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COULD HOUSEPLANTS IMPROVE INDOOR AIR QUALITY IN SCHOOLS?

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Previous studies performed by the National Aeronautics Space Administration (NASA) indicated that plants and associated soil microorganisms may be used to reduce indoor pollutant levels. This study investigated the ability of plants to improve indoor air quality in schools. A 9-wk intensive monitoring campaign of indoor and outdoor air pollution was carried out in 2011 in a primary school of Aveiro, Portugal. Measurements included temperature, carbon dioxide (CO_2), carbon monoxide (CO), concentrations of volatile organic compounds (VOC), carbonyls, and particulate matter (PM_{10}) without and with plants in a classroom. PM_{10} samples were analyzed for the water-soluble inorganic ions, as well for carbonaceous fractions. After 6 potted plants were hung from the ceiling, the mean CO_2 concentration decreased from 2004 to 1121 ppm. The total VOC average concentrations in the indoor air during periods of occupancy without and with the presence of potted plants were, respectively, 933 and 249 $\mu g/m^3$. The daily PM_{10} levels in the classroom during the occupancy periods were always higher than those outdoors. The presence of potted plants likely favored a decrease of approximately 30% in PM_{10} concentrations. Our findings corroborate the results of NASA studies suggesting that plants might improve indoor air and make interior breathing spaces healthier.

Various studies have demonstrated that plants may be used to remove pollutants from indoor air (Liu et al. 2007; Matsumoto and Yamaguchi 2007; Wolverton et al. 1989; Wood et al. 2006). Plants have been suggested to serve as an attractive and cost-effective way to improve indoor air quality (IAQ). Indoor potted plants were shown to remove most types of airborne pollutants arising from either outdoor or indoor sources. The benefits of plants on attendance and well-being of building occupants has been documented (Berg 2002; Fjeld 2002).

This issue arose when the National Aeronautics Space Administration (NASA) tried to find ways to reduce pollutants inside future space habitats (NASA 1974). Wolverton et al. (1984; 1985; 1989) placed potted plants inside sealed Plexiglas chambers, injecting substances commonly found in indoor air. The results showed that leaves, soil, and plant-associated microorganisms serve an important function in reducing indoor air pollutants such as cigarette smoke, organic solvents, and bioaerosols.

In schools, IAQ is often worse than outdoor air quality (Kotzias et al. 2009; Pegas et al. 2010; 2011a; 2011b). Studies carried out by the U.S. Environmental Protection Agency (EPA) indicated that indoor air pollutant concentrations may be two- to fivefold higher and occasionally more than 100-fold higher than outdoor levels.

There are several reasons to consider IAQ at primary schools a public concern. One is that children breathe higher volumes of air

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relative to their body weights. Children's physiological vulnerability to air pollution arises from their narrower airways and the fact that their lungs are still developing (Foos et al. 2008; Ginsberg et al. 2008). In addition, many children breathe through their mouths, bypassing the nasal passages' natural defenses. Thus, children are more likely to suffer the consequences of indoor pollution (Selgrade et al. 2008). Another reason for environmental deficiencies in schools is due to chronic shortages of funding, which contribute to inadequate operation and maintenance of facilities (Mendell and Heath 2005).

Previous measurements of particulate matter (PM_{10}), volatile organic compounds (VOC), and carbonyls carried out in elementary schools in Lisbon revealed indoor/outdoor (I/O) ratios above unity, showing the influence of indoor sources, building conditions, and inappropriate ventilation on IAQ, indicating the need to take decisive remedial actions (Almeida et al. 2011; Pegas et al. 2010; 2011a; 2011b). The aim of the present study was to assess the effectiveness of three common species of houseplants in the fight against rising levels of air pollution in classrooms.

MATERIAL AND METHODS

Study Design

This study investigated the effectiveness of potted plants suggested by NASA (1974) in reducing the air pollutant concentrations in classrooms. A school located in the city centre of Aveiro, Portugal, was selected to carry out this study. The selected school is located at 40° 38′ 16.76′′ N, 8° 39′ 09.85′′ W. This school started its activities in the 1960s. The school is surrounded by commercial and residential buildings and in front of the school there are a car parking lot and a busy road. The main classroom studied has a wood floor, water-based paint covering the walls, blackboard and chalk, white board and markers, and five wooden windows. The area of the room was 52.5 m^2. The number of students in the classroom is approximately 25.

Comfort parameters such as temperature, relative humidity, carbon dioxide (CO_2), carbon monoxide (CO), VOC, carbonyls, and particulate matter <10 μm (PM_{10}) concentrations were measured between February and May 2011, for 3 wk without plants (February 28 to March 20, 2011) and 6 wk with potted plants indoors (March 21 to May 28, 2011).

Dracaena deremensis (striped dracaena or Janet Craig), *Dracaena marginata* (red-edge dracaena, Madagascar dragon tree, or Marginata), and *Spathiphyllum* (Mauna Loa or peace lily) were the selected houseplants, since in test-chamber studies (Orwell et al. 2004; Tarran et al. 2002; Wolverton et al. 1989; Wood et al. 2002; 2006) these were found to be reliably effective in removing benzene, toluene, ethylbenzene, and xylenes (BTEX).

The potted plants were all of similar size, weight, and age. In classrooms, plants were placed on metallic holders to ensure there was enough height from the floor and a free space under the pot for air circulation (about 30 cm). The number of potted plants was defined according to the area of the classroom. The Associated Landscape Contractors of America (ALCA) recommendation is one plant per 9.29 m^2. Thus, six potted plants (300-mm diameter pots) were placed in the selected classroom.

Sampling and Analytical Methods

Continuous measurements of temperature, relative humidity (RH), CO_2, CO, and total VOC were performed with an automatic portable Indoor Air IQ-610 quality probe (Gray Wolf monitor) and a TSI monitor, simultaneously in the classroom and at the playground, respectively, during 9 wk. Every week, during 9 wk, passive samplers for VOC and carbonyls (Radiello) were used to obtain indoor and outdoor average concentrations. Another set of Radiello passive samplers was only exposed from 8:30 a.m. to 5:30–6 p.m. to obtain VOC and carbonyl concentrations for the occupancy periods. VOC adsorbed in activated charcoal cartridges were extracted with 2 ml carbon disulfide (CS_2) containing the internal standard, in accordance with the Radiello procedure. Analyses were performed by gas chromatography (Thermo Scientific Trace GC Ultra) coupled to flame ionization detection (GC/FID). The equipment was calibrated before and during the analyses of samples by injecting standard solutions of all compounds identified in CS_2 (Pegas et al. 2010).

Carbonyls were extracted with 2 ml acetonitrile following 30 min; the extract was filtered through 0.45-μm membrane disc filters (filtration kit RAD 174) and injected into the high-performance liquid chromatography (HPLC) system. The carbonyl concentrations were quantified with external calibration curves constructed from standard solutions—aldehyde/ketone-DNPH TO11/IP-6A mix (U.S. EPA 1999).

Active sampling of carbonyls was performed during two days in the first period without plants (March 24 and 25) and during two days in the second period with plants (May 25 and 26). Carbonyl active collection involved a sampling train consisting of a Thomas pump to draw in air at a flow rate of 2 L/min for a sampling time of 1–2 h in agreement with the classroom cycles, through silica-gel cartridges, impregnated with 2,4-dinitrophenylhydrazine reagent (Sep-Pak DNPH-silica cartridges), a dry gas meter to measure the volume of air, and ozone (O_3) scrubbers to minimize O_3 interference. The analytes were extracted with 5 ml acetonitrile by filtration through gravity-feed elution; the extract was collected and later analyzed by high-performance liquid chromatography (HPLC) with ultraviolet (UV) detection at an absorption wavelength of 360 nm (ASTM 1997).

Two low-volume samplers were used to simultaneously collect indoor and outdoor PM_{10} on a daily basis, during the occupancy period, from 8:30 a.m. to 5:30–6 p.m., over a period of 9 wk. The PM_{10} samples were collected onto prebaked (6 h at 550°C) quartz filters 47 mm in diameter. Before weighing, the filters were conditioned in a desiccator at least for 24 h in a temperature- and humidity-controlled room. Before and after sampling, gravimetric determination was performed with a microbalance Mettler Toledo AG245 (readability 0.1 mg/0.01 mg). Filter weights were obtained from the average of 10 measurements, with weight variations less than 5%.

The elemental carbon and organic carbon (EC and OC) contents in PM_{10} were analyzed by a homemade thermal-optical transmission system, after passive exposure of sampled filters to HCl vapors to remove carbonate interferences. This procedure was first developed by Carvalho et al. (2006) and recently adapted by Alves et al. (2011). Carbonates present in PM_{10} samples were analyzed through the release of CO_2, and measured by the same nondispersive infrared analyzer coupled to the thermo-optical system, when a punch of each filter was acidified with orthophosphoric acid (20%) in a free CO_2 gas stream (Alves et al. 2011).

For the determination of water-soluble inorganic ions (WSII), a filter fraction (2 discs of 13 mm diameter) were extracted with ultra pure Milli-Q water. Dionex AS14 and CS12 chromatographic columns with Dionex AG14 and CG12 guard columns coupled to Dionex AMMS II and Dionex CMMS III suppressors, respectively, were used for anions and cations.

To evaluate the significance of differences between variables, the nonparametric Mann–Whitney *U*-test was preferred rather than the Student's *t*-test (Brown and Hambley 2002). A difference between two means was considered to be statistically significant when the value of the two-tailed Mann–Whitney *U*-test was $p < .05$. All statistical computations were conducted with R software (http://www.r-project.org/).

RESULTS AND DISCUSSION

The indoor average temperature ranged from 18.7 ± 1.99°C in the first period of the study, without plants, to 20.0 ± 2.22°C in the second period, with plants. The relative humidity (RH) values did not change markedly throughout the investigation (55.9 ± 8.32% and 51.7 ± 7.98%). The CO concentrations in the classroom were always low (0.05 ± 0.04 ppm).

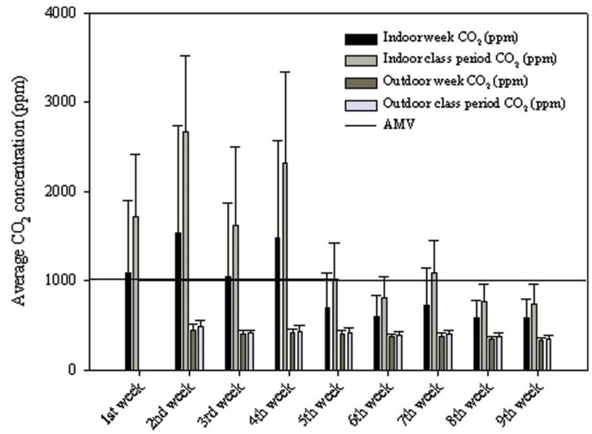

FIGURE 1. Indoor and outdoor average CO_2 concentration week by week (color figure available online).

However, the CO_2 levels (Figure 1) were significantly different between the period without (2004 ± 580 ppm) and with plants (1121 ± 600 ppm) in the classroom. Several studies demonstrated that high levels of CO_2 might exert a negative influence on students' learning ability (Coley and Greeves 2004; Shendell et al. 2004; Smedje et al. 1996). It is noteworthy that during the entire study windows were kept closed. During the hottest days, three exceptions to this condition were registered, when one or two windows were partially opened for a few minutes. Taking into account that these time durations with higher natural ventilation represented less than 5% of the occupancy period, the possible dilution effect of concentrations was considered negligible.

The National System for Energy and Indoor Air Quality Certification of Buildings established an acceptable maximum value (AMV) for CO_2 concentrations of 1000 ppm in indoor environments in Portugal (RSECE 2006). Over the period without plants, as well during the week of their acclimatization, the CO_2 concentrations were always markedly higher than the AMV. High indoor CO_2 levels are normally considered as indicative of inadequate ventilation. Based on indoor and outdoor CO_2 concentrations, it is possible to estimate ventilation rates under different degrees of window openings or when they are fully closed. When unoccupied there are no CO_2 emissions from the tenants, so ventilation rate is obtained by

$$Q = -\frac{V}{t} \times \ln\left(\frac{C_t - C_{ext}}{C_0 - C_{ext}}\right) \qquad (1)$$

where C_t is the indoor concentration of CO_2 at time t (ppm), C_{ext} the concentration of CO_2 in the external air (ppm), C_0 the concentration of CO_2 in the indoor air at time 0 (ppm), Q the ventilation rate of air entering the space (m^3 s^{-1}), V the volume of the classroom (m^3) and t is the interval since $t = 0$ (s) (Griffiths and Eftekhari 2008).

The estimated ventilation rates ranged from 11 to 23 L/s. The maximum ventilation value, which corresponds to about 0.9 L/s/person, represented only 35% of the minimum value of 2.5 L/s/ person recommended by the ANSI/ASHRAE Standard 62–1999, and only 10% of that recommended by RSECE (8.33 L/s/person). The CO_2 levels measured from wk 5 onward, during the occupancy periods, were not as high as those of the first 3 wk, in the absence of plants (Figure 1). Tarran et al. (2007), in a study aimed at evaluating the capacity of indoor plants to remove pollutants, reported that CO_2 concentrations were reduced by approximately 10% in air-conditioned offices and 25% in naturally ventilated rooms.

Concentrations of VOC were always higher indoors than outdoors, including nighttime periods (Figure 2). A concentration

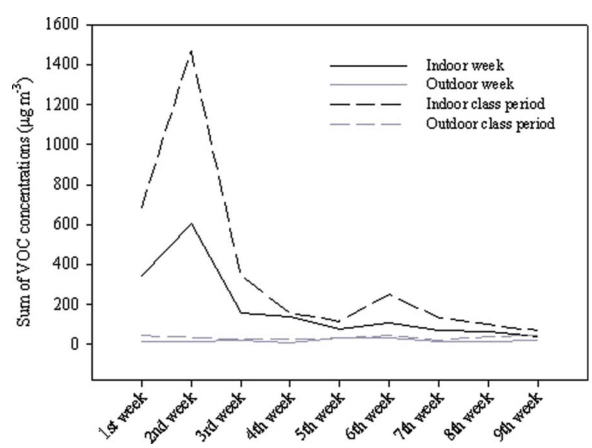

FIGURE 2. Indoor and outdoor concentrations of all VOC identified (color figure available online).

decrease during the non-occupancy period was observed. Higher indoor levels of many VOC species were also registered in previous studies involving 14 elementary schools of the Portuguese capital, Lisbon (Pegas et al. 2010; 2011a; 2011b). The VOC concentrations during teaching periods ranged from 933 ± 577 μg/m^3 in the absence of plants to 249 ± 74.2 μg/m^3 in the presence of plants. The difference between VOC levels without and with plants was statistically significant. The approximately 73% reduction of VOC concentrations observed in this study is in agreement with the results of previous investigations in 60 offices by Wood et al. (2006), who examined the effectiveness of potted-plant and root-zone microcosms with and without air conditioning. Wood et al. (2006) observed that the root-zone microcosm substantially reduced high concentrations of VOC within 24 h. In the current study, the decrease of indoor VOC levels was observed whether in samples obtained during school hours or in weekly samples continuously exposed. The main difference between the two sets of samples is the magnitude of concentrations. VOC levels in weekly samples continuously exposed as noted in Portugal by Pegas et al. (2010; 2011a; 2011b) did not truly reflect the levels of exposure. Outside the room, the VOC levels remained almost uniform over the entire sampling period (Figure 2). Methylacetate, 1,1,1-trichloroethane, and isopropanol were systematically more abundant in the classroom. Acetone, methanol, and 1,1,1-trichloroethane were prevalent outdoors. These compounds may derive from both indoor and outdoor sources, including felt pens, personal care products, polyvinyl chloride (PVC) cement and primer, various adhesives, contact cement, model cement, degreasers, aerosol penetrating oils, brake cleaner, carburettor cleaner, commercial solvents, electronics cleaners, and spray lubricants (Mendell 2007).

Among all monitored VOC, BTEX are of particular interest due to their known carcinogenic effects (Kotzias et al. 2009). Ethylbenzene showed a decrease from levels in the 1.48–2.53 μg/m^3 range during the period without plants to values below the limit of detection (LOD) during the period with potted plants indoors. The average toluene concentrations were 7.62 ± 1.73 μg/m^3 and 4.09 ± 0.66 μg/m^3, respectively, when plants were absent or present, displaying a fall of approximately 57%. A reduction of 80% between the two periods was observed in *m*+*p*-xylene and *o*-xylene concentrations. Benzene is a carcinogenic compound for which the World Health Organization (WHO) has not yet established a safe value (WHO 2000). The average benzene concentration was 1.09 ± 0.21 μg/m^3 in the absence of plants, decreasing to 0.84 ± 0.03 μg/m^3 during the presence of potted vegetation, which represents a decline of approximately 15%. Outdoor toluene, ethylbenzene, *m*+*p*-xylene, and *o*-xylene levels were significantly lower than air concentrations in the classroom, reflecting the contribution of indoor sources. Although Wolverton et al. (1989) found a reduction in benzene concentration in controlled chambers of 77.3, 79.5, and 79% for the species Janet Craig, marginata, and peace lily, respectively, this reduction did not exceed 15%. However, it is important to note that the chamber experiments refer to static testing, where pollutants are injected and then their decay is measured. A classroom is an open system and there are many other cross factors influencing concentration values. The benzene levels were always within the same order of magnitude as or smaller than the outside concentrations, denoting that the major contribution is likely from the outdoor environment.

Carbonyl compounds are the most important chemical contaminants affected by chemical and physical processes in the environment (Cerón et al. 2007). Among the five carbonyls identified in the indoor environment, butyraldehyde (40.8 ± 2.20 μg/m^3) and formaldehyde (22.6 ± 3.54 μg/m^3) were the most abundant in the classroom in the absence of plants. Formaldehyde is a ubiquitous pollutant that is found in almost all indoor and outdoor environments. Formaldehyde indoor sources include pressed wood products and furniture, insulation, combustion and tobacco smoke, some textiles and glues. Figure 3 shows

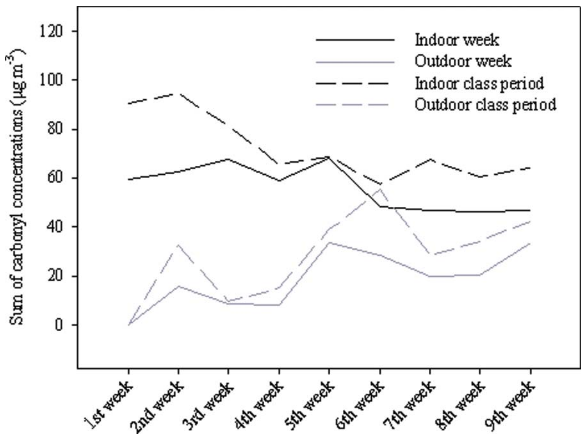

FIGURE 3. Indoor and outdoor concentrations of all carbonyls identified (passive sampling) (color figure available online).

that there was a significant decrease in the sum of carbonyl concentrations after hanging potted plants from the ceiling in the classroom. During the first 3 wk without plants, the sum of aldehyde concentrations ranged from 81.3 to 94.3 μg/m^3 at an average temperature of 18.7°C. Between the wk 5 and wk 9, with plants in the classroom, the concentrations of total carbonyls ranged from 57.4 to 68.7 μg/m^3 at an average temperature of 24.8 ± 1.35°C. Even with increasing temperature, a reduction in carbonyl concentrations of up to 40% was registered. Normally, the carbonyl concentrations rise with increasing temperatures due to evaporation from building materials (Pang and Mu 2006). In chamber studies with controlled conditions, the decrease in formaldehyde concentration due to the effect of plants ranged from 47 to 70% (Wolverton et al. 1989). Results from active sampling in office environments suggested that achieving 11% reduction in formaldehyde levels in a real-life situation would require the equivalent of 1 plant/m^3 or 2.4 plants/m^2 (Dingle et al. 2000). Table 1 presents results from active samplings carried out before and after having plants in the classroom. An approximate 40% fall in the indoor concentrations of 4 carbonyl compounds measured by active sampling whose determination was also conducted by passive sampling was observed. The outdoor levels rose with increasing temperature.

TABLE 1. Active Sampling of Carbonyl Concentrations (μg/m^3)

	Sum of carbonyl concentrations (μg m^{-3}			
	Without Plants		With Plants	
	Average	STDEV	Average	STDEV
Indoor	52.9	3.89	32.1	11.9
Outdoor	16.3	3.86	27.5	28.1

Atmospheric particles have been associated with increased respiratory symptoms (Delfino 2002; Simoni et al. 2002; Weisel 2002; Samet and Krewski 2007). Indoor PM_{10} may transport toxic pollutants and reaction products into the airways, inducing inflammatory responses through the generation of oxidative stress (Leem et al. 2005; Selgrade et al. 2008). In this study, the daily indoor PM_{10} levels were always higher than outdoors (Figure 4), suggesting that the physical activity of the pupils leads to emission/resuspension of coarse particles and greatly contributes to enhanced PM_{10} in classrooms (Almeida et al. 2011). Lohr et al. (1996) reported an approximately 2% reduction in PM_{10} levels in a computer lab and in an office after introducing plants into these building environments. A statistically significant decrease in PM_{10} levels was observed in our study. The indoor PM_{10} mean values ranged from 137 ± 7.7 μg/m^3, without plants to 91.2 ± 13.2 μg/m^3, with plants (Figure 4). The outdoor PM_{10} mean values ranged from 28.2 ±

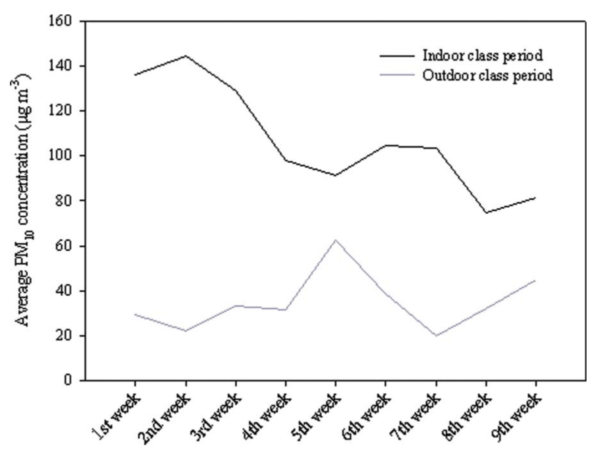

FIGURE 4. Indoor and outdoor PM_{10} concentrations week by week (color figure available online).

5.78 μg/m^3 in the first period to 38.2 ± 14.4 μg/m^3 in the second period of the investigation. Even with an increase of approximately 35% of outdoor PM_{10} concentration, there was a reduction of about 34% in indoor levels. This may be related to the gravitational settling of particles onto foliage and potting soil. Lohr et al. (1996) suggested that the plants do not simply prevent the fall of particles. Plants may also remove PM through impaction of particles carried across their foliage by eddy currents.

On average, the OC represented a mass fraction of PM_{10} of 30.0% indoors. A lower mass fraction was obtained outdoors (OC/PM_{10} = 21.3%). The total carbon (TC = OC + EC) levels were higher indoors than outdoors (Figure 5). Clearly, OC is enriched in indoor as compared to outdoor air. An indoor enhancement of OC/EC ratios is likely to be due to indoor sources of organic compounds, such as submicrometer fragments of paper, skin debris, and clothing fibers. A significant decrease from 36.9 ± 4.81 μg/m^3 to 24.6 ± 6.32 μg/m^3 in OC concentrations was observed between the periods without and with plants, respectively, although no significant difference was found outdoors. There was no significant difference in EC levels between the two periods of the study and between the indoor and outdoor air (Figure 5).

The water-soluble ions contributed, on average, to 20.4% and 14.1% of the particle

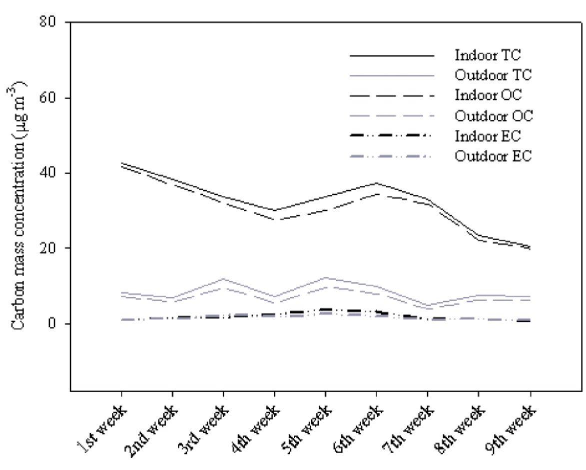

FIGURE 5. Indoor and outdoor carbon mass concentration week by week (color figure available online).

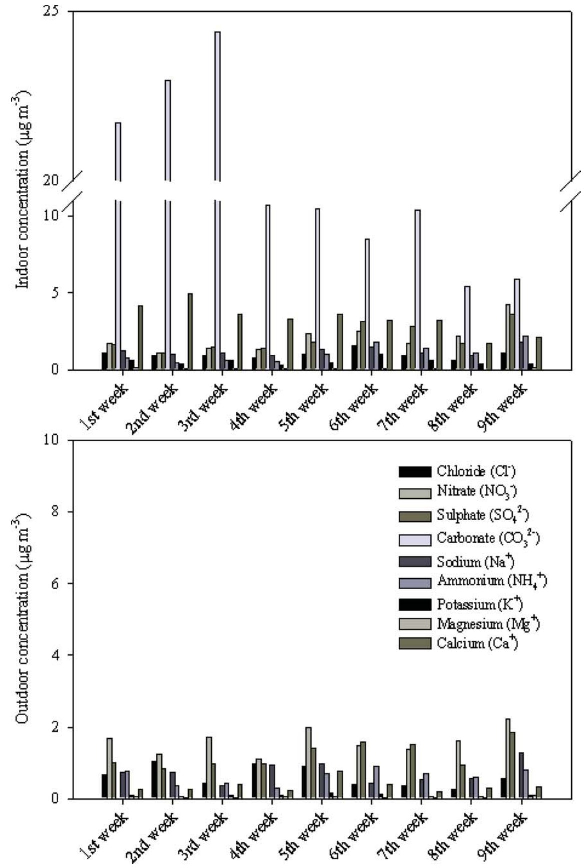

FIGURE 6. Indoor and outdoor soluble ion concentrations week by week (color figure available online).

mass in the classroom and playground, respectively (Figure 6). Carbonate was the dominant ion of indoor-sampled particles, representing on average 10.2% of the mass of all analyzed ions. Carbonate levels in the indoor air ranged from 21.8 ± 1.33 μg/m^3, without plants, to 6.93 ± 2.31 μg/m^3 in the presence of plants, and this significant reduction of carbonate levels was followed by a concomitant marked fall in calcium levels from 4.25 ± 0.66 μg/m^3 to 2.78 ± 0.81 μg/m^3 without and with plants, respectively. Compared with other soluble ions, the calcium mass fractions were higher in the indoor environment (2.76% of the PM_{10} mass) than outdoors (0.76% of the PM_{10} mass). The higher indoor levels are probably related to the use of chalk crayons on the blackboard. This observation is corroborated by the high carbonate concentrations in the classrooms. The indoor carbonate concentrations were about 10-fold higher than amounts found outdoors during the weekdays. Magnesium represented one of the less abundant ions in the indoor and outdoor environments. The outdoor sodium and chloride levels were about twofold higher than indoor levels, probably because these two ions likely have a strong contribution from sea spray. A significant reduction in levels of nitrate, sulfate, and ammonia between periods in the absence and presence of plants was observed. Atmospheric PM, and especially some of its constituents (e.g., nitrates and ammonium), may affect vegetation directly following deposition on foliar surfaces or indirectly by changing soil chemistry. Indirect effects through the soil, however, are usually the most significant because these alter nutrient cycling (Grantza et al. 2003; Prajapati 2012).

CONCLUSIONS

This study determined whether common houseplants are useful in improving overall IAQ. In spite of some possible confounding factors, such as variable ventilation rates throughout the monitoring study, that might lead to misinterpretation of results, it seems that plants do have the ability to remove certain pollutants from the air. After the placement of six potted plants in the classroom, a significant reduction in CO_2, VOC, carbonyl, PM_{10}, OC, nitrate, sulfate, ammonia, calcium, and carbonate concentrations was observed. The decrease in indoor air pollutant levels resulting from the use of plants may represent a low-cost solution to reduce exposure to many compounds and lifetime risk, and to further improve performance, attendance, and welfare of students and teachers in classrooms. This simple measure does not invalidate, however, the adoption of other abatement or preventive strategies, such as use of low-VOC-emitting materials and consumer products, lowering the occupancy rates in classrooms, use of air cleaner and humidity control systems, and increasing the ventilation rates (through natural openings or mechanical devices). The rate at which the plants interfere with air pollutants depends on the growing conditions, and removal performance depends on the plant species. This study indicates that this is an important issue to pursue, especially as it may relate to potential adverse human health effects.

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