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BRIEF COMMUNICATION

Assessment of photosynthetic potential of indoor plants under cold stress

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Abstract

Photosynthetic parameters including net photosynthetic rate (P_N), transpiration rate (E), water-use efficiency (WUE), and stomatal conductance (g_s) were studied in indoor C_3 plants *Philodendron domesticum* (*Pd*), *Dracaena fragans* (*Df*), *Peperomia obtussifolia* (*Po*), *Chlorophytum comosum* (*Cc*), and in a CAM plant, *Sansevieria trifasciata* (*St*), exposed to various low temperatures (0, 5, 10, 15, 20, and 25°C). All studied plants survived up to 0ºC, but only *St* and *Cc* endured, while other plants wilted, when the temperature increased back to room temperature (25°C). The P_N declined rapidly with the decrease of temperature in all studied plants. *St* showed the maximum P_N of 11.9 μmol m^{-2} s^{-1} at 25ºC followed by *Cc, Po, Pd*, and *Df*. *E* also followed a trend almost similar to that of P_N. *St* showed minimum *E* (0.1 mmol m^{-2} s^{-1}) as compared to other studied C_3 plants at 25ºC. The *E* decreased up to ~4-fold at 5 and 0ºC. Furthermore, a considerable decline in WUE was observed under cold stress in all C_3 plants, while *St* showed maximum WUE. Similarly, the g_s also declined gradually with the decrease in the temperature in all plants. Among C_3 plants, *Pd* and *Po* showed the maximum g_s of 0.07 mol m^{-2} s^{-1} at 25ºC followed by *Df* and *Cc*. However, *St* showed the minimum g_s that further decreased up to ~4-fold at 0ºC. In addition, the content of photosynthetic pigments [chlorophyll *a*, *b*, (*a*+*b*), and carotenoids] was varying in all studied plants at 0ºC. Our findings clearly indicated the best photosynthetic potential of *St* compared to other studied plants. This species might be recommended for improving air quality in high-altitude closed environments.

Additional key words: house plants; low-temperature stress; net photosynthetic rate; photosynthetic pigment; stomatal conductance; transpiration rate, water-use efficiency.

Considerable parts of human populations, including armed forces, are deployed in inaccessible snow-bound/high-altitude areas of strategic importance at country borders. The environmental conditions in such areas are very harsh, adverse, and with extremely low temperatures and a very low oxygen content (hypoxia) that creates a lot of physiological and psychological stresses affecting their health and performance (West 1995). Therefore, only oxygen enrichment can counteract the effects of hypoxia under such conditions, since plant produce oxygen as a byproduct of photosynthesis (Wood 2003). Thus, by placing indoor air-purifier plants could enrich the oxygen content in closed environments at high-altitude (Wolverton *et al.* 1984). It does not increase only an aesthetic value inside such an environment but it can be also used to improve the air quality together with removing carbon dioxide and other harmful gasses (Papinchak *et al.* 2009).

There are several air-purifying indoor C_3 plants, namely, *Philodendron domesticum* (*Pd*), *Dracaena fragans* (*Df*), *Peperomia obtussifolia* (*Po*), *Chlorophytum comosum*

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Abbreviations: *ANOVA* – analysis of variance; Car – carotenoids; *Cc – Chlorophytum comosum*; Chl – chlorophyll; *Df – Dracaena fragans*; DMF – N,N-dimethyl formamide; *E* – transpiration rate; FM – fresh mass; g_s – stomatal conductance; LSD – least significant difference; *Pd – Philodendron domesticum*; P_N – net photosynthetic rate; *Po – Peperomia obtussifolia*; *St - Sansevieria trifasciata*; WUE – water-use efficiency.

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(*Cc*), and CAM plant, *Sansevieria trifasciata* (*St*). They are known to be effective in high oxygen productivity even during night hours by significant reduction of indoor air pollutants in a closed environment (Wolverton *et al.* 1984, Maroni *et al.* 1995, Gupta *et al.* 2015).

Low temperature is one of the most important abiotic factors that may limit photosynthetic performance of plants (Oliveira and Peñuelas 2004, Ashraf and Harris 2013). It causes severe restrictions to plant function and growth. Therefore, plants have adapted different types of photosynthetic mechanisms (C_3, C_4, and CAM) for specific climate zones (Orsenigo *et al.* 1997, Doubnerová and Ryšlavá 2011, Freschi and Mercier 2012). Also, the overall photosynthetic performance of plants depends upon various stomatal or nonstomatal factors under cold stress (Freschi and Mercier 2012, Yamori *et al.* 2014). Therefore, it is not easy to discriminate between the effects of these limitations on overall photosynthetic capacity of plants. However, some studies have shown the effects of cold stress on various photosynthetic parameters including net photosynthetic rate (P_N), transpiration rate (E), water-use efficiency (WUE), stomatal conductance (g_s), photosynthetic pigments content, *etc.* in many plants (Roden *et al.* 1999, Oliveira and Peñuelas 2004).

The present study was aimed to assess the photosynthetic potential of some air-purifying indoor C_3 and CAM plants under low temperature in order to select a best candidate for improving air quality in closed, high-altitude environments including army bunkers.

The selected indoor potted plants were grown up to 30–50 cm at ambient room temperature (25 ± 2°C) in laboratory conditions before exposing them to low-temperature stress. After that, various low temperatures (25, 20, 15, 10, 5, and 0ºC) were set for one week in a decreasing temperature order in a plant growth chamber *LT-105* (*Percival Scientific Inc.*, *Perry*, Iowa, USA) equipped with cold fluorescent light [350 μmol(photon) m^{-2} s^{-1}] with a photoperiod of 12/12 h (day/night) at 500 ppm CO_2 and relative humidity of 70 ± 2%. All photosynthetic parameters (P_N, E, WUE, and g_s) were measured after 1-week adaptation of the plants under respective low temperatures by using a portable leaf chamber analyser (*LCA-4*, *ADC Bio Scientific Ltd.*, Hoddesdon, UK). P_N, E, and g_s were measured on uppermost, fully expanded, terminal leaflets (abaxial surface) at 11:00 h. The same plants were brought to ambient room temperature (25 ± 2ºC) inside laboratory to overcome the effect of previous cold stress, before exposing them to next low-temperature stress. WUE was calculated as the ratio of the P_N to E. Chl *a*, Chl *b,* and total Chl (*a*+*b*) and total carotenoids (Car) contents were determined from fresh leaf samples (FM). Fresh leaf discs were placed in a test tube containing 10 ml of N,N-dimethyl formamide (DMF) and stored for 24 h at 4ºC. The absorbance of the coloured supernatant was read at 480, 647, and 666 nm by a monochromater-based multimode detector (*BioTek*, *Snergy 2*, USA) with DMF as a blank. The contents of Chl *a*, *b,* and total Chl (*a*+*b*) were calculated according to the method of Moran and Porath (1980).

All measurements were carried out in triplicates by using three independent plants for each treatment. *CropStat* program developed at IRRI, Philippines was used for analysis of variance (*ANOVA*) of experiments. The treatment means were compared by least significant difference (LSD) test at a significance level of $P \leq 0.05$.

Each plant species has its unique temperature requirements; thus, what is an optimum for one plant species it might be stressful for another one. In general, photosynthesis can function without any harm between 0 and 30ºC in cold-adapted plants that are active in the winter (Ashraf and Harris 2013). Most plant species are able to acclimate to changes in growth temperature by modifying the photosynthetic apparatus in a manner that helps in their survival under low-temperature stress conditions (Biswal *et al.* 2011).

In our case, all studied plants survived morphologically up to 0ºC, but when the temperature increased later to room temperature of 25ºC, only *St* and *Cc* were able to recover from cold stress (0ºC for 1 week), while the rest of the plants wilted due to permanent cold injury. The optimum temperature for photosynthesis differs depending on plants species and differs also in dependence on growth and measurement temperatures even in a single plant species (Yamori *et al.* 2010). Among studied plants, *St* showed the best survival potential (Fig. 1S, *supplementary material available online*). Most of the CAM plants show very species-specific behaviour in regard to photosynthetic gas exchange and many of them can switch between C_3 and CAM photosynthesis depending on various environmental conditions including low-temperature stress. However, the selected CAM plant, *St*, is obligatory in its nature since it cannot revert into the C_3 phenotype, when the environmental stress is eliminated.

Under low-temperature stress, P_N declined rapidly with the decrease in the temperature in all plants (Fig. 1*A*). Among all plants, *St* showed maximum P_N of 11.9 μmol m^{-2} s^{-1} followed by *Cc, Po, Pd*, and *Df* with P_N value of 8.8, 7.4, 7.3, and 4.3 μmol m^{-2} s^{-1}, respectively, at 25ºC (Fig. 1*A*). The P_N was ~3-fold higher in *St* as compared to *Cc*. Also, *St* plant showed minimum 7.5 and 15.5-fold decrease in P_N at 5 and 0ºC, respectively, as compared to other studied plants. However, the maximum ~390 and ~33-fold decrease in P_N was observed in *Po* and *Cc* plants, respectively, at 0ºC. Reduction in P_N due to cold stress may be attributed to impairment in photosynthetic pigment biosynthesis or destruction which leads to impairment in the electron transport (Krivosheeva *et al.* 1996). In our case, the P_N also declined significantly with a decrease in temperature in all studied plants, which was

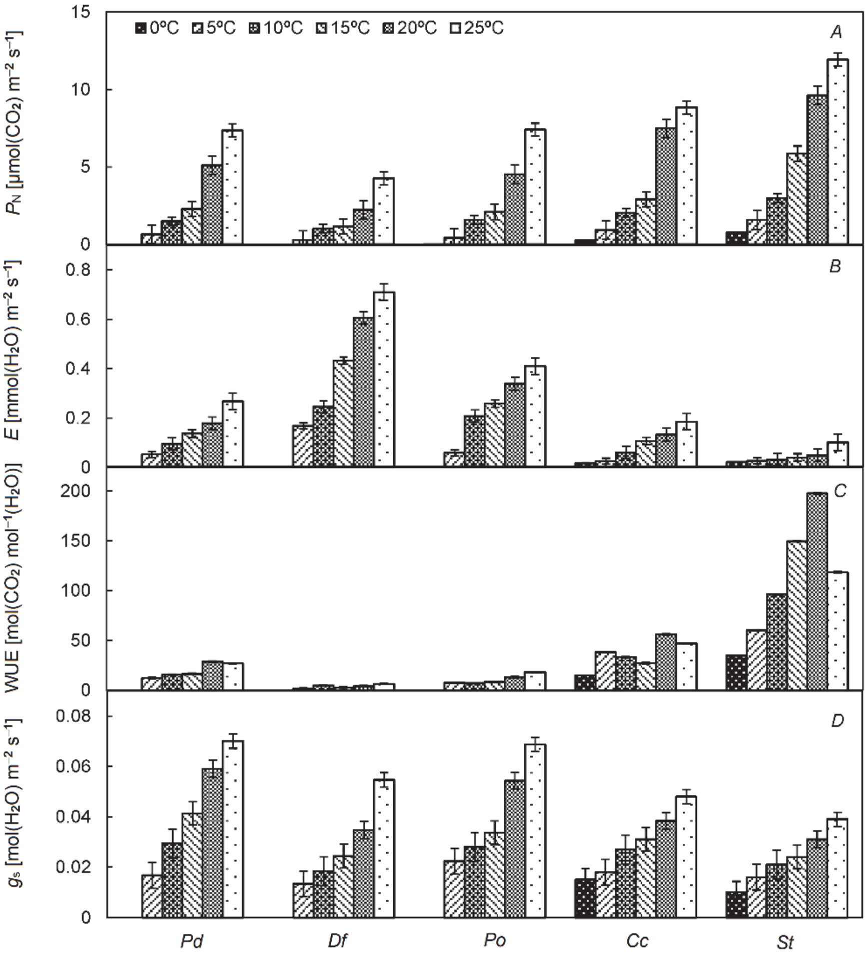

Fig. 1. Effect of various low temperatures (0, 5, 10, 15, 20, and 25°C) on (*A*) net photosynthetic rate (P_N), (*B*) transpiration rate (*E*), (*C*) water-use efficiency (WUE), and (*D*) stomatal conductance (g_s) in air-purifying indoor C_3 plants: *Philodendron domesticum* (*Pd*), *Dracaena fragans* (*Df*), *Peperomia obtussifolia* (*Po*), *Chlorophytum comosum* (*Cc*), and CAM plant, *Sansevieria trifasciata* (*St*). Bar shown means ($n = 3$) ± SE are statistically significant ($P \le 0.05$) according to LSD test.

in accordance with earlier reports (Tewari and Tripathy 1998, Biswal *et al.* 2011). The C_3 plants generally possess a greater ability for temperature acclimation of photosynthesis across a broad temperature range (10–35ºC), while CAM plants acclimated day and night photosynthetic process differentially with respect to temperature (Yamori *et al.* 2014). Moreover, in CAM plants the optimum temperature for photosynthesis is lower as compared to C_3 and C_4 plants, since their photosynthetic enzymes are stabilized even at low temperatures (Freschi and Mercier 2012). Also, CAM plants are well adapted for cold, dry, and arid environments and have usually higher P_N as compared to C_3 plants (Freschi and Mercier 2012, Yamori *et al.* 2014). Thus, higher P_N in *St* was in agreement with above mentioned.

The *E* followed a trend almost similar to that of P_N. A sharp decrease was observed in *E* under low-temperature stress in all studied plants except of *St*. Among C_3 plants, *Df* showed maximum *E* (0.7 mmol m^{-2} s^{-1}) at 25ºC that decreased up to ~4-fold upon subsequent low-temperature stress. The higher *E* was observed also in *Po* followed by *Pd* and *Cc*. However, *St* plants showed minimum *E* (0.1 mmol m^{-2} s^{-1}) as compared to other C_3 plants at 25ºC; it further smoothly decreased up to ~4-fold at 5 and 0ºC (Fig. 1*B*). It is known that CAM plants close their stomata during the day to avoid water losses by transpiration (Freschi and Mercier 2012, Yamori *et al.* 2014). Therefore, there was no surprice that the least *E* was observed in *St* as compared to other studied C_3 plants.

WUE is defined as the ratio of carbon gain (dry matter accumulation) to water loss (amount of water transpired during a period of dry matter accumulation) (Sinclair *et al.* 1984). A considerable decline in WUE under low-temperature stress was observed in all studied C_3 plants due to the higher *E* as compared to the CAM plant, since their stomata remained opened during the daytime (Freschi and Mercier 2012), while in *St* (being the CAM plant), the decrease was comparatively lesser (Fig. 1*C*). *St* showed maximum WUE as compared to all studied C_3 plants and thus proved its fitness to survive under low temperature. CAM plants can effectively save metabolic energy and water during harsh environmental conditions as compared to C_3 plants (Freschi and Mercier 2012). Among the C_3 plants, *Cc* plants showed the best WUE followed by *Pd, Po*, and *Df.* Plants can achieve high WUE through either high P_N, low *E*, or both. Both processes are at least partially regulated by g_s (Cowan 1982). When water is limiting, conductance decreases as a result of stomatal

Table 1. Effect of low-temperature stress (0°C for 1 week) on alteration of photosynthetic pigments [chlorophyll (Chl) *a*, Chl *b*, total Chl (*a*+*b*) and carotenoids (Car)] in air-purifying indoor C_3 plants, such as *Philodendron domesticum* (*Pd*), *Dracaena fragans* (*Df*), *Peperomia obtussifolia* (*Po*), *Chlorophytum comosum* (*Cc*) and CAM plant, *Sansevieria trifasciata* (*St*). Means ($n = 3$) ± SE value of the treatments are statistically significant ($P \leq 0.05$) according to LSD test. FM – fresh mass.

Parameter	Chl *a* [$\mu g\ g^{-1}$(FM)]		Chl *b* [$\mu g\ g^{-1}$(FM)]		Total Chl (*a*+*b*) [$\mu g\ g^{-1}$(FM)]		Car [$\mu g\ g^{-1}$(FM)]	
Temperature	25°C	0°C	25°C	0°C	25°C	0°C	25°C	0°C
Pd	0.14	0.08	0.07	0.04	0.22	0.13	1.34	1.46
Df	0.02	0.02	0.01	0.01	0.03	0.03	1.05	2.26
Po	0.14	0.41	0.05	0.43	0.19	0.94	1.03	1.75
Cc	0.17	0.05	0.06	0.03	0.24	0.09	1.42	0.60
St	0.26	0.89	0.09	1.07	0.36	2.03	0.70	0.51
SE (M)	0.05	0.08	0.02	0.05	0.07	0.10	0.25	0.04
LSD ($P \leq 0.05$)	0.15	0.28	0.07	0.16	0.22	0.34	0.80	0.13

closure. Stomatal closure has a greater effect on photosynthesis than on transpiration due to the additional resistance associated with diffusion of CO_2 relative to H_2O in the leaf (Medici *et al*. 2007). Therefore, the increase in WUE caused by stomatal closure resulted in the decrease in the carbon assimilation. However, when water is limited, plants, which use a finite water supply more efficiently, should grow more rapidly (Nobel 1996). CAM plants open their stomata and incorporate CO_2 during night, when evapo-transpiration rates are low; it results in high WUE as compared to C_4 and C_3 plants (Nobel 1996). Therefore, under low-temperature stress, plants with a high WUE should have greater ability to survive than the plants with the low WUE (Sinclair *et al*. 1984); it was in accordance with our results.

The g_s declined gradually with the decrease in the temperature in all studied plants (Fig. 1*D*). The regulation of leaf g_s is a key phenomenon in plants as it is vital for both prevention of desiccation and CO_2 acquisition (Medici *et al*. 2007). Stomata closure in response to cold stress generally occurs due to decreased leaf turgor and atmospheric pressure ultimately alters photosynthesis and the mesophyll metabolism (Medici *et al*. 2007, Xu *et al*. 2008). Among the C_3 plants, *Pd* and *Po* showed maximum g_s of 0.07 mol m^{-2} s^{-1} followed by *Df* and *Cc* with g_s value of 0.05 and 0.04 mol m^{-2} s^{-1}, respectively, at 25ºC (Fig. 1*D*). On the other hand, *St* showed minimum g_s (0.03 mol m^{-2} s^{-1}), which further deceased up to ~4-fold at 0ºC, since the CAM plants close their stomata during daytime (Freschi and Mercier 2012, Yamori *et al*. 2014). Therefore, the higher *g*s in the studied C_3 plants as compared to CAM plants was expected.

The alteration of photosynthetic pigments [Chl *a*, *b*, and total Chl (*a*+*b*)] content was found in all studied plants at 0ºC. The pigment amount was significantly reduced (~0.3 to 0.9-fold) as compared to 25ºC in *Pd*, *Df*, and *Cc* plants (Table 1). It is well known that the chloroplast is the main organelle rapidly and deeply affected during cold stress (Ensminger *et al*. 2006). When plants are exposed to low-temperature stress, Chl biosynthesis is inhibited. Therefore, an imbalance in PSII is created after exposure to low temperature because of the alterations in the Chl antenna complexes (Habibi *et al*. 2011). In contrast, in *Po* and *St*, no such decrease in photosynthetic pigments was observed (Table 1). It might suggest a less harmful effect of Chl bleaching and photoinhibition under cold stress (Habibi *et al*. 2011). Similarly, the total carotenoids (Car) content was also found varying in all studied plants at 0ºC. In *Pd*, *Df*, and *Po* plants, the Car content slightly increased (~1.1 to 2-fold) at 0ºC as compared to 25ºC (Table 1). At low temperature, the alterations in the content of total Car showed a tendency to a sharp increase, probably in order to increase photon capture, as a strategy against cold-induced photoinhibition (Habibi *et al*. 2011). However, in *Cc* and *St*, no significant change in the Car content was observed at 0ºC (Table 1), which might suggest their better survival potential at 0ºC.

Our findings clearly indicated the best photosynthetic potential of *Sansevieria trifasciata* (*St*) compared to other studied plants. Therefore, it may be recommended to be pot-grown in high-altitude closed environments for improving air quality under low temperature.

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