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# EFFECT OF DAILY LIGHT INTEGRAL ON PHYSIOLOGICAL AND MORPHOLOGICAL PARAMETERS OF INDOOR PLANTS IN VERTICAL GARDEN

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### ABSTRACT

Performance and appearance of vertical gardens are affected by plant quality, which is why creating conditions for their proper growth is crucial. Insufficient amount of light inside buildings significantly limits plant development, especially in the autumn and winter in the northern hemisphere. The objective of this study was to investigate physiological and morphological quality of plant species, *Asplenium*, *Chlorophytum* and *Philodendron,* in an indoor vertical garden exposed to two levels of daily light integral (DLI, 0.1–0.3 or 1.1–1.7 mol m$^{-2}$ day$^{-1}$). Higher DLI level improved plant diameter, height, leaf length and width, leaf area, total area of leaf blades, dry weight, and carotenoid content, however did not affected leaf fresh weight and leaf number. *Chlorophytum* and *Asplenium* were particularly responsive to natural light supplementation and were distinguished by the best growth habit and compactness.

**Key words:** green walls, pot plant development, PPFD, shade tolerant plants, vertical systems

## INTRODUCTION

The introduction of green areas to cities is one of the sustainable measures taken to create conditions conducive to mental, physical and social health. Greenery can be introduced to cities in the form of public areas, as greenery on buildings, and as an element of building interior design [Zielinska-Dabkowska et al. 2019]. Vertical gardens are an important factor in improving urban indoor environments, allowing the cultivation of a large number of plants in a limited space [Chaipong 2020].

Numerous studies have shown that indoor plants have a beneficial effect on physical and mental health [Han and Ruan 2019] among others by improving air quality and microclimate: capturing and removing atmospheric PM particles [Gawrońska and Bakera 2015], lowering levels of $CO_2$, $SO_2$, and volatile organic compounds, lowering the temperature [Cao et al. 2019]; and influencing people's well-being, decreasing stress levels, reducing mental fatigue, increasing efficiency [Tennessen and Cimprich 1995]. The incorporation and maintenance of a large number of good quality plants is of great importance for the efficiency of indoor environment improvement and psychological effect.

Among many important factors (air, water, substrate, nutrition, temperature) influencing the growth and development of plants, light is essential [Kami et al. 2010]. It regulates physiological processes like photosynthesis, morphogenesis, metabolism and gene expression. Sunlight is the best source of light that guarantees the proper development and quality of plants. The total amount of PAR received by a plant in a unit area during 24 hours can be quantified as the daily light integral (DLI), which is a function of light

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intensity as well as duration of exposure [Korczynski et al. 2002]. Unfortunately, the quality of light and DLI levels in the rooms of buildings are usually insufficient and it is necessary to provide artificial supplementary lighting to compensate for these deficiencies especially in the autumn and winter when day length and photoperiod become shorter [Rehman et al. 2017]. Adequate intensity, spectral composition of the light source, timing and duration of light are necessary for plant photosynthetic performance and decorativeness [Rehman et al. 2017, Zielinska-Dabkowska et al. 2019]. For many shade tolerant plants, an increase in lighting intensity within a certain range has a positive effect on their growth and appearance [Yeh and Wang 2000, Manda et al. 2018].

So far, several works have been published on lighting of indoor green walls [Egea et al. 2014, Tan and Wang 2017, Kaltsidi et al. 2020]. But there is still a lack of new knowledge about the suitability of various species and varieties of indoor plants for use in low light conditions typical of the interior of buildings. The main research objective was to analyze the influence of DLI level on the physiological and morphological parameters determining the quality of plants as well as their ornamental value in an indoor vertical garden. It was examined how the increase of the DLI value affects growth and development of *Asplenium*, *Chlorophytum* and *Philodendron* in the context of their use in the design of living walls under low light conditions.

## MATERIALS AND METHODS

**Plant material.** Three genotypes of indoor plants were selected as plant material: *Asplenium dimorphum* 'Parvati' (Aspleniaceae), *Chlorophytum comosum* 'Bonnie' (Anthericaceae), *Philodendron scandens* (Araceae). Plants were planted in plastic 14 cm Pixel Garden pots filled with a peat substrate (Hollas, Pasłęk, Poland; pH 5.5–6.5), with a mineral fertilizer dose of 0.6 kg m$^{-3}$ (NPK 14-16-18) for *Chlorophytum* and *Philodendron*, and a peat substrate (SUBSTRAL Osmocote, Scotts, Poland; pH 5.5–6.0) based on high peat and low peat with an admixture of expanded clay with an Osmocote fertilizer dose of 1.9 g L$^{-1}$ (mixture of Osmocote NPK 15-09-09 and Plant Starter NPK 10-52-10) for *Asplenium*.

**Experimental setup**. The experiment was conducted in the autumn period from October 24, 2019 to December 5, 2019 in the Krakow District (lat. 50.08°N, long. 19.44°E). Two vertical garden panels (130.2 cm high and 59.7 cm wide) were established using the Pixel Garden (pixel-garden.eu) modular system for vertical garden constructions. Twenty-eight PG14 modules with dimensions of 186 × 298.5 × 90 mm, containing 56 plants, were used. Plants were grown under a 16 h photoperiod (from 6 am to 10 pm) in experimental room under 2 different DLI (daily light integral) levels: 0.1–0.3 mol m$^{-2}$ day$^{-1}$ (DLI-L) for panel 1 and 1.1–1.7 mol m$^{-2}$ day$^{-1}$ (DLI-H) for panel 2. Ambient daylight plus supplemental LED lighting of 13 μmol m$^{-2}$ s$^{-1}$ for panel 2 and 0.13 μmol m$^{-2}$ s$^{-1}$ for panel 1 were provided. As supplemental lighting two Vaxer Led PAR 30 E27 growing lamps (model LED1506R10, IKEA, Sweden) with a nominal useful luminous flux of 800 lm, color temperature of 4000 K, beam angle of 30° and a power of 10 W were used. The lamps were placed on the ceiling at a distance of 97 cm from the vertical garden. A LI-250A light meter with a Q 50604 sensor (LI-COR, Lincoln, NE, USA) was used for PPFD measurements. Photosynthetic photon flux density (PPFD) measurements were made at 16 points of the vertical garden on the leaf surface. Accumulated PPF was calculated as the daily integration of data collected at a 30 min resolution (Fig. 1). Plants on vertical garden panels were irrigated with tap water automatically once a week for 30 minutes. Temperature during the experiment was 21 ±1°C.

**Morphological parameters.** Measurements were made in three terms: at the start of the experiment (control) – term 1, midway through (after 3 weeks) – term 2, at the end of the experiment (after 6 weeks) – term 3. Plant height (Plant H), from the bottom of the pot to the uppermost part of the plant, plant diameter (Plant D), between the most distant points, number of leaves per plant (leaf N), leaf blade length (leaf L), from the base of the leaf blade to the blade apex, leaf width (leaf W), estimated as the widest leaf width, leaf area (leaf A), estimated as the area of the ellipse into which the leaf is inscribed, and total area of the leaf blades (leaf TA) were measured. The pots with plants were taken out of the system for measurements.

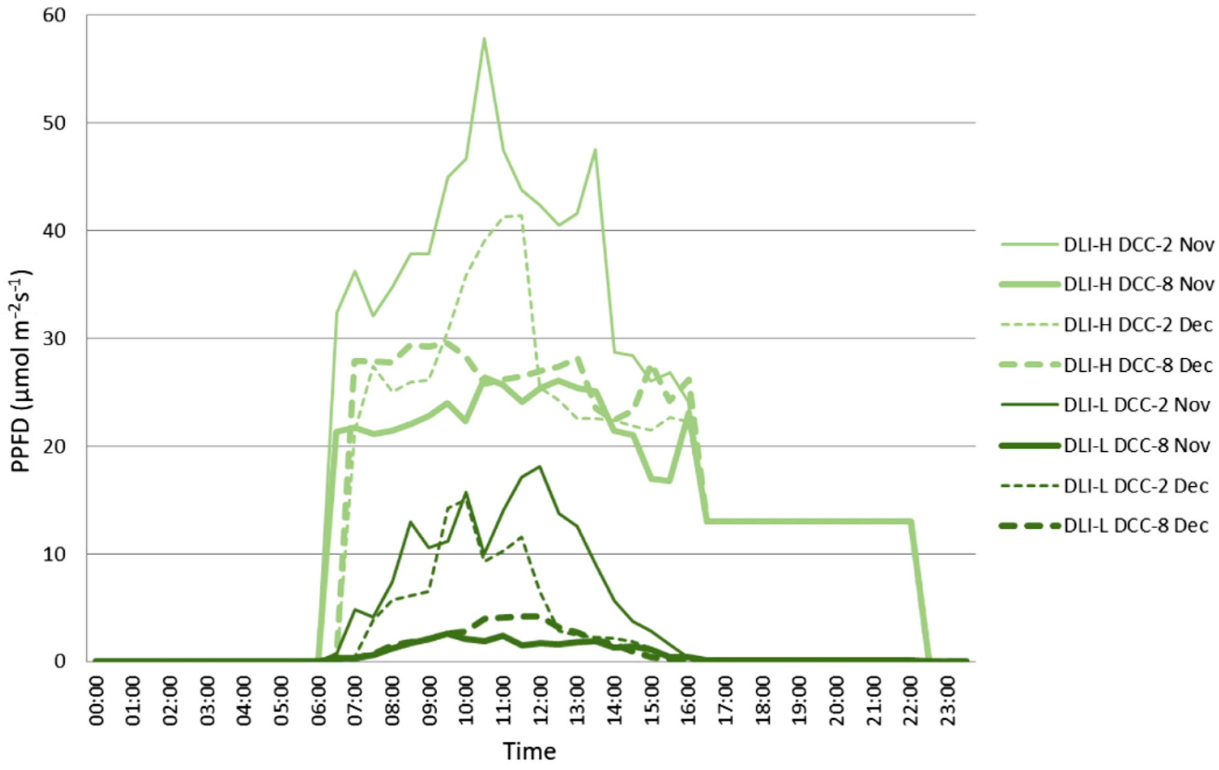


**Fig. 1.** The daily light integral delivered to vertical garden panel 1 (DLI-L – 0.1–0.3 mol $m^{-2}$ $day^{-1}$) and panel 2 (DLI-H – 1.1–1.7 mol $m^{-2}$ $day^{-1}$) (DCC-2, DCC-8 – daily cloud cover value measured in oktas (eighths), where 0 represents completely clear sky, 4 – half cloudy sky, 8 – completely cloudy sky; Nov, Dec – measurement dates)

**Determination of fresh and dry weight.** For the determination of fresh weight of the leaves (leaf FW), three leaves from the middle part of stems or rosettes (avoiding the youngest and the oldest leaves) were randomly collected for each species. Ten discs were cut out from the leaf blade with a 12-mm cork borer and then weighed. leaf FW was converted to mg $cm^{-2}$. For the determination of leaf dry weight (leaf DW), the discs were oven-dried in an air sterilizer (Sanyo Electric Co MOV-112S, Osaka, Japan) at 65°C until constant weight. Measurements were made at three terms: at the start of the experiment (control), midway through, and at the end. Three analytical replications were performed for each treatment.

**Determination of photosynthetic pigments.** Chlorophyll and carotenoid concentrations were determined spectrophotometrically [Lichtenthaler and Buschmann 2001, Sumanta et al. 2014]. leaf samples (0.2 g) were subjected to the extraction procedure and dissolved in 95% ethanol. Solutions were filtered until fully transparent. The absorbance was measured using a UV/VIS Helios Alpha spectrophotometer (Unicam Ltd., Cambridge, UK). The content of chlorophyll *a*, *b*, and carotenoids was measured at the following wavelength maxima (Amax): chlorophyll *a* – 664 nm (Ch *a*), chlorophyll *b* – 649 nm (Ch *b*), total carotenoids – 470 nm (Car). The measurements were calculated according to the following formulas [Sumanta et al. 2014]: chlorophyll $a$ (μg $ml^{-1}$) = 13.36 $A_{664}$ – 5.19 $A_{649}$, chlorophyll $b$ (μg $ml^{-1}$) = 27.43 $A_{649}$ – 8.12 $A_{664}$, carotenoids (μg $ml^{-1}$) = (1000 $A_{470}$ – 2.13 Ch $a$ – 97.63 Ch $b$)/209. Measurements were made at three terms: at the start of the experiment (control), after three and six weeks. Three analytical replications were performed for each treatment.

**Statistical analysis.** This experiment was set up for each genotype using a two-factorial design consisted of 6 treatments – combinations of factor levels (2 DLI levels × 3 terms) with 3 replications, each consisting of 2–4 pots with a plant (depending on the genotype). All data were analyzed using the Statistica 13.3 software (TIBCO Software Inc., Palo Alto, CA, USA). The experimental data were subjected to analysis of variance (ANOVA), and Tukey's multiple range test was used to separate mean values at the significance level of $p \leq 0.05$.

## RESULTS AND DISCUSSION

Vertical garden is a technology that is becoming increasingly popular, especially in cities with dense morphology, where green surfaces are being given away to commercial land development. Green surfaces are appearing in public and private interiors due to numerous advantages related to beneficial effects on indoor environment quality, human health and overall wellbeing, as well as extraordinary decorative value [Moya et al. 2019]. This technology requires knowledge about the possibility of using various species and varieties of indoor plants for vertical cultivation and their specific requirements, e.g. their reaction to DLI value.

Plant growth and development are closely correlated with DLI. Many studies have shown that increasing DLI, within a certain range, improves plant quality, as well as shoot and root growth [Faust and Logan 2018]. To obtain the minimal acceptable quality in greenhouse production, DLI about 2 mol $m^{-2}$ $day^{-1}$ is required for many shade tolerant plants. But as noted by Tan and Wong [2017] light requirements are different for indoor greenery as in case of interior landscaping yield is not a priority. For indoor plants DLI should reach minimum values for sustainability of net carbon gained by the plant and total carbon required for metabolic activities (light compensation point) allowing plant survival of unfavorable period of low light conditions and avoiding lighting energy wastage. The whole-plant light compensation point was determined for *Philodendron erubescens* and *Dracaena surculosa* and ranged between 0.5 mol $m^{-2}$ $day^{-1}$ to 1.0 mol $m^{-2}$ $day^{-1}$ [Tan and Wong 2017].

Supplementation of natural light in indoor environments and related to it enhance of DLI involves also shade tolerant plants most commonly used for interior plantscaping due to their ability to grow under low light conditions [Giorgioni 2010]. Our experiment was carried out in low light conditions on a vertical garden panels installed in an experimental room under two DLI levels: 0.1–0.3 mol $m^{-2}$ $day^{-1}$ for panel 1 (in ambient light) and 1.1–1.7 mol $m^{-2}$ $day^{-1}$ for panel 2 (in ambient light with LED light supplementation). Experiment was conducted in the autumn in the northern hemisphere, where in autumn and winter the light available for plant growth decreases dramatically. Days in Krakow in November and December last less than 10 hours and the sky is the cloudiest (up to 79.6%) [Matuszko and Celiński-Myslaw 2016]. As plants optimally require about 14 hours of light exposure, followed by 10 hours of darkness [Zielinska-Dabkowska et al. 2019, Kaltsidi et al. 2020], it is necessary to apply supplementary lighting in this case.

*Asplenium* and *Chlorophytum* were particularly responsive to increased DLI, for which LED light application significantly improved the morphology. The greatest number of morphological parameters (plant D, plant H, leaf L, leaf W, leaf A and leaf TA) increased in the case of *Chlorophytum*. Higher DLI had a positive effect on 3 morphological parameters of *Asplenium*: leaf W, leaf A and leaf TA. *Asplenium* subjected to higher DLI (regardless of term) had on average 0.5 cm wider leaves, their area was increased by 8.9 $cm^2$ and the total area of leaf blades was increased by 0.09 $m^2$. Under these conditions *Chlorophytum* had on average 3.7 cm larger diameter, 3.6 cm larger height, 4.7 cm longer and 0.4 cm wider leaves, and their area was increased by 11.2 $cm^2$ and total area by 0.17 $m^2$ (Tabs 1, 2). The increases in the values of parameters occurred after three, and at the latest after six weeks of exposure to DLI-H (Fig. 2).

In *Philodendron*, no increase in morphological parameters but an increase in dry matter content was observed, that wasn't in other species (Tabs 1, 2). Compared to the control (term 1), at terms 2 and 3, the ambient light conditions decreased the leaf DW, while under the influence of higher DLI it did not change (Fig. 3).

Increase in dry matter content in the tissues of irradiated plants was consistent with other studies on indoor plants [Mortensen and Gislerød 1990, Bergstrand and Schüssler 2013]. Higher light intensity resulted in enhanced dry weight, frond area and frond number in *Adiantum raddianum* [Yeh and Wang

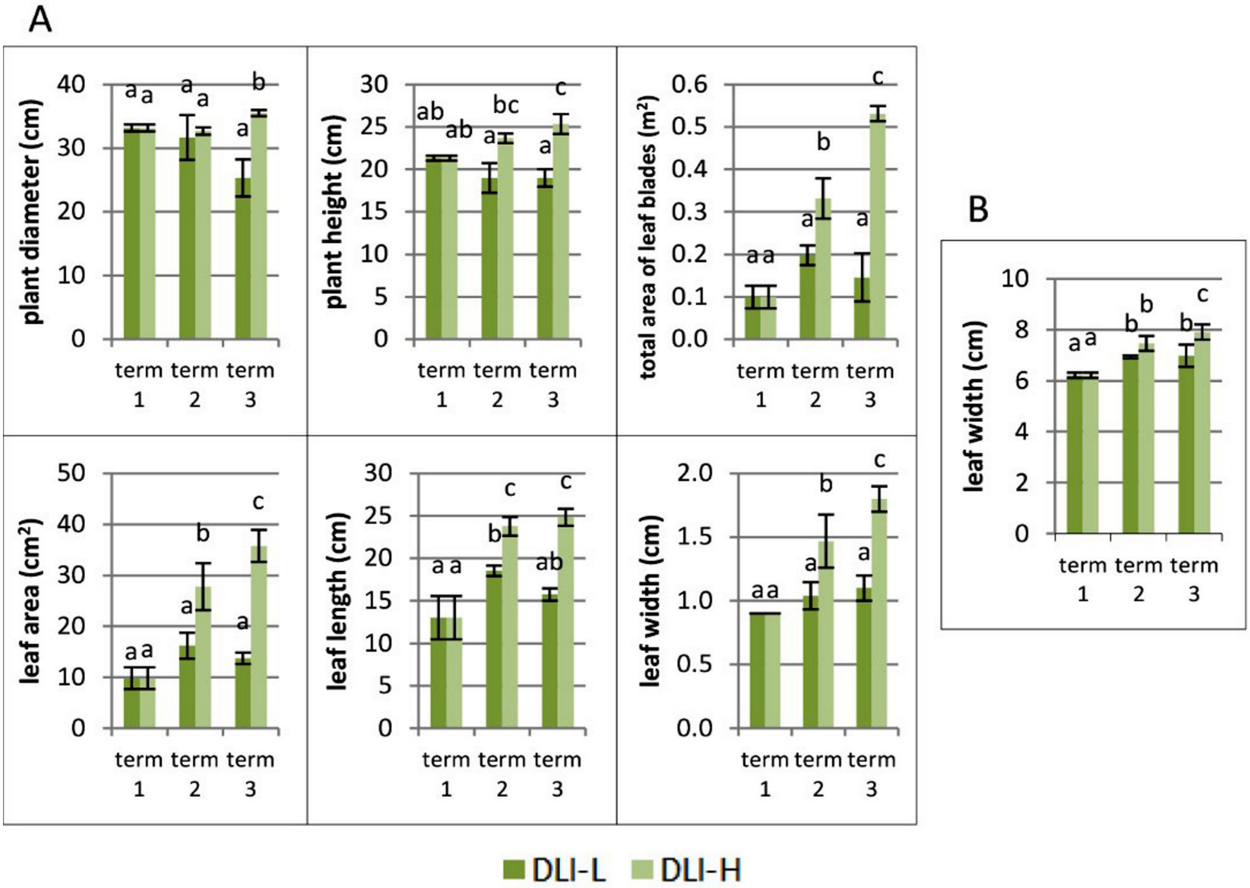


**Fig. 2.** Effect of daily light integral level (DLI-L – 0.1–0.3 mol m$^{-2}$ day$^{-1}$, DLI-H – 1.1–1.7 mol m$^{-2}$ day$^{-1}$) and term (term 1 – control, term 2 – after 3 weeks, term 3 – after 6 weeks) on: (A) plant diameter, plant height, total area of leaf blades, leaf area, leaf length and leaf width of *Chlorophytum*, (B) leaf width of *Asplenium*

2000], leaf width and leaf number in *Chlorophytum amaniense* 'Fire Flash' [Manda et al. 2018] and leaf area in *Tetrastigma hemsleyanum* [Dai et al. 2009]. Studies carried out in a greenhouse with 23 plant species, including *Chlorophytum comosum*, under natural and supplementary lighting (60 µmol m$^{-2}$ s$^{-1}$ 20 hours a day) [Mortensen and Gislerød 1990] and experiment under white LED lamps applied 16 hours a day [Bergstrand and Schüssler 2013] demonstrated an increase in height. Shade tolerant plants are capable of efficiently utilizing even short series of sunflecks [Giorgioni 2010, Middleton 2001] that in our experimental conditions resulted from changing lighting conditions throughout the day.

Different reactions of species to low light conditions may indicate the acceptance of different strategies. Two low light tolerance strategies specific to shade tolerant plants include maximizing net carbon gain (optimum use of available energy) and enhancing persistence and increasing investments in storage and defense (conservation of energy) [Middleton 2001, Valladares et al. 2016]. Optimal photosynthetic efficiency and resource utilization in response to quantitative and qualitative light changes are related to dynamic acclimation of the photosynthetic apparatus under environmental stress [Vänninen et al. 2010]. The shade plants typically have thinner leaves [Goto 2003] with relatively high chlorophyll content [Yeh and Wang 2000], dark green color of the foliage in deep shade [Middleton 2001], large leaf area [Valladares et al. 2016], less conductive tissue per unit leaf area [Yeh and Wang 2000], lower respiration rates, high-

**Table 1.** Results of ANOVA for the analyzed parameters affected by daily light integral (DLI) and term in *Philodendron, Asplenium* and *Chlorophytum*

| Parameter | ANOVA source of variation | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *Philodendron* | | | *Asplenium* | | | *Chlorophytum* | | |
| | DLI (L) | Term (T) | L × T | DLI (L) | Term (T) | L × T | DLI (L) | Term (T) | L × T |
| Plant D | ns | *** | ns | ns | ns | ns | *** | ns | *** |
| Plant H | ns | ns | ns | ns | *** | ns | *** | ns | *** |
| Leaf N | ns | ** | ns | ns | ** | ns | ns | ns | ns |
| Leaf L | ns | ns | ns | ns | ns | ns | *** | *** | *** |
| Leaf W | ns | ns | ns | *** | *** | ** | *** | *** | *** |
| Leaf A | ns | ns | ns | ** | ** | ns | *** | *** | *** |
| Leaf TA | ns | ns | ns | ** | *** | ns | *** | *** | *** |
| Leaf FW | ns | ns | ns | ns | *** | ns | ns | *** | ns |
| Leaf DW | *** | ns | *** | ns | ** | ns | ns | ns | ns |
| Ch *a* | ns | ns | *** | ns | *** | ns | ns | ns | ns |
| Ch *b* | *** | *** | *** | ns | *** | ns | *** | ns | ns |
| Car | *** | *** | *** | *** | *** | *** | *** | *** | *** |

Levels of significance for ANOVA: ** $p < 0.05$; ***$p < 0.01$; ns, not significant; Plant H – plant height, Plant D – plant diameter, Leaf N – number of leaves per plant, Leaf L – leaf blade length, Leaf W – leaf width, Leaf A – leaf area, Leaf TA – total area of the leaf blades, Leaf FW – leaf fresh weight, Leaf DW – leaf dry weight, Ch *a* – chlorophyll *a*, Ch *b* – chlorophyll *b,* Car – total carotenoids

**Table 2.** Daily light integral effect on growth, development and quality of indoor plants in the vertical garden

| Parameter | Genotype | | | | | |
|---|---|---|---|---|---|---|
| | *Philodendron* | | *Asplenium* | | *Chlorophytum* | |
| | DLI – L | DLI – H | DLI – L | DLI – H | DLI – L | DLI – H |
| Plant D (cm) | 30.7 ±1.6 a[4] | 31.4 ±1.9 a | 44.7 ±3.9 a | 43.72 ±3.20 a | 30.1 ±4.3 a | 33.8 ±1.4 b |
| Plant H (cm) | 22.3 ±1.4 a | 22.8 ±1.0 a | 28.5 ±2.6 a | 28.8 ±2.7 a | 19.8 ±1.5 a | 23.4 ±1.9 b |
| Leaf N (no.) | 20.1 ±2.9 a | 20.0 ±3.2 a | 60.4 ±6.8 a | 63.7 ±6.6 a | 110.2 ±25.2 a | 123.3 ±23.8 a |
| Leaf L (cm) | 6.6 ±0.8 a | 7.0 ±0.5 a | 14.8 ±1.7 a | 14.9 ±0.8 a | 15.8 ±2.7 a | 20.5 ±5.9 b |
| Leaf W (cm) | 4.2 ±0.6 a | 4.4 ±0.5 a | 6.7 ±0.4 a | 7.2 ±0.8 b | 1.0 ±0.1 a | 1.4 ±0.4 b |
| Leaf A ($cm^2$) | 23.3 ±6.5 a | 25.2 ±4.2 a | 79.4 ±9.5 a | 88.3 ±7.9 b | 13.3 ±3.3 a | 24.5 ±11.9 b |
| Leaf TA ($m^2$) | 0.05 ±0.02 a | 0.05 ±0.01 a | 0.48 ±0.08 a | 0.57 ±0.10 b | 0.15 ±0.05 a | 0.32 ±0.19 b |
| Leaf FW ($mg\ cm^{-2}$) | 30.0 ±1.8 a | 29.3 ±3.2 a | 16.8 ±1.4 a | 17.2 ±1.2 a | 28.5 ±0.4 a | 29.6 ±3.1 a |
| Leaf DW (%) | 10.8 ±1.7 a | 13.7 ±1.5 b | 17.6 ±1.1 a | 17.1 ±0.9 a | 5.7 ±1.1 a | 6.7 ±1.7 a |
| Ch *a* ($\mu g\ ml^{-1}$) | 1.7 ±0.2 a | 1.3 ±0.3 a | 5.3 ±1.2 a | 4.6 ±1.2 a | 5.6 ±0.7 a | 6.0 ±0.6 a |
| Ch *b* ($\mu g\ ml^{-1}$) | 0.99 ±0.17 a | 1.14 ±0.21 b | 5.67 ±2.28 a | 4.98 ±1.54 a | 3.86 ±0.63 a | 4.90 ±0.82 b |
| Car ($\mu g\ ml^{-1}$) | 0.15 ±0.05 a | 0.31 ±0.18 b | 0.46 ±0.18 b | 0.35 ±0.09 a | 0.94 ±0.24 b | 0.73 ±0.36 a |

Plant H – plant height, Plant D – plant diameter, Leaf N – number of leaves per plant, Leaf L – leaf blade length, Leaf W – leaf width, Leaf A – leaf area, Leaf TA – total area of the leaf blades, Leaf FW – leaf fresh weight, Leaf DW – leaf dry weight, Ch *a* – chlorophyll *a*, Ch *b* – chlorophyll *b,* Car – total carotenoids. DLI–L – 0.1–0.3 mol $m^{-2}$ $day^{-1}$; DLI–H – 1.1–1.7 mol $m^{-2}$ $day^{-1}$. Mean (±SD) values in row with different letters are significantly different according to Tukey's multiple range test at $p \leq 0.05$

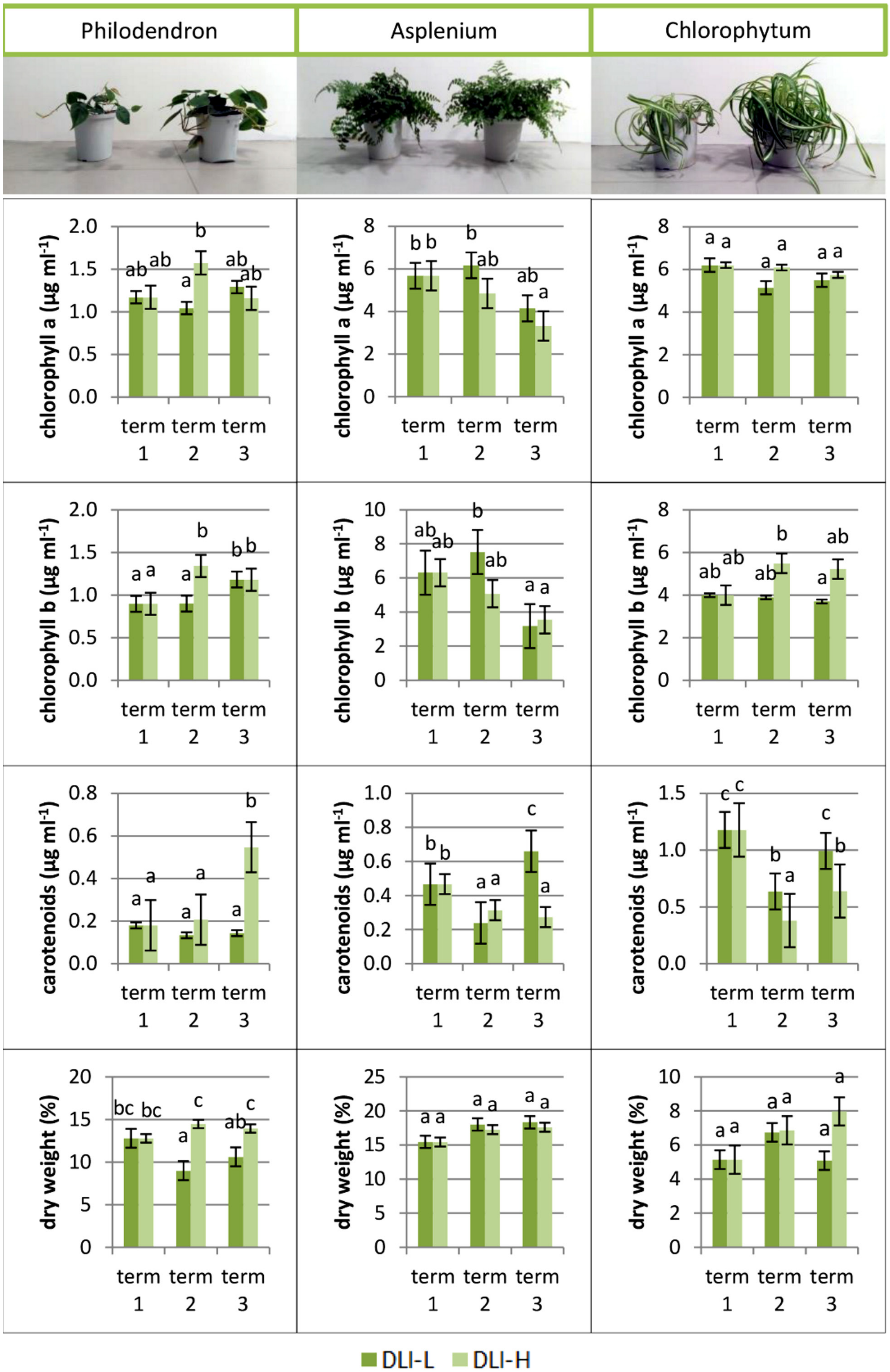


**Fig. 3.** Effect of daily light integral level (DLI-L – 0.1–0.3 mol $m^{-2}$ $day^{-1}$, DLI-H – 1.1–1.7 mol $m^{-2}$ $day^{-1}$) and term (term 1 – control, term 2 – after 3 weeks, term 3 – after 6 weeks) on chlorophyll *a*, chlorophyll *b*, carotenoids and dry weight contents in *Philodendron*, *Asplenium* and *Chlorophytum* (in the photos, plants after 6 weeks of cultivation under DLI-L on the left and DLI-H on the right)

er photosynthetic rates in low light, and lower leaf light compensation and saturation points [Walters and Reich 1999] than shade intolerant plants.

Exposition to DLI-H did not affect leaf FW and leaf N in any of the tested plants. Plants under DLI-H covered the vertical garden surface intended for them to a greater extent and were denser and better colored than those from the control group (growing under DLI-L). The plants were larger and compact (Fig. 3). Importantly, there was no decrease in fresh weight per leaf area unit in plants (Tab. 2).

Changes of light intensity affect plant chloroplasts. Research has shown that shading of plants leads to an increase in the content of chlorophylls and carotenoids in leaves, while a significant reduction in the number of chloroplasts may indicate deterioration of plant quality [Zaika and Bondarenko 2018]. The results of the current study showed not significant differences between chlorophyll *a* contents for all tested plants under different DLI levels and interaction between the DLI level and term for *Philodendron* and *Asplenium* (Tabs 1, 2, Fig. 3). *Philodendron* and *Chlorophytum* had increased chlorophyll *b* under higher DLI, while *Asplenium* showed no changes in the content (Tabs 1, 2). Interactions between the DLI level and term was found for carotenoids. After 6 weeks, the level of carotenoids in *Philodendron* increased compared to the control under DLI-H and has not changed under DLI-L, in *Asplenium* decreased under DLI-H and increased under DLI-L and in *Chlorophytum* decreased under DLI-H and DLI-L (Tab. 2, Fig. 3).

Zheng and van Labeke [2017] reported similarly genotype dependent results. The latter authors applied white LED illumination for 16 hours a day and observed a decrease in chlorophyll content in *Syningia speciosa* 'Sonata Red' and no effect in *Ficus benjamina* 'Exotica' and *Cordyline australis* 'Red Star'. Kaltsidi et al. [2020] also noted a decrease in chlorophyll content in *Soleirolia* and *Spathyphyllum* at higher PPFD values. Full sun exposure and 50% shade treatments resulted in significant reductions in chlorophyll *a*, chlorophyll *b* and total chlorophyll contents in *Tetrastigma*, and these values were higher with increased shading [Dai et al. 2009]. Thus, the effect of illumination on the content of chlorophylls and carotenoids is largely dependent on the species subjected to illumination.

## CONCLUSIONS

It was observed in this study that DLI had an impact on the growth, development and quality of pot plants in vertical garden. *Chlorophytum* and *Asplenium* responded best to higher DLI, which resulted from supplementing natural light with a LED light source, and achieved the highest values of morphological parameters, indicating great potential for application in the design of vertical gardens. On the other hand, the *Philodendron* maintained the morphological quality and improved the physiological one, confirming that it can be grown in the vertical technology. Increasing the DLI to 1.1–1,7 mol $m^{-2}$ $day^{-1}$ by using LED lighting allows the cultivation of shade-tolerant indoor plants without compromising their quality. Therefore, it is possible to develop vertical gardens in rooms with low natural light availability in the unfavorable autumn and winter period in the northern hemisphere.

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