the coil. The chamber was illuminated continuously with ten Sylvania wide spectrum Gro Lux lights. The average irradiance reaching the plants inside the chamber was 3500 lux (325 fc). Air inside the chamber was continuously circulated with a battery-operated, portable fan. The thermometer and hygrometer were mounted inside the chamber for internal temperature and relative humidity measurements.

B. Experimental Procedure. Experimental runs were conducted with all components of the system described above in place in the following manner with:

1. no pots or plants in order to leak test the system;
2. two watered, soil-filled pots (3.8ℓ capacity each) to establish the sorbency of the potting medium;
3. two spider plants (*Chlorophytum elatum* var. *vittatum*) potted in 3.8ℓ containers;
4. two spider plants with surface area of potting soil at base of plants covered with aluminum foil (for NO₂ experiments only);
5. two golden pothos (*Scindapsus aureus*) potted in 3.8ℓ containers (carbon monoxide experiments only).

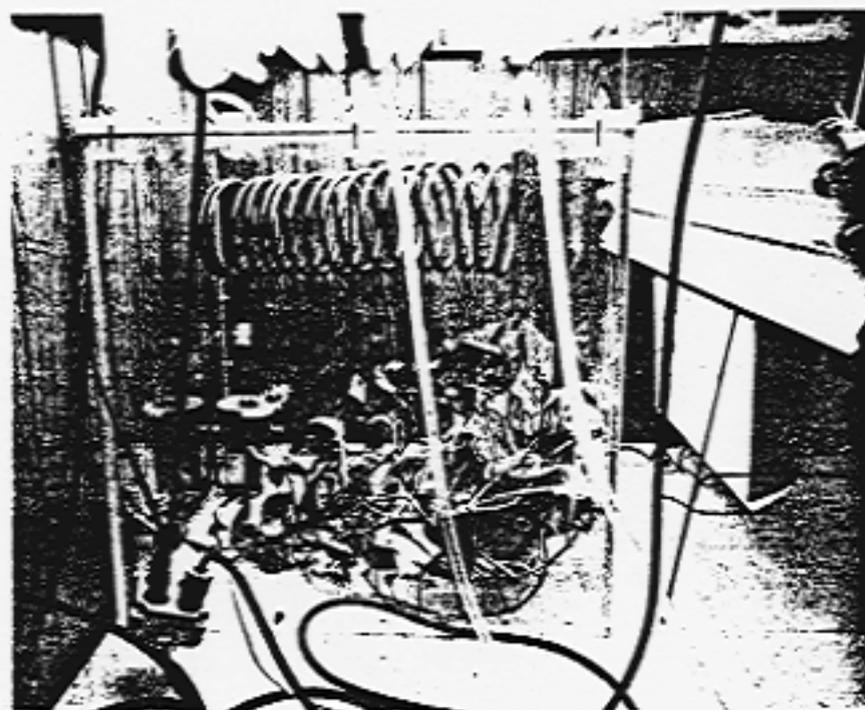


Figure 1. Plexiglas test chamber containing golden pothos (*Scindapsus aureus*).

The chamber atmosphere was contaminated by metering in either a carbon monoxide mixture (939 ppm CO, 20.6% O₂, N₂ balance) or nitrogen dioxide mixture (0.672% NO₂, balance air). Following contamination, the system was allowed to equilibrate 5 min, and an initial measurement performed. The contaminant of interest was monitored with an appropriate Dräger gas detector tube. Subsequent measurements were made at regular time intervals. In addition, the internal temperature and relative humidity were recorded, and the atmospheric barometric pressure noted. The actual volume of contaminated air was calculated as the total internal volume of the chamber less the volume of the copper coil, fan, monitoring devices, and filled pots excluding the emergent leaf biomass.

The plants were acclimated for several weeks to approximately the same environmental conditions of temperature, lighting, etc., in order to minimize stress. The leaf surface area was determined by tracing the leaves on paper of uniform consistency, weighing the tracings, and converting the total paper mass to its equivalent surface area.

Results and discussion. General data collected for each set of experiments pertinent to calculating mass quantities for gases is presented in Table I. Table II contains the actual atmospheric concentrations of CO and NO₂ under various conditions as a function of exposure time in the sealed chamber.

System closure was verified with the CO control w/o pot experiments. When pots were added to the otherwise empty chamber, the soil sorbed 14% of the CO in 24 h. The *S. aureus* and *C. elatum* var. *vittatum* removed 75% and >96% of the CO in 24 h. Based on the photosynthetic areas (Table III), the *C. elatum* var. *vittatum*'s removal rate for CO was approximately 3 times faster at 6 h, resulting in 2.86 µg CO/cm² leaf surface removed as compared to 0.98 µg CO/cm² leaf surface for *S. aureus*.

Nitrogen dioxide was very unstable as demonstrated in the control experiments. In order to separate the removal of NO₂ due to the plants versus the removal due to the potting soil, a set of plant experiments were conducted with the surface of the soil covered with foil. The emergent leaf surface area by itself could remove >99% of the initial 47 ppm (34, 234 µg) of NO₂ in 6 h, as well as the soil exposed *Chlorophytum* system. The plant systems, soil-exposed and soil-covered, removed 3.63 and 3.29 µg NO₂/cm² leaf surface area in 6 h.

If a kitchen contained 50 ppm CO and 0.05 ppm NO₂ and had an approximate void volume of 22 m³, a purification system would need to be capable of removing 1.4 x 10⁶ µg CO and 2.3 x 10³ µg NO₂ per hour, recognizing the fact that a significant fraction of NO₂ at high concentrations will be lost by sorption on most exposed surfaces, dissolving in water, etc. Based on this data, one spider plant per room where combustion is occurring in conjunction with the normal air exchange and other factors would help to alleviate the buildup of NO₂.

Due to much higher potential concentrations of CO and its greater stability as compared to NO₂, more plants would be needed to provide reliable assurance of better air quality. In a previous report by Wolverton *et al.* (1984)

Table I. Mean general parameter values for all experiments.

Experiment	Vca, l ^a	Temp, °C	Barometric pressure, mm	Relative humidity, %	Leaf surface area, cm ²	No. of replicates
Carbon monoxide:						
1. Controls w/o pots	365.7	25.8	765.7	66.3	—	3
2. Controls w/pots	366.8	26.4	764.6	83.8	—	3
3. <i>Scindapsus aureus</i>	355.5	27.8	765.5	79.5	13,083	4
4. <i>Chlorophytum elatum</i> var. <i>vittatum</i>	367.9	27.5	769.9	87.6	9,393	8
Nitrogen dioxide:						
1. Control w/o pots	364.6	27.4	768.0	67.6	—	8
2. Control w/pots	357.8	26.3	766.5	83.1	—	3
3. <i>Chlorophytum elatum</i> var. <i>vittatum</i> (soil exposed)	351.1	27.2	754.4	77.8	9,635	14
4. <i>Chlorophytum elatum</i> var. <i>vittatum</i>	354.7	28.6	765.6	72.7	10,305	3

^aActual volume contaminated air corrected to 0°C (273°K) and 760 mm pressure.

on formaldehyde, an example home of 167 m² heated area with 2.5 m ceilings on a worst case basis would need up to 70 spider plants in 3.82 (1 gal) pots to sorb the formaldehyde outgassed from urea-foam insulation, resins and other synthetic products and evolved from a gas stove. An average situation with low background contaminant levels would only require 15-25 such plants to maintain a clean atmospheric environment indoors as well as provide a buffer for transient vapors from new products. These plants could be contained in a solarium through which air from the central heat/air conditioning system is pulled. The same system could help remove $2.3 \times 10^5 \mu\text{g CO}$ per hour. This capacity, in addition to the CO lost through the normal air exchange, would greatly increase the air quality of the entire home.

Table II. Mean contaminant concentrations as a function of exposure time.

Experiment	Concentration, ppm@			
	0 h	2 h	6 h	24 h
Carbon monoxide:				
1. Controls w/o pots	110		110	107
2. Controls w/pots	125		115	107
3. <i>Scindapsus aureus</i>	113		84	28
4. <i>Chlorophytum elatum</i> <i>var. vittatum</i>	128	98	68	<5
Nitrogen dioxide:				
1. Controls w/o pots	43	19	16	8
2. Controls w/pots	44	8	2	1
3. <i>Chlorophytum elatum</i> <i>var. vittatum</i> (soil exposed)	49	2	<0.5	<0.5
4. <i>Chlorophytum elatum</i> <i>var. vittatum</i> (soil covered)	47	7	<0.5	<0.5

Table III. Total contaminant mass and the change in mass (Δ) at each interval per area leaf surface.

Experiment	Total contaminant (μg) @				Δ Contaminant/area leaf surface $\mu\text{g}/\text{cm}^2$	
	0 h	2 h	6 h	24 h	6 h	24 h
Carbon monoxide:						
1. Controls w/o pots	50,280		50,280	48,910	-	-
2. Controls w/pots	55,750		51,290	47,720	-	-
3. <i>Scindapsus aureus</i>	50,210		37,330	12,440	0.98	2.89
4. <i>Chlorophytum elatum</i> <i>var. vittatum</i>	57,260	43,840	30,420	<2,240	2.86	5.86
Nitrogen dioxide:						
1. Control w/o pots	32,200	14,230	11,980	5,960	-	-
2. Control w/pots	32,330	5,880	1,470	735	-	-
3. <i>Chlorophytum elatum</i> <i>var. vittatum</i> (soil exposed)	35,330	1,442	<361	<361	3.63	3.63
4. <i>Chlorophytum elatum</i> <i>var. vittatum</i> (soil covered)	34,234	5,100	<364	<364	3.29	3.29

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