PROBLEMS OF STANDARDISING ILLUMINATION FOR PLANTS IN GREENHOUSES AND GREEN STRUCTURES

Tetiana Tkachenko[1], Viktor Mileikovskyi[1], Anna Moskvitina[1], Iryna Peftieva[1],
Viktoriia Konovaliuk[1], Adam Ujma[2]
[1]Kyiv National University of Construction and Architecture, Ukraine;
[2]Czestochowa University of Technology, Poland
tkachenkoknuba@gmail.com, mileikovskyi@gmail.com, adam.ujma@pcz.pl

Abstract. Today greenhouses are transformed. In the middle of the past century, they were almost glazing buildings above the ground. Due to the development of planting technologies, including mats or trays with substratum, aero – and hydroponics, etc., greenhouses now can be anywhere, including underground. This gives impetus for urban agriculture with optimal logistics (growing near consuming). Indoor green structures become more and more popular. The illumination of them is very important because plants lose decorative properties in unfavourite conditions. At the beginning of this century, there was an analysis of a lot of failed attempts to create winter gardens on underground floors. The illumination was calculated successfully by today's norms, but the plants withered. This is because the norms were developed for natural-illumination greenhouses. Usually, the illumination is measured in lux or μmol/day. The first unit is weighted by wavelength according to the people's eyes sensitivity. The second one accumulates all photons. But the plants have another photosynthetic activity curve. They use two photosynthetic substances – chlorophyll and beta-carotenoid (active on the green light). The chlorophyll changes its absorption curves dependent on solvent presence (a and b). This allows some variability for adapting to the light spectrum, which is used by water plants. Thus, both units do not apply to artificial illumination. In this work, we analyse the curves of solar and phytolamp spectrums, averaged sensibility and spectral luminous efficiency for photopic vision. Integration of the curves allows recalculation of the lux-meter reading to the equivalent solar illumination or the last one to the phytolamp power. We propose a new unit system – phytocandela-phytolumen-phytolux – according to the photosynthesis efficiency curve that is numerically equal to candela-lumen-lux under sunlight. This shows that lux may not be a base unit because it is related to a single biological species but not a physical property.

Keywords: greenhouse; illumination; phytolamp; lux; photosynthesis.

Introduction

Today greenhouses are transformed. In the middle of the past century, they were almost glazing buildings above the ground. Due to the development of planting technologies, including grows on artificial substratum [1] in mats or trays [2], aero – [3] and hydroponics [4], etc., greenhouses now can be anywhere, including underground. This gives impetus for urban agriculture [5] with optimal logistics (growing near consuming). Indoor green structures and indoor greening become more popular [6,7]. The illumination is very important as plants lose decorative properties in unfavourite conditions. Outdoor green structures are promising places for urban agriculture with different benefits for buildings [8-12]. Nevertheless, they are dependent on seasons, but indoor agriculture gives harvest year-round. The authors perform systematic laboratory tests and theoretical investigations [12] with outdoor and indoor green structures using wind tunnels and special mathematical approaches [13]. The research gives a possibility to calculate the energy and indoor air quality benefits for a building by using outdoor green structures and other-purpose premises for agriculture.

At the beginning of this century, the authors' analyses of a lot of failed attempts to create winter gardens on underground floors were performed. The illumination was calculated successfully by today's norms, but the plants withered. This is because the norms were developed for natural-illumination greenhouses, but fluorescent lamps with different spectra were used. Now, LED phytolamps are more effective due to the optimised spectrum. They are different – red and blue or full-spectrum. Usually, the illumination is measured in lux [14] or $\mu mol \cdot m^{-2} s^{-1}$ [15]. The first unit is weighted by wavelength according to the people's eyes sensitivity. The second one accumulates all photons. But the plants have another photosynthetic activity curve. They use at least two photosynthetic substances – chlorophyll (a or b dependent on solvents) and beta-carotenoid (active on the green light) [16]. This allows some variability for adapting to the light spectrum, which is used by alga. Thus, both units are not applicable to artificial illumination. We should propose a new photometric unit for plants. As there are no special measuring devices, we should measure this value by a commonly used and cheap lux-meter or pyranometer with additional recalculations.

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Materials and methods

We should analyse the curves of solar and phytolamp spectrums, photosynthetic action spectrum and spectral luminous efficiency for photopic vision (Fig. 1).

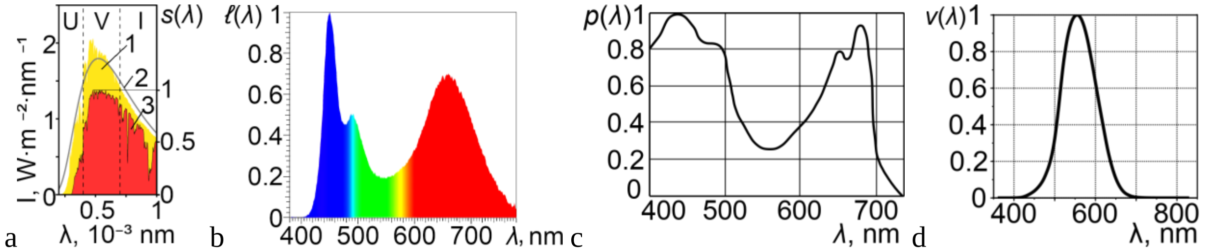

Fig. 1. **Spectrums:** a – fragment of solar radiation spectrum $s(\lambda)$ [17]; b – phytolamps spectrum $\ell(\lambda)$ based on LED 2835 growing [18]; c – photosynthetic action spectrum $p(\lambda)$ [19]; d – spectral luminous efficiency for photopic vision $V(\lambda)$ by the tabular data in [20]: 1 – above the atmosphere; 2 – 5778 K blackbody; 3 – at the sea level; U – ultraviolet; V – visible; I – infrared

LEDs (or other light sources) have a specific spectral radiation density of $0 \le \ell(\lambda) \le 1$. Spectral density of irradiance of a surface, W·m^{-2}, if the maximum of it is $E_{e,\lambda}(\lambda_{m,\ell})$, W·m^{-2},

$$E_{e,\lambda}(\lambda) = E_{e,\lambda}(\lambda_{m,\ell})\cdot\ell(\lambda). \tag{1}$$

Using spectral luminous efficiency for photopic vision $0 \le V(\lambda) \le 1$ and a conversion factor K_m, lm·W^{-1}, the illuminance, lux, can be found by integration from minimum λ_{min}, nm, to maximum λ_{max}, nm, wavelength of the photosynthetic action spectrum, as (Fig. 1 c,d) outside the range $V(\lambda) \approx 0$ taking into account equation (**Error! Reference source not found.**):

$$X = K_m\cdot \int E_{e,\lambda}(\lambda)\cdot V(\lambda)\cdot d\lambda = K_m\cdot E_{e,\lambda}(\lambda_{m,l})\cdot \int l(\lambda)\cdot V(\lambda)\cdot d\lambda. \tag{2}$$

The illuminance, lux, for solar radiation with specific spectral radiation density $0 \le s(\lambda) \le 1$, the irradiance of the surface $E_{e,\lambda,s}(\lambda)$, W·m^{-2} and the maximum of it $E_{e,\lambda,s}(\lambda_{m,s})$W·m^{-2}

$$X_s = K_m\cdot E_{e,\lambda,s}(\lambda_{m,s}) \int s(\lambda)\cdot V(\lambda)\cdot d\lambda. \tag{3}$$

Let us introduce a new reduced photometric value system – phytocandela-phytolumen-phytolux – according to the photosynthesis efficiency curve, which is numerically equal to candela-lumen-lux under sunlight. This will leave the old recommendations intact. Using the conversion factor K_{ph}, phlm·W^{-1}, we have illuminance, phlux

$$X_{ph} = K_{ph}\cdot E_{e,\lambda,s}(\lambda_{m,s}) \int s(\lambda)\cdot p(\lambda)\cdot d\lambda. \tag{4}$$

By the definition, $X_s = X_{ph}$ at the same $E_{e,\lambda,s}(\lambda_{m,s})$, so by equations (5) and (6), phlm·W^{-1},

$$K_{ph} = K_m\cdot \int s(\lambda)\cdot V(\lambda)\cdot d\lambda / \int s(\lambda)\cdot p(\lambda)\cdot d\lambda. \tag{5}$$

If we create a phytolux-meter with the sensitivity curve as $p(\lambda)$ and the conversion factor K_{ph} we will obtain analogically to expression (4), W·sr^{-1}·m^{-2}

$$X_{ph} = K_{ph}\cdot E_{e,\lambda}(\lambda_{m,l})\cdot \int l(\lambda)\cdot p(\lambda)\cdot d\lambda. \tag{6}$$

And finally, we can use the equation system (4) and (9) to convert lux to phytolux

$$X_{ph} = \kappa\cdot X, \tag{7}$$

where κ – converting factor specific for a light source, phlux·lux^{-1}:

$$\kappa = X_{ph}/X = K_{ph}\cdot \int l(\lambda)\cdot p(\lambda)\cdot d\lambda/(K_m\cdot \int l(\lambda)\cdot V(\lambda)\cdot d\lambda) =$$

$$= (\int s(\lambda)\cdot V(\lambda)\cdot d\lambda\cdot \int l(\lambda)\cdot p(\lambda)\cdot d\lambda)/(\int l(\lambda)\cdot V(\lambda)\cdot d\lambda\cdot \int s(\lambda)\cdot p(\lambda)\cdot d\lambda). \tag{8}$$

Integration of the curves in equations (2-8) can be done numerically in two ways. The first is tabulating of the graphical data in Fig. 1 with a very fine step and numerical integration of the tabular data. This way is very time-consuming. A more effective approach is vectorising Fig. 1 a-c. SVG graphics are used, which contain a plain text description of each line. It can be done by open-source software (in this work – Inkscape). The file has a “path” command for Bezier [21] splines using linear $B(t) = (1-t)\cdot P_0 + t\cdot P_3$, square $B(t) = (1-t)^2\cdot P_0 + 2\cdot(1-t)\cdot t\cdot P + t\cdot P_3$, and cubic segments

$$B(t) = (1-t)^3 \cdot P_0 + 3 \cdot (1-t)^2 \cdot t \cdot P_1 + 3 \cdot (1-t) \cdot t^2 \cdot P_2 + t^3 \cdot P_3, \quad (9)$$

where P_0 – starting point;
P_3 – endpoint;
P_1, P_2, and P – control points; operations on points P_i mean the same operations on each coordinate x_i and y_i. m.

We should parse the “d” parameter of the “path” commands. After that, we need to integrate products of functions. To avoid the realisation of all type combinations, we can convert all segments to cubic. It is very simple by expanding the corresponding equations into the monomial form and equating the coefficients at the same power at the parameter t. To convert a linear segment between points P_0 and P_3 to cubic, we need two control points $P_1 = (P_3 + 2 \cdot P_0)/3$ and $P_2 = (2 \cdot P_3 + P_0)/3$. For a quadratic segment between points P_0 and P_3 with a control point P to cubic, we should cancel point P adding two control points $P_1 = (P_0 + 2 \cdot P)/3$ and $P_2 = (P_3 + 2 \cdot P)/3$.

The most problematic tasks are taking y by x and integrating a product of curves. The first task requires the solution of the cubic equation (**Error! Reference source not found.**) in non-trivial cases u sing Viète’s trigonometric formula [22] and Holmes’s hyperbolic formulas [23] avoiding complex numbers. Integration of products is not trivial. A relation between parameters is required – a cubic equation, produced by equating the equations of $x(t)$. Numerical integration is used instead. The integrand is the product of the results of De Casteljau’s [24] algorithm, applied to the solution of the cubic equation (**Error! Reference source not found.**) replacing $B(t)$ by x and P_i by x_i. For the m ultiplication of Bezier curves, both are split to achieve corresponding nodes using De Casteljau’s [24] algorithm.

Fig 1 d is built using the tabular data. It is not effective to approximate it by Bezier curves. In this work, a Hermit cubic spline is used by SciLab’s “splin” function. Not-a-knot conditions give higher approximation precision order if no additional artefacts (extremums, kinks) appear in some particular cases. To test this, the spline has been built using 100 points between the tabular ones (Fig 1 d). As no additional artefacts were found, the spline is accepted.

The software has been written in SciLab to parse Bezier-vectorized graphs in SVG format and integrate products of two Bezier curves or such curve and Hermit-spline-approximated tabular data. At first, the program parses the curve description in SVG and converts all non-cubic Bezier segments to cubic ones. The second stage is splitting both curves-multipliers to achieve the same ranges of segments by x. Because of the high plication of the curves in Fig. 1 a, b, the number of segments reaches hundreds. De Casteljau’s [24] algorithm warrants preserving the curves. The third stage is the numerical integration using the “intg” function with the absolute/relative tolerance of $10^{-13}/10^{-8}$. For this, the integrand is coded as a function that takes any x-value, solves non-trivial or trivial cases of a cubic equation (9) with auto-selection of the corresponding formula (Viète’s, Holmes’s, quadratic, or linear equation solution) to find the parameter t, and calculates the corresponding y-value by equation (9) for the first curve. If the second curve is Bezier one, it repeats the steps above for the same x-value. If it is a Hermit spline, it uses “interp” to take the second multiplier. And finally, the function returns the product of both values of curves to the integration function.

Results and Discussion

The integration using the software gives the values of the integrals: in formula (2) – 32.31374; in equation (3) – 103.0464; in expression (4) – 173.1475; in formulae (6) – 91.47271.

At $K_m = 683.002\ \mathrm{lm \cdot W^{-1}}$ [20], by equations (5) and (8) $K_{ph} = 406.480\ \mathrm{phlm \cdot W^{-1}}$ and $\kappa = 1.68469\ \mathrm{phlux \cdot lux^{-1}}$, which fully defines phytocandela, phytolumen and phytolux allowing measurements by the cheapest and the most available devices – lux-meters. For rough measurements in solar energetics, which is a promising technology in Ukraine and the world [25-35], we can use the same approach applying the corresponding spectrums in full ranges. Also, we can see that candela cannot be a universal physical value. It is a more physiological one related to single biological species. Thus, it cannot be a base unit. If not, dB(A) is also a base unit as it has similar properties but for sound – dependent on the spectrum of perception and cannot be converted from other values directly.

Conclusions

Known units used for plant illuminance are not fully complying with the plant physiology for modern artificial illumination with special spectrums. We propose using a new unit system – phytocandela-phytolumen-phytolux – according to the photosynthesis efficiency curve that is numerically equal to candela-lumen-lux under sunlight. It is an appropriate unit system for the illuminance of plants that allows keeping old recommendations for growing under sunlight. Integration of spectrums allows measuring illumination by the cheap and most available devices – lux-meters. We see that a candela is a unit belonging to single biological species and not a universal physical unit. Thus, it could not be a base unit.

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Author contributions

Conceptualization, T.T.; methodology, T.T., V.M., A.M., I.P and V.K.; software, V.M.; validation, A.M., I.P and A.U.; formal analysis, V.M and V.K..; investigation, I.P., V.K. and A.U.; data curation, V.M. and A.U.; writing – original draft preparation, V.M.; writing – review and editing, T.T., A.M., I.P, V.K. and A.U.; project administration, T.T.; funding acquisition, T.T. All authors have read and agreed to the published version of the manuscript.

References

[1] Tuckeldoe R. B., Maluleke M. K., Adriaanse P. The effect of coconut coir substrate on the yield and nutritional quality of sweet peppers (Capsicum annuum) varieties. Scientific Reports, vol. 13, 2023, article no 2742

[2] Wei H., Liu C., Jeong B. R. An Optimal Combination of the Propagation Medium and Fogging Duration Enhances the Survival, Rooting and Early Growth of Strawberry Daughter Plants. Agronomy, vol. 10, 2020, article no 557

[3] Grzelka K., Matkowski A., Ślusarczyk S. Electrostimulation improves plant growth and modulates the flavonoid profile in aeroponic culture of Scutellaria baicalensis Georgi. Frontiers in Plant Science, vol. 14, 2023, article no 1142624

[4] Nanda M. A., Dwiratna S., Amaru K. Hydroponic cultivation training and its product processing for sustainable ecosystems in Lebakgede Area, Bandung City. Abdimas: jurnal pengabdian masyarakat universitas merdeka malang, vol. 8, p. 103-112

[5] Haitsma Mulier M.C.G. van de Ven F.H.M, Kirshen P. Circularity in the Urban Water – Energy – Nutrients – Food nexus. Energy Nexus, vol. 7, 2022, article no 100081.

[6] Tkachenko T., Mileikovskyi V. Solution of sick building syndrome problem using indoor plants. Procedia Environmental Science, Engineering and Management, vol. 6, p. 405-411

[7] Tkachenko T., Mileikovskyi V., Dziubenko V., Tkachenko, O. Improvement of the safety of multi – floor housing. Innovative Technology in Architecture and Design (ITAD 2020), May 21 – 22, 2020, Kharkiv, Ukraine. IOP Conference Series: Materials Science and Engineering, vol. 907, 2020, article no 012064

[8] Gioannini R., Al – Ajlouni M., Kile R., VanLeeuwen D., St. Hilaire R. Plant Communities Suitable for Green Roofs in Arid Regions. Sustainability, vol. 10, 2018, article no 1755

[9] Tkachenko T., Mileikovskyi V. Capturing Carbon Dioxide from Human-Driven Vehicles by Green Structures for Carbon Neutrality. 3rd International Symposium of Earth, Energy, Environmental Science, and Sustainable Development, August 27 – 18, 2022, Jakarta, Indonesia. IOP Conference Series: Earth and Environmental Science, vol. 1111, 2022, article no 012056

[10] Tkachenko T., Mileikovskyi V. Assessment of Light Transmission for Comfort and Energy Efficient Insolation by “Green Structures”. 19th International Conference on Geometry and Graphics ICGG 2020, January 18 – 22, 2021, São Paulo, Brazil. Advances in Intelligent Systems and Computing, vol. 1296, 2021, pp. 139-151

[11] Tkachenko T., Mileikovskyi V. Geometric basis of the use of “green constructions” for sun protection of glazing. 18th International Conference on Geometry and Graphics ICGG 2018,

August 3 – 7, 2018, Milan. Advances in Intelligent Systems and Computing, vol. 809, 2019, Pages 1096-1107

[12] Tkachenko T. “Energy Efficiency of “Green Structures” in Cooling Period.” International Journal of Engineering & Technology, Vol. 7, 2018, pp. 453-457.

[13] Mileikovskyi, V., Tkachenko, T. Using Telescopic Mapping for Infinity Representation with an Example of Ventilation. Proceedings of the 20th International Conference on Geometry and Graphics ICGG 2022, August 15–19, 2022, São Paulo, Brazil. Lecture Notes on Data Engineering and Communications Technologies, vol. 146, 2023, pp. 394-405.

[14] Bhat S. A., Huang N. – F., Hussain I., Bibi F., Sajjad U., Sultan M., Alsubaie A. S., Mahmoud K. H. On the Classification of a Greenhouse Environment for a Rose Crop Based on AI-Based Surrogate Models. Sustainability, vol. 13, 2021, article no 12166

[15] W Bhuiyan R., van Iersel M. W. Only Extreme Fluctuations in Light Levels Reduce Lettuce Growth Under Sole Source Lighting. Frontiers in Plant Science, vol. 12, 2021, article no 619973

[16] Guidi L., Tattini M. Landi M. How Does Chloroplast Protect Chlorophyll Against Excessive Light? In: Jacob – Lopes E., Zepka L. Q., Queiroz M. I. (Eds). Chlorophyll, 2017, Rijeka, Intech, pp. 21-36

[17] Torres C. C., Fortes R., Prieto M. H. Solar Radiation Effect on Crop Production. In: Babatunde E. B. (ed.) Solar Radiation, 2012, Rijeka, Intech, pp. 167-194

[18] ZVISION: LED Photometric Colorimetric and Electric test report: Growing Phase [online] [06.09.2020]. Available at: https://ae01.alicdn.com/kf/H7981e949698442c0ad09101f024a70b6l.png

[19] Whitmarsht J., Govindjee. The Photosynthetic Process. In: Singhal G. S., Renger G., Sopory S. K., Irrgang K – D., Govindjee (Eds.). Concepts in Photobiology: Photosynthesis and Photomorphogenesis. Dordrecht: Springer – Science + Business Media, B. V., 1999. pp. 11-51.

[20] Ohno Y., Goodman T., Blattner P., Schanda J, Shitomi H., Sperling A, Zwinkels J. Principles governing photometry (2nd edition). Metrologia, vol. 57, article no 020401.

[21] Ismail N. H. M., Misro M. Y. An improved image encryption algorithm based on Bézier coefficients matrix. Journal of King Saud University – Computer and Information Sciences, vol. 34, 2022, pp. 10056-10067.

[22] Zucker I. J. The cubic equation – a new look at the irreducible case. Mathematical Gazette, no. 92, 2008. 264-268

[23] Holmes G. C. The use of hyperbolic cosines in solving cubic polynomials. Mathematical Gazette, No 86, 2002, pp. 473-477.

[24] Gracia J. D. Compensated Evaluation of Tensor Product Surfaces in CAGD. Mathematics, vol. 8, 2020, article no 2219

[25] Jurczak M.A., Skotnicka-Siepsiak A., Comparing the efficiency of evacuated tube and flat-plate solar collectors in real installation conditions. Construction of Optimized Energy Potential, vol. 9, 2020, pp. 31-38

[26] Shapoval S., Spodyniuk N., Datsko O., Shapoval P. Research of efficiency of solar coating in the heat supply system. Pollack Periodica, vol. 17, 2022, pp. 128-132.

[27] Sobol Ł., Dyjakon A., Supplying low energy consuming catering trailers with solar energy. Construction of Optimized Energy Potential, vol. 10, 2021, pp. 19-26

[28] Shapoval S., Spodyniuk N., Zhelykh V., Shepitchak V., Shapoval P. Application of rooftop solar panels with coolant natural circulation. Pollack Periodica, vol. 16, 2021, pp. 132-137

[29] Shapoval S., Venhryn I., Kozak K., Klymenko H. Clarification of Thermal Characteristics of the Solar Collector Integrated into Transparent Facade. 2nd International Scientific Conference on EcoComfort and Current Issues of Civil Engineering EcoComfort 2020, September 16-18, 2020, Lviv, Ukraine. Lecture Notes in Civil Engineering, vol. 100, 2021, pp. 402-408

[30] Stanka N., Aboltins A., The efficiency of grid-tied PV systems on small farms in Latvia. Construction of Optimized Energy Potential, vol. 10, 2021, pp. 111-118

[31] Shapoval, S., Zhelykh, V., Venhryn, I., Kozak, K., Krygul, R. Theoretical and experimental analysis of solar enclosure as part of energy-efficient house. Eastern-European Journal of Enterprise Technologies, vol. 2, 2019, pp. 38-45

[32] Savhenko O., Lis A. Efficiency of solar energy use in domestic hot water systems in Poland. Construction of Optimized Energy Potential, vol. 10, 2021, p. 42-52

[33] Zhelykh V., Shepitchak V., Innovative technological solutions for heat supply in recreational complexes of the Lviv Polytechnic educational institution. Construction of Optimized Energy Potential, vol. 10, 2021, pp. 113-118.
[34] Shapoval S. Comparison of the results of researching the gelioroof in field and laboratory conditions. Eastern-European Journal of Enterprise Technologies, vol. 2, 2015, pp. 41-46.
[35] Walichnowska P., Mroziński A., Idzikowski A., Fröhlich S. R., Energy efficiency analysis of 1 MW PV farm mounted on fixed and tracking system. Construction of Optimized Energy Potential, vol. 10, 2022, pp. 75-83.