I

RESEARCH ARTICLES

LEAF COLOR SEGMENTATION AND POT VOLUME INFLUENCE ON THE CO_2 ABSORPTION EFFICIENCY IN TWO COMMON GREEN-WALL PLANTS

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ABSTRACT

Green walls can improve indoor air-quality by reducing concentrations of carbon dioxide (CO_2) and other air pollutants. Our study focused on the spider plant, *Chlorophytum comosum*, and devil's ivy, *Epipremnum aureum*, both common green-wall plants that have been found to be efficient CO_2 absorbers. Both species have multiple variants with varying degrees of leaf green-white segmentation. Since photosynthesis depends on the concentration of leaf chlorophylls, we hypothesized that green variants are more efficient carbon absorbers than green-white variants. In addition, we tested the hypothesis that the photosynthetic rate of plants is affected by pot volume, as suggested by previous studies. We used a portable gas exchange system to determine the rate of photosynthesis of the study plants. No evidence was found for better photosynthetic performance in the green vs. green-white variants of each species. In fact, our results suggest the opposite. It was observed that a spider plants assimilated carbon more efficiently when grown in a larger pot volume. In conclusion, our study shows that in terms of carbon assimilation, green-white variants of spider plants are the better choice for indoor green walls. Their efficiency can be improved dramatically by increasing pot volume.

KEYWORDS

air quality; carbon dioxide; *Chlorophytum comosum*; *Epipremnum aureum*; indoor green wall; photosynthesis.

INTRODUCTION

The indoor areas in which we spend up to 90 percent of our time have poor air quality in most cases (Marques et al. 2019). Indoor air pollution can be reduced by using indoor plants that have been shown capable of reducing carbon dioxide (CO_2) concentrations along with other volatile organic compounds (VOCs) and air pollutants (Wolverton et al. 1989). Indoor green

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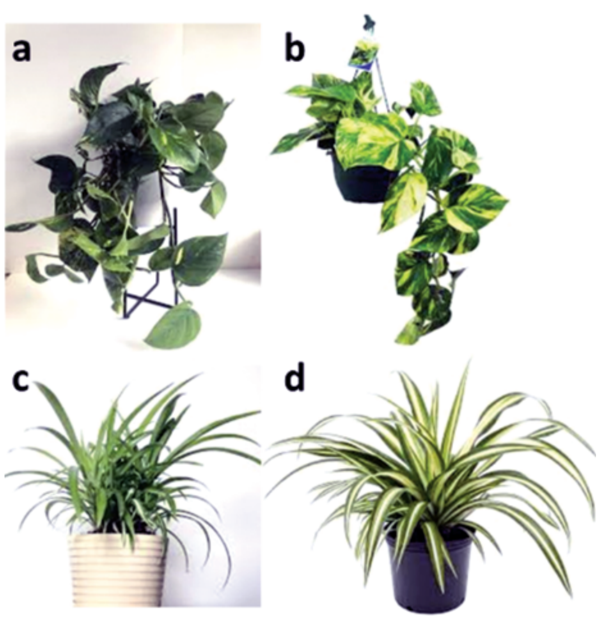
walls are space-efficient means of increasing the density of plants. Their vertical arrangement may improve the environmental impact of indoor-plant systems (Soreanu 2016). So far, studies that tested the effects of green walls on indoor air quality have focused on the removal of VOC's (Wang et al. 2014), whereas CO_2 removal has only scarcely been tested (Torpy et al. 2017).

Today, green facades and green roofs are considered an intrinsic part of residence sustainability and resilience (Tapsuwan et al. 2018), as well as enhancing health and heat capacity properties (Takebayashi et al. 2014; Wong et al. 2017; Xue et al. 2017). In some aspects, green walls are an evolution of the green roof concept, which has been applied successfully in many cities (Jim et al. 2017). Although green walls in buildings are gaining much popularity, much remains unknown about the various effects of green-wall plants on the indoor environment, and many potential effects await testing (Weinmaster 2009). For instance, green wall carbon sequestration rates have been measured in a few cases (e.g. Amir et al. 2011), but information is scarce.

Compared with CO_2 absorption measured on green roofs (Agra et al. 2017a), indoor green-walls are expected to show lower uptake rates but much higher light-use efficiency in the photosynthetic process (Torpy et al. 2017). In addition, the stable conditions indoors avoid the effects of summer desiccation on photosynthetic processes observed in green roof plants (Agra et al. 2017b).

Species selection can substantially affect the properties of functional green walls (Irga et al 2019). The spider plant, *Chlorophytum comosum*, and devil's ivy, *Epipremnum aureum*, are two common shade-tolerant green-wall plants which have been found to be efficient in terms of CO_2 absorption (Torpy et al. 2017). Both plant species have multiple variants with varying degrees of leaf green-white segmentation (Figure 1). Since photosynthesis depends on the concentration of leaf chlorophylls, higher photosynthetic capacity is expected in green vs. partly green leaves (Kursar & Coley 1992).

FIGURE 1. Green devil's ivy (a), white-green devil's ivy (b), green spider plant (c) and white-green spider plant (d).



Pot volume is another important factor shown to affect photosynthetic performance of plants (Poorter et al. 2012). Preliminary examination of the effects of pot size on plant growth showed that increasing pot volume increased the overall biomass production. Further analysis suggested that reduced growth in smaller pots is caused mainly by a reduction in photosynthesis per unit leaf area (Poorter et al. 2012). In addition to reducing CO_2 levels, green-wall plants also affect indoor humidity (Fernández-Cañero et al. 2012).

Here we tested two main hypotheses: a) the green variants of the spider plant and devil's Ivy are more efficient carbon absorbers than variants with green-white coloring, and b) increasing the pot volume positively affects the photosynthesis rate of the study species. In addition, we measured the stomatal conductance of the study plants in order to assess the addition of humidity via transpiration to indoor areas.

MATERIALS AND METHODS

The effect of leaf green-white segmentation

To examine the effect of leaf green-white segmentation on carbon assimilation, we isolated two variants of the spider plant and devil's ivy. For each species one variant was entirely green and the second had a green and white pattern. Five plants of each species × variant were grown in separate 0.5 L pots. All 20 pots were placed on one shelf (1 × 2 m) in four rows of five pots each in random arrangement under similar conditions in a greenhouse operated by Vertical Field Ltd. in Ramot Hashavim, Israel (32°15′ N, 34°88′ E).

Plants were grown for approximately three months (October-December 2018). Net carbon assimilation and stomatal conductance (gs) were measured using a portable gas exchange system (Walz GFS-3000, Walz, Effeltrich, Germany). In order to plot light response curves, leaves were measured under six light intensities of photosynthetic active radiation maintained in the measurement chamber (15, 30, 50, 70, 100 and 150 μmol $m^{-2}s^{-1}$). We measured leaf gas exchange in four replications for each plant, randomly choosing a fully developed leaf of the selected plant and inserting it into the measurement chamber (8 cm^2). Inside the chamber there are LED lights that mimic sunlight. We chose common indoor light intensities. Temperature and relative humidity in the chamber were ambient. In order to expose the leaves to different levels of light, we started at the minimum light and increased the intensity after 10 minutes (the time required for the stabilisation of the net carbon assimilation). Measurements were conducted in different hours of the day in order to avoid a circadian rhythm bias. Considering the four species, five plants per species, four leaf replicates, and six light levels, a total of 480 independent measurements were performed. These measurements were further used in the calculation of intrinsic water-use efficiency (WUEi, in μmol CO_2 mol^{-1} H_2O) according to the equation:

$$\text{WUEi} = \frac{A}{gs} \quad (A\text{: net carbon assimilation rate, } gs\text{: stomatal conductance})$$

Net carbon assimilation and stomatal conductance of the plants were analyzed using two-way ANOVA to test the effects of plant species, variant type and their interactions under each light intensity.

The effect of pot volume

Following analysis of results from the first part of the experiment, we used spider plants of the green-white variant to examine the effect of pot volume. Five plants were grown in 0.2 L pots, five in 0.5 L pots and three in 2 L pots. Pots were placed in random order under similar conditions in the same greenhouse described above. Since measurements showed that there was no significant variation in carbon assimilation between different leaves of the same plant, we used one leaf from each plant to measure net carbon assimilation and stomatal conductance under five different light intensities (15, 50, 70, 100 and 150 µmol $m^{-2}s^{-1}$). The effect of pot size on net carbon assimilation and stomatal conductance of the study plants was analyzed using mixed ANOVA and Bonferroni post-hoc tests (SPSS: mixed model, linear) with pot volume as the between-subject factor and the five light intensities as repeated measures. To determine plants above-ground dry biomass all above-ground parts of the plants were cut at the end of the experiment, oven dried and weighed. The effect of pot size on above-ground dry biomass was analyzed using one-way ANOVA and Bonferroni post-hoc test.

RESULTS

The effect of leaf green-white segmentation

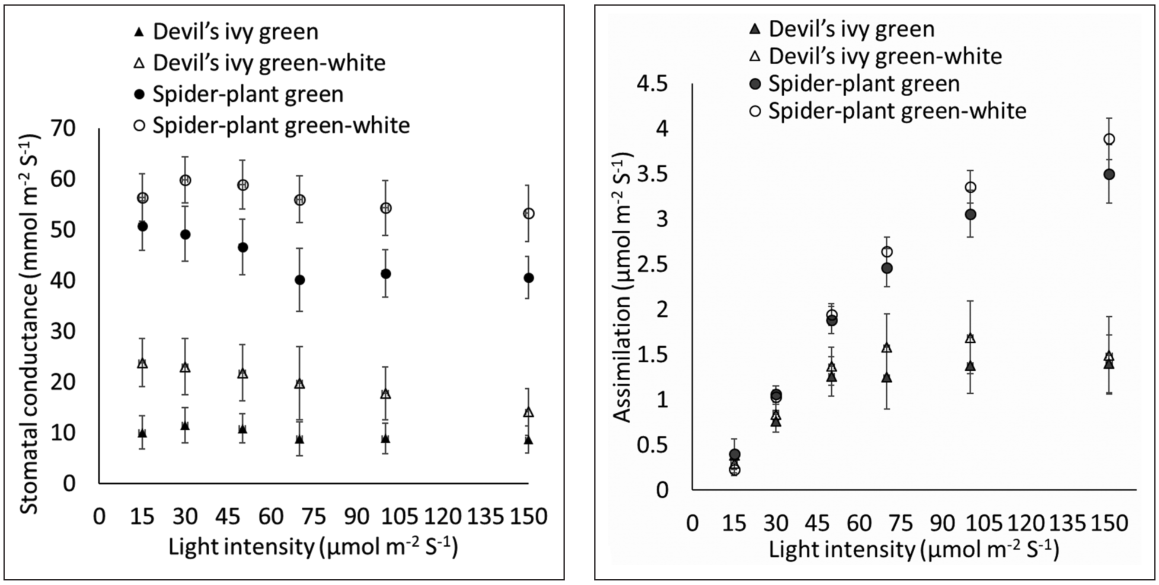
At the lowest light intensity (15 µmol $m^{-2}S^{-1}$), the net carbon assimilation rate ranged from 0.2 to 0.4 µmol CO_2 $m^{-2}s^{-1}$ in both variants of both plant species. At light intensities above 50 µmol $m^{-2}S^{-1}$, the spider plant assimilated carbon faster than devil's ivy and the difference increased with light-intensity (Fig. 2a). Interestingly, in both plant species, the green-white variants assimilated carbon faster than the green variants (Fig. 2a). Stomatal conductance was higher in the spider plant than in devil's ivy, and higher in green-white than in green variants of both species, under all light intensities (Fig. 2b). The ratio between carbon assimilation and stomatal conductance, namely, the intrinsic water use efficiency (WUEi) was higher on average in devil's ivy (0.09 µmol CO_2 / mmol H_2O) compared to spider plant (0.04 µmol CO_2 / mmol H_2O; data not shown). The maximum WUEi of devil's ivy plants occurred in light intensity of 75 µmol $m^{-2}S^{-1}$, whereas in spider plants, maximum WUEi occurred in 150 µmol m^{-2} S^{-1}. In both species, green-white variants had similar WUEi as green variants.

At light intensities of 15 and 30 µmol $m^{-2}S^{-1}$ there were no effects of the species or variant on net carbon assimilation rate (ANOVA models: $F_{3,15} = 0.469$, $P = 0.708$ and $F_{3,15} = 1.840$, $P = 0.183$, respectively). However, at 70, 100 and 150 µmol $m^{-2}S^{-1}$ there was a significant effect of the species ($F_{1,15} = 15.754$, $P = 0.001$; $F_{1,15} = 31.790$, $P < 0.001$; $F_{1,15} = 45.883$, $P < 0.001$, respectively), but not of the variant ($F_{1,15} = 0.785$, $P = 0.389$; $F_{1,15} = 1.053$, $P = 0.320$; $F_{1,15} = 0.543$, $P = 0.475$, respectively).

Stomatal conductance was significantly affected by the species under all light intensities ($F_{1,15} > 37.353$, $P < 0.001$). In addition, stomatal conductance was significantly affected by the variant at light intensities of 30, 50, 70 and 100 µmol $m^{-2}S^{-1}$ ($F_{1,15} > 4.987$, $P < 0.042$), but not at 15 and 150 µmol $m^{-2}S^{-1}$ ($F_{1,15} = 4.434$, $P = 0.052$ and $F_{1,15} = 4.286$, $P = 0.055$, respectively).

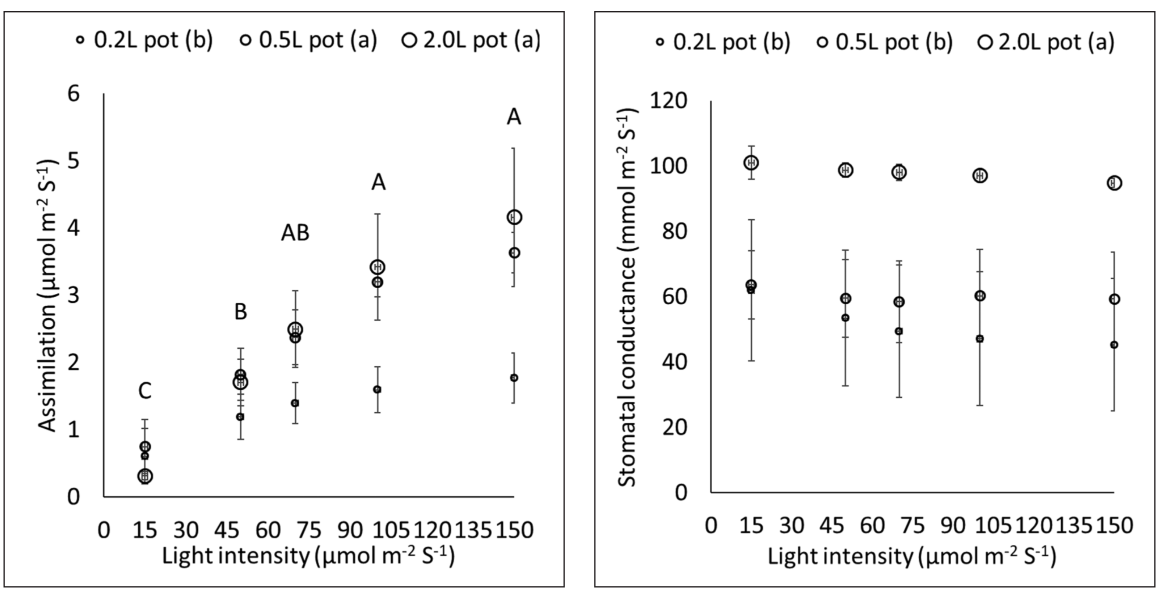
For both net carbon assimilation rate and stomatal conductance, at all light intensities, there was no significant effect of the interaction species × variant ($F_{1,15} < 0.809$, $P > 0.383$). For complete ANOVA results see Appendices A and B.

FIGURE 2. Net carbon assimilation rate (a) and stomatal conductance (b) of green and green-white variants of the spider-plant, *Chlorophytum comosum*, and devil's ivy, *Epipremnum aureum*, under a gradient of light intensites; each data point represents a mean of five plants. Error bars denote standard errors from the mean.



(a) (b)

FIGURE 3. Net carbon assimilation rate (a) and stomatal conductance (b) of the spider plant *Chlorophytum comosum* grown in 0.2L, 0.5L and 2.0L pots, under a gradient of light intensites (15, 50, 70, 100 and 150 µmol $m^{-2}s^{-1}$). For 0.2L and 0.5L pots, each data point represent a mean of five plants; for 2.0L pots each data point represent a mean of three plants. Error bars denote standard errors from the mean. Different letters in brackets next to the headlines are for significant differences between Pot-volumes (Bonferroni $P < 0.05$). Different capital letters are for significant differences in assimilation rate between light intensities (Bonferroni $P < 0.05$).



(a) (b)

The effect of pot volume

Carbon assimilation rate was similar for all three pot volumes at the lowest light intensity (15 μmol $m^{-2}S^{-1}$), and increased markedly in 0.5L and 2.0L pots with increasing light intensity, but only moderately in 0.2L pots (Fig. 3a). Stomatal conductance was almost double in 2.0L pots compared with 0.5L and 0.2L pots, and remained similar under all light intensities (Fig. 3b).

Net carbon assimilation rate was affected by both pot volume ($F_{2,47.6} = 11.642$, $P < 0.001$) and light intensity ($F_{4,17.7} = 16.693$, $P < 0.001$) (Fig. 3a). Stomatal conductance was affected by pot volume ($F_{2,49.9} = 9.042$, $P < 0.001$), but not by light intensity ($F_{4,18.1} = 0.125$, $P = 0.971$) (Fig. 3b). The interaction pot volume × light-intensity was insignificant for both net carbon assimilation rate band stomatal conductance ($F_{8,17.7} = 1.506$, $P = 0.224$ and $F_{8,18.1} = 0.032$, $P = 1.000$, respectively). Above ground plant biomass was affected by pot volume ($F_{2,10} = 12.650$, $P = 0.002$), it increased with pot size from 1.03 ± 0.05 g to 1.89 ± 0.20 g and 3.29 ± 0.70 g at 0.2, 0.5, and 2.0L pots, respectively. The latter plants were significantly larger than those growing in the smaller pots (Bonferroni $P < 0.05$).

DISCUSSION

The aim of this study was to test the effects of intrinsic plant and layout characteristics (i.e. leaf color segmentation and pot volume) on CO_2 assimilation efficiency of common green-wall plants. Our two study species, the spider plant and devil's ivy, are commonly used on green walls and are well-established as efficient CO_2 absorbers (Torpy et al. 2017). We show that both species can assimilate carbon at very low light intensities (as low as 15 μmol $m^{-2}S^{-1}$; Fig. 2), demonstrating their extreme shade tolerance and hence advantage as indoor plants. At light intensities between 70 and 150 μmol $m^{-2}s^{-1}$, the spider plant assimilated CO_2 at a faster rate than devil's ivy (Fig. 2a), which points to this species as the better choice when planning indoor green walls for the purpose of air purification.

Our findings do not support the first hypothesis that green variants of the spider plant and devil's ivy assimilate more CO_2 than variants with green-and-white segmentation, as no evidence was found for better photosynthetic performance in the green variants of each species in terms of net carbon assimilation. In fact, results revealed that green-white variants assimilated more efficiently than green variants in these plant species (Fig. 2a). These results are further emphasized by the significantly higher stomatal conductance in green-white compared with green variants for the spider plant (Fig. 2b). One possible explanation for these findings is that compounds in the white segments of the leaves protect the highly-sensitive, shade-adapted chloroplasts in these plants (Gould et al. 2002). Indeed, in a study examining soybean leaves, light attenuation was more gradual in light-green leaves than in dark-green leaves (Slattery et al. 2016).

Spider plants grown in larger pots assimilated carbon more efficiently, partially supporting our second hypothesis that increasing pot volume raises plant photosynthetic rate of the study plants (Fig. 3). The increase in carbon assimilation with pot size translated into higher biomass at the large pots. The results might indicate a positive feedback between carbon assimilation and growth, since only the large pot plants, and not the medium pot plants, grew significantly larger than the small pot plants. Medium pot plants assimilated faster than small pot plants, but probably lacked the increase in leaf area, which permitted the higher growth of large pot plants. An open question is whether the carbon assimilation and biomass increase with pot size can compensate for the smaller number of plants per wall area. Since our measurements were per leaf area, if the leaf area of the wall is unchanged, then larger pots are certainly advantageous.

CONCLUSIONS

We found that when considering both carbon assimilation and air moistening efficiency, green-white variants of spider plants are the better choice for indoor green walls. The efficiency of both processes provided by the green wall can be improved dramatically by increasing the pot volume of this species. Future studies evaluating air purification performance must therefore utilize full-scale modules of green wall structures incorporating different pot volumes and leaf area.

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APPENDIX A

Results summary of a two-way ANOVA for the effects of the plant species, variant and their interactions on net carbon assimilation rate of the plants.

Light intensity μmol $m^{-2}S^{-1}$	**Source**	*df*	*F*	*P*
15	Corrected Model	3	0.469	0.708
	Species	1	0.066	0.801
	Variant	1	1.194	0.292
	Species * Variant	1	0.118	0.736
	Error	15		
30	Corrected Model	3	1.840	0.183
	Species	1	5.339	0.035
	Variant	1	0.044	0.838
	Species * Variant	1	0.229	0.639
	Error	15		
50*	Corrected Model	3	3.614	0.036
	Species	1	10.591	0.005
	Variant	1	0.235	0.634
	Species * Variant	1	0.016	0.902
	Error	16		
70	Corrected Model	3	5.534	**0.008**
	Species	1	15.754	**0.001**
	Variant	1	0.785	0.389
	Species * Variant	1	0.064	0.804
	Error	16		
100	Corrected Model	3	10.948	**<0.001**
	Species	1	31.790	**<0.001**
	Variant	1	1.053	0.320
	Species * Variant	1	0.000	0.994
	Error	16		
150	Corrected Model	3	15.542	**<0.001**
	Species	1	45.883	**<0.001**
	Variant	1	0.534	0.475
	Species * Variant	1	0.210	0.653
	Error	16		

* Data did not meet the homoscedasticity criteria (Levene's test $P < 0.05$)

APPENDIX B

Results summary of a two-way ANOVA for the effects of the plant species, variant and their interactions on stomatal conductance of the plants.

Light intensity μmol $m^{-2}S^{-1}$	Source	*df*	*F*	*P*
15	Corrected Model	3	22.221	**<0.001**
	Species	1	63.863	**<0.001**
	Variant	1	4.434	0.052
	Species * Variant	1	0.809	0.383
	Error	15		
30	Corrected Model	3	19.785	**<0.001**
	Species	1	55.941	**<0.001**
	Variant	1	4.978	**0.042**
	Species * Variant	1	0.008	0.930
	Error	15		
50	Corrected Model	3	20.991	**<0.001**
	Species	1	57.154	**<0.001**
	Variant	1	5.803	**0.028**
	Species * Variant	1	0.017	0.899
	Error	16		
70	Corrected Model	3	14.468	**<0.001**
	Species	1	37.353	**<0.001**
	Variant	1	5.856	**0.028**
	Species * Variant	1	0.193	0.666
	Error	16		
100	Corrected Model	3	20.226	**<0.001**
	Species	1	55.011	**<0.001**
	Variant	1	5.485	**0.032**
	Species * Variant	1	0.182	0.675
	Error	16		
150	Corrected Model	3	23.594	**<0.001**
	Species	1	65.820	**<0.001**
	Variant	1	4.286	0.055
	Species * Variant	1	0.674	0.424
	Error	16		