MAU J AGR NAT (2022) 2(2): 92-100
DOI: -
e-ISSN: 2822-3500

dergipark.org.tr/en/pub/maujan
maujan@alparslan.edu.tr
maujan.alparslan.edu.tr

MUŞ ALPARSLAN ÜNİVERSİTESİ
TARIM VE DOĞA DERGİSİ

MUŞ ALPARSLAN UNIVERSITY
JOURNAL OF AGRICULTURE AND NATURE

The effect of solar radiation on the growth and development of hydroponically grown lettuce in two areas with different climates

Jonathan Kummer[1]✉ • Demet Çekin[1]✉ • Hani Sewilam[1]

[1] RWTH Aachen University, Academic and Research Department Engineering Hydrology 52074, Aachen, GERMANY

✉ Corresponding Author: cekin@lfi.rwth-aachen.de

Please cite this paper as follows:
Kummer, J., Çekin, D., & Sewilam, H. (2022). The effect of solar radiation on the growth and development of hydroponically grown lettuce in two areas with different climates. *Muş Alparslan University Journal of Agriculture and Nature*, 2(2), 92-100.

Research Article

Article History
Received: 05.09.2022
Accepted: 19.09.2022
Published online: 21.09.2022

Keywords:
Solar radiation
Photoperiod
Hydroponic, lettuce
Daily light integral
Photosynthetic active radiation

A B S T R A C T

Leafy vegetable production in hydroponic systems under a controlled environment by regulating lighting has many advantages. Nonetheless, the high initial start-up and operation costs are limiting factors. In order to design an optimal lighting environment for plant growth, quality and quantity of the provided light energy must match each crop's demand. For lettuce, this demand is established as a daily light integral (DLI) of 17 mol/m²/day within the photosynthetic active radiation (PAR) spectra. Sunshine data from the two considered locations Aachen and Cairo have been collected and edited. With these data, the available PAR-fraction was calculated with the Angstrom-Prescott equation and compared to the plants demand. The available sunlight energy exceeds the crops demand all year round in Cairo (maximum in June, five times higher than demand) and in the summer months in Aachen. In the winter months in Aachen the sunlight energy is lacking (only 14% of the required DLI in December). The results reveal that light intensity and duration of light (photoperiod) should be controlled for an optimal balance between artificial light and shading nets, which promotes lettuce growth and enhances hydroponic cultivation in semi-controlled environments. Moreover, results of this study may contribute to estimate the amount of energy use for CapEx (capital expenditures) and OpEx (operating expenses) in environmental closed agricultural settings.

1. INTRODUCTION

The size of the increasing global population is estimated to reach 9.7 billion people by 2050 according to the report of the United Nations (United Nations Department of Economic and Social Affairs, 2022). The rapid increase of the world's population also raises global food consumption and necessitates agricultural and expansion of global food supply (Searchinger, 2019). Although the technology for increasing food production has remarkably progressed, the crop production volume per land area has steadily decreased (Javadinejad et al., 2020). The arable lands are decreasing due to natural disasters and global warming which causes an increase in the rate of dry land (Dai et al., 2018). Additionally, rapid urbanisation leads to losses in arable lands, and agricultural productivity in urban and peri-urban areas (Barthel et al., 2019). Furthermore, climate change causes droughts by shrinking surface and groundwater resources.

As agricultural production is highly dependent on water, it is increasingly subject to water scarcity risk (Mahato, 2014; Leng et al., 2015; Hamed et al., 2018).

A hydroponic growing system is a cultivation method in which plant roots are surrounded by nutrition solution without using any soil and instead mediums such as vermiculite or rockwool to provide mechanical support (Sharma et al., 2018). This soilless technique allows more efficient use of natural resources such as water and land (Chen et al., 2020). Moreover, hydroponics have potential benefits such as shorter cropping periods and a higher yield per land compared to conventional agriculture, even though they consume a certain amount of energy, need know-how and high investment (Aires, 2018). Another possible advantage of hydroponic cultivation is that these systems allow the growth of crops at any time of the year. Moreover, indoor soilless farming systems enable agricultural production in urban areas (Kozai, 2016). Nonetheless, the light energy demand of the plants is an important limiting factor for all-season and urban cultivation (Albright et al., 2000).

Lettuce (*Lactuca sativa* L.) is one of the leafy vegetables that can be successfully and easily grown in a hydroponic system in greenhouses (Sharma, 2018). Climatic conditions, especially temperature and light intensity, affect growth and yield of plants in closed systems. Moreover, the light intensity has an effect on the nutrient component and antioxidant contents of plants. Lettuce is also known to have a high content of antioxidant compounds, primarily vitamin C and polyphenols, as well as fibre (Kang et al., 2013; Sharma et al., 2018; Materska et al., 2019; Song et al., 2020). Light quality, light intensity, and photoperiod are three significant elements consisting of the light conditions for plant growth, development, and nutritional quality. Morover, light quality influences the root organic carbon and autotoxin secretions. Previous studies have shown that increased light intensity usually promoted lettuce growth, above-ground biomass, and the activity of antioxidative enzymes (Fu et al., 2012; Kang et al., 2013; Viršilė et al., 2019, Zhou et al., 2020). To achieve good plant growth through photosynthesis every crop needs a certain amount of light energy which is to be measured in photosynthetic photon flux density (PPFD, $\mu mol/m^2/s$) and summed up to a daily light integral (DLI, $mol/m^2/d$) (Ge et al., 2011). Only a part of the solar spectrum can be absorbed by plants, which is called photosynthetic active radiation (PAR) and ranges between 400 nm and 700 nm (Feng et al., 2018). In regions where solar radiation is not sufficient, all-year-round supplemental light could provide the absent PPFD. For areas with excessive solar radiation, shading materials or devices are necessary to protect the crops from diseases and disorders. (Namgyel et al., 2018).

The different morphogenetic and photosynthetic responses of each plant to different DLIs vary for the plant species. Many studies have demonstrated that the optimal light requirement is 17 $mol/m^2/d$ for lettuce growth. The supplemental lighting and moveable shade can be used to provide a target amount of light requirement (Kang et al., 2013; Mattson, 2015; Chinchilla et al., 2018). Another affecting factor of lettuce growth in a controlled system is the photoperiod, which affects vegetative and reproductive growth, and the level of secondary metabolites (Kang et al., 2013). Therefore, this total amount of 17 mol/m^2 per day is recommended as a balanced light energy supply in a photoperiod of 16:8 h (light:dark).Therefore, supplemental light can be provided before sunrise and after sunset if necessary (Shimizu et al., 2011; Zhang et al., 2018).

LED-lamps became the common supplemental light source in horticulture in the last decade (Gómez and Mitchell, 2015). LED-lamps consist of semiconductor diode chips that emit light energy following the principle of electroluminescence. Compared to other light sources LED-lamps are advantageous due to their small energy demand and their long lifetime. Moreover, the light spectrum of LED-lamps can be adjusted suitably to the characteristics of the crop and provide light energy with matching wavelengths (Nhut et al., 2017). If the supply of sunlight energy exceeds the crops' demand the plants could be protected through the installation of shading nets. Shading nets are available with different shading factors which reflect and absorb different shares of PAR (Stagnari et al., 2015).

In this study, the two locations, that are, Aachen in Germany and Cairo in Egypt, are examined on their light balance for lettuce growth in environmentally controlled greenhouse conditions. The PAR-fraction of the solar radiation is calculated by sunshine data from 2019 and 2020 through the Angstrom-Prescott equation and then compared to the crop's requirement. This study aims at providing the daily light requirements of lettuce, comparing them with the available sunlight energy thereby contributing to optimising hydroponic systems and maximising the economic benefit of obtaining high quality and quantity of lettuce growth in a semi-controlled system.

2. MATERIAL AND METHODS

Study Location and Data Collection

In this study, calculations were performed based on meteorological data in Aachen and Cairo. Aachen is located in western Germany (50.775 latitude, 6.084 longitude, 173 m asl) and is exemplary for the middle European temperate climate. Egypt's capital Cairo is located in the northeast of Africa (30.056 latitude, 31.239 longitude, 23 m asl) and next to the Nile delta. Cairo is situated in the subtropical climate zone (Westermann, 2022).

Two main data series were required to calculate the photosynthetically active radiation (PAR): Sunshine duration (n, hours) and global solar radiation (H_0, kWh/m²). These parameters were provided by the German weather service (CDC, 2022). The following settings were used for the sunshine duration: Station data, radiation and sunshine duration, sunshine duration, and monthly mean. The global radiation values H0 were found by the following settings: Grid data, satellite and station data, radiation and sunshine duration, global radiation, and monthly sum (CDC, 2022).

The solar radiation data for Cairo used in this study was collected in a weather station from the American University of Cairo. The sunshine duration shown in Table 1 is the average sunshine duration between 1999 and 2019. It is calculated through measured cloud covering data by Climate-Data.org (Climate Data, 2019).

Table 1. The Data used in calculations for photosynthetically active radiation

Months	Aachen 2019		Aachen 2020		Cairo 2019		Cairo 2020	
	H_0	n	H_0	n	H_0	n	H_0	n
Jan	20	1.55	23	1.92	102	7.9	97	7.9
Feb	53	4.74	34	1.84	110	8.8	108	8.8
Mar	69	3.19	90	5.51	159	10	161	10
Apr	129	6.79	153	9.55	191	11.1	198	11.1
May	139	5.44	185	9.66	231	11.9	235	11.9
Jun	188	9.45	162	7.15	227	12.1	244	12.1
Jul	162	7.34	155	6.53	232	11.6	244	11.6
Aug	144	7.50	140	6.66	213	10.9	228	10.9
Sep	97	5.24	102	6.66	X	10.3	163	10.3
Oct	47	2.67	42	1.71	X	9.6	151	9.6
Nov	27	2.29	35	3.90	118	8.6	105	8.6
Dec	17	1.87	15	1.41	102	7.9	96	7.9

Note: H_0: the global solar radiation value in kWh/m², n: sunshine duration in hour

Angstrom – Prescott Model

In this study, the PAR fraction of sunlight was calculated using the linear Angstrom-Prescott equation (compare equation 1). This empirical formula establishes a relationship between global solar radiation, sunshine duration, and PAR fraction using the two Angstrom coefficients a and b as well as geographic characteristics (Udo and Aro, 2000; Khalil and Shaffie, 2016).

$$\frac{H_{par}}{H_0} = a + b * \frac{n}{N_0} \quad (1)$$

The two empirical Angstrom coefficients a and b are calculated by regression analysis using PAR measurements and can be expressed as either monthly or annual averages. For both Aachen and Cairo these coefficients are not available due to a lack of data. As Aachen is located in the centre of Europe, the available Angstrom coefficients for the European average (shown in Table 2) were used in this study (Paulescu et al., 2015).

Angstrom coefficients from Tripolis, Libya's capital, were used for the calculation of the PAR fraction of Cairo, since Tripolis has a very similar climate to Cairo. Only annual values are available. Due to the subtropical, cloudless climate, this simplification is acceptable. The Angstrom coefficients a = 0.215 and b = 0.53 were used for Cairo (Paulescu et al., 2015).

Besides these Angstrom coefficients, the geographical location was involved in the Angstrom-Prescott formula in terms of the maximum day length N0 which was calculated through equation 2 considering geographical latitude and solar declination.

$$N_0 = \frac{2}{15} * cos^{-1}(-tan\emptyset * tan\delta) \quad (2)$$

The solar declination δ was evaluated through equation 3 according to Spencer (Spencer, 1971) using the day angle calculated through equation 4 (Udo and Aro, 2000).

$$\delta = (0{,}006918 - 0.399912cos\varphi + 0.070257sin\varphi - 0.006758cos2\varphi + 0.000907sin2\varphi - 0.002697cos3\varphi + 0.00148sin3\varphi) * \left(\frac{180}{\pi}\right) \quad (3)$$

The day angle φ is calculated for the 15. day of every month assuming an average value.

$$\varphi = 2 * \pi * (d_n - 1) * \frac{1}{365} \quad (4)$$

Table 2. Monthly Angstrom coefficients from European average (Paulescu et al., 2015)

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
a	0.18	0.2	0.22	0.2	0.24	0.24	0.23	0.22	0.2	0.19	0.17	0.18
b	0.66	0.6	0.58	0.62	0.52	0.53	0.53	0.55	0.59	0.6	0.66	0.65

Table 3. Geographical and sun parameters

Months	d_n	φ in rad	δ in °	N_0 in h in Aachen	N_0 in h in Kairo
Jan	15	0.24	-21.28	8.2	10.26
Feb	46	0.77	-13.05	9.8	10.97
Mar	74	1.26	-2.59	11.58	11.8
Apr	105	1.79	9.48	13.57	12.74
May	135	2.31	18.73	15.27	13.51
Jun	166	2.84	23.3	16.25	13.92
Jul	196	3.36	21.65	15.88	13.77
Aug	227	3.89	14.32	14.43	13.13
Sep	258	4.42	3.44	12.56	12.27
Oct	288	4.94	-8.21	10.64	11.36
Nov	319	5.47	-18.25	8.82	10.53
Dec	349	5.99	-23.23	7.77	10.08

Note: d_n: The day number of the year.,φ: the day angle which is calculated for the 15. day of every month assuming an average value, δ °: solar declination in rad, N_0: maximum day length in h

Solar declination and day angle were calculated using equation 2 and equation 3 and are presented in Table 3.

By using these solar declination values and the geographical latitude the maximum day length N_0 can be determined using equation 2 (see Table 3). Since all variables are determined, the PAR fraction H_{par} of the global radiation H_0 can be calculated in dependence on the sunshine duration. The global radiation and PAR fraction were measured in kWh/m². However, the demand of crops is often indicated as mol/m²/dor µmol/m²/s. Therefore, the PAR fraction was converted with the McCree-factor 4.57 µmol/J and the translation of kWh in MJ with 3600 s/h (McCree, 1972).

Hydroponic growing beds

Plants inside greenhouses are protected from unstable weather conditions, which could limit plant growth. In this study, a hydroponically grown lettuce cultivation in an environmentally semi-controlled greenhouse with partially transparent cover is presumed. How light balance tools such as supplemental lighting or shading nets contribute to optimal growing conditions and a balanced light energy supply is conducted in this study (Brechner and Both, 2013; Aires, 2018). In addition to these light balance tools, the greenhouse cover itself influences the light balance. A fraction of the solar radiation, depending on the cover material, is reflected, and cannot be used by the crops. For this study, transmission of 85% is presumed, which is a typical proportion for common polyethylene cover (Baeza et al., 2018; Sahdev et al., 2019).

To maintain the target DLI of 17 mol/m²/d, additional light balance tools can be introduced. If the supply of sunlight energy is deficient, supplemental light sources can be installed above the crops to provide additional light energy (Figure 1). We simulated the supplementary lighting using LED lamps in our study, since these lamps have become most preffered horticulture lighting in the last decade (Gómez and Mitchell, 2015; Nhut et al., 2017).

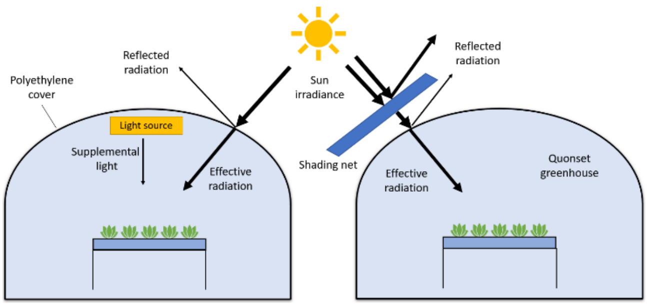

Figure 1. Lighting balance using tools supplemental light and shading net in greenhouse in two different season (left: winter, right: summer)

If the supply of sunlight energy exceeds the crops' demand the plants should be somehow protected from the excessive light energy to prevent pests like tip burn (Mattson, 2015). An affordable and feasible solution for reducing solar radiation is the installation of shading nets. These shading nets are available with different shading factors, which provide information about the share of sunlight that can be absorbed or reflected. Shading nets with shading factors between 20% and 80% are common (Abdel-Ghany et al., 2019).

3. RESULTS

The Angstrom-Prescott equation is used to calculate the PAR-fraction (DLI) of global solar radiation, which is summarized in Table 4. The finding reveals that the DLI in Aachen is significantly lower than in Cairo. The proportional difference is greatest in December and January, with a ratio of about one to ten, and smallest in June and July, with a ratio of one to two, respectively. Furthermore, the DLI in Cairo exceeds the DLI required by lettuce every month, with the maximum DLI being five times higher than the required DLI in the summer months of June and July.

Table 4. Daily light integrals for Aachen and Cairo in 2019, 2020, and available average

Months	Aachen 2019	Aachen 2020	Available DLI	Difference	Cairo 2019	Cairo 2020	Available DLI	Difference
Jan	3,23	4,08	3,11	13,89	33,73	32,08	27,97	10,97
Feb	15,27	5,02	8,62	-8,38	41,38	40,62	34,85	17,85
Mar	13,91	23,69	15,98	-1,02	56,04	56,75	47,94	30,94
Apr	36,1	53,39	38,03	21,03	70,89	73,49	61,36	44,36
May	31,37	55,86	37,07	20,07	83,59	85,04	71,67	54,67
Jun	56,52	42,04	41,89	24,89	84,12	90,42	74,18	57,18
Jul	40,84	36,85	33,02	16,02	81,44	85,66	71,02	54,02
Aug	38,66	35,21	31,4	14,4	74,04	79,25	65,15	48,15
Sep	23,73	28,69	22,28	5,28	0	58,99	58,99	41,99
Oct	8,49	6,38	6,32	-10,68	0	53,12	53,12	36,12
Nov	5,05	8,86	5,92	-11,08	41,92	37,30	33,67	16,67
Dec	3,04	2,37	2,3	-14,7	34,12	32,12	28,15	11,15

Note: The difference is calculated with the daily demand of lettuce. All elements are in mol/m²/d. (The values for Cairo in September 2019 and October 2019 are not available due to irregularities in the data documentation).

Table 5. Light balance tools overview for Aachen and Cairo

Months	Supplemental light duration	Power	Shading factors Aachen	Shading factors Cairo
Jan	13.4	166.1	0	39.22
Feb	8.08	100.1	0	51.22
Mar	0.98	12.1	0	64.54
Apr	0	0	55.3	72.29
May	0	0	54.1	76.28
Jun	0	0	59.4	77.08
Jul	0	0	48.5	76.06
Aug	0	0	45.8	73.91
Sep	0	0	23.7	71.18
Oct	10.3	127.7	0	68
Nov	10.69	132.5	0	49.51
Dec	14.18	175.8	0	39.61

Note: Supplemental light duration in hours per day, Power in kWh per lamp per month, and Shading factors in percent

Table 4 shows the differences between the calculated DLI and the optimal target DLI for lettuce growth. The available DLI is the arithmetic mean from the presented PAR-fraction of 2019 and 2020 including the transmission share of the greenhouses.

Between October and March, negative values in Aachen indicate a light energy deficit that could be addressed by installing supplemental lighting. For this study, the LED-lamp with a power requirement of 400 Watt is used for further calculations. Its constant PPFD of 288 µmol/m²/s and its light spectra with peaks in blue and red wavelengths is suitable for lettuce growth. According to the results, the months of April to September have positive values and thereby require light protection. The same applies to Cairo all-year-round. Especially noticeable is the great surplus in the summer months in Cairo. Light balance requirements are calculated with equation 5 and summarized in Table 5, which provides an overview of the needed duration time and energy requirements of supplemental light as well as the shading factors for Aachen and Cairo.

The amount of required electric power of one LED-lamp for the required duration in a certain month is shown in Table 5.

The configuration of LED-lamps in a particular greenhouse must be calculated individually. To give an order of magnitude of the area with sufficient light intensity of one LED-Lamp, we recommend that the lighting distance can be set 40 cm with a 40° angle light beam, based on the distance between the crop and the bottom of the LED bars. This setup results in a radiated area of 0.353 m². Through convenient alignment of multiple LED-lamps, this area can be increased through the overlapping of sections with lower intensities.

Table 5 points out the high energy demand of supplemental light for winter months in temperate regions with a continental climate like Aachen. Even though shading nets do not cause running costs and have low initial costs the different shading requirements between 39% in January and 77% in June require adjustment of shading devices throughout the year.

4. DISCUSSION

The amount of solar radiation and the subsequent PAR-fraction is calculated in monthly averages. This simplification provides no information about day-specific DLIs but allows an annual overview and helps to scale further applications. The monthly averages are compared to the light energy demand of lettuce (17 mol/m²/d) measured in controlled environments (Pinho et al., 2012; Zhang et al., 2018; Viršilė et al., 2019). Based on the difference, approximations of supplemental light demand and shading measures were determined. The calculated data indicates that there is a general oversupply of sunlight energy in Cairo and in Aachen during the summer months. Ilíc et al. (2017) showed that the reduction of solar radiation through shading nets helps to create optimal growing conditions. The study shows that a reduction from a peak point of 2020 μmol/m²/s in the open field to a peak point of 934 μmol/m²/s with shading nets significantly increases fresh weight and leaf number of lettuce as well as contents of phenol, flavonoid, and antioxidant properties. Statuto et al. (2020) has demonstrated that reducing the sun irradiance through shading nets benefits plant growth in arid regions. Besides the positive effect on the light balance, shading nets also reduce the temperature inside the greenhouse and especially on the leaf surface, which is also an advantage for plant growth (Michelon et al., 2020).

For the winter months in Aachen, a light energy deficit has been detected which could be balanced by introducing LED-lamps. That LED-lamps provide sufficient light spectra for plant growth and ensure high quality and quantity yield is proven not only for lettuce (Shimizu et al., 2011; Dzakovich et al., 2015). The main challenge in the present semi-controlled system is the unsteady solar irradiation. With the available data, the LED-lamp would radiate a certain time every day e.g. 13.4 hours in January. If the natural solar radiation on a certain day of a month is very different from the average DLI presented in table 4 two problems can occur. Firstly, if the solar irradiance exceeds the average DLI significantly, the crops are exposed to too much light energy and can be harmed (Mattson, 2015; Ahmed et al., 2020). Additionally, the overspent artificial light energy requires electricity, and thereby causes unnecessary costs. Secondly, if the solar irradiance undercuts the average significantly, plant growth is reduced (Viršilė et al., 2019).

Indicated artificial light and shading nets with shading factors ranging from 40% to 75% promote the plant growth and allow an advanced approach of hydroponic agriculture. For further development, the short-term day-by-day variations in solar radiation must be handled. Recent studies like Namgyel et al. (2018) and Jiang et al. (2020) showed that smart solutions with real-time solar irradiance measurement and adapted artificial light intensity could improve plant growth. Besides that, real-time data and weather forecasts could be implemented as well in those smart lighting control panels. Not only artificial light can be real-time regulated, but also shading devices like nets or photovoltaic modules can be adjusted considering the solar irradiance and the sun's revolution (Svanera et al., 2021). The more data processed from real-time sensors or external sources, the more computing capacity and networking are required which increases investment costs (Botero-Valencia et al., 2022). Even though further development of real-time light balance management would increase yield and quality of lettuce, it's economically feasibility depends on the difference which must be balanced besides external factors like power prices.

Overall, our findings suggest that the use of light balance tools should take opportunities and costs into account that can influence the hydroponic farming system. Further research in the development of real-time light balance by considering economic factors is necessary.

5. CONCLUSION

The cultivation of lettuce with supplemental lighting in controlled environments like plant factories is subject of many research, whereas for the semi-controlled scenario with sunlight and artificial light balance tools only little research is applicable. Based on optimal light energy demand for lettuce daily light integral (DLI) of 17 mol/m²/day, this study processed sunshine data from Aachen and Cairo and determined the available PAR-fraction in monthly averages. Comparing the available sunlight energy with the light demand of lettuce showed a great surplus of light energy in Cairo, especially in the summer. In Aachen, the available sunlight energy is lacking in the winter months and excessive in the summer months.

Overall, our findings suggest that the use of light regulator tools like supplemental lighting (LED-lamps) or shading nets iron out these imbalances between summer and winter months. This study may contribute to upscale semi-controlled hydroponic systems in similar climate conditions to achieve optimized growing conditions for high quality and quantity of lettuce production.

ACKNOWLEDGEMENTS

This research was financially supported by the AWESOME project. The project is part of the Prima programme, having received funding from the European Union´s Framework programme for Research and Innovation under grant agreement No: 1942. The PRIMA programme is an Art. 185 initiative supported and funded under Horizon 2020 (AWESOME 1942 to D.Ç.). We thank Dr. Khaled Tarabieh (American University in Cairo, Egypt) for providing weather data the Building Sciences Lab at

American University in Cairo directed by Dr. Khaled Tarabieh.

Compliance with Ethical Standards

Author Contributions

All authors contributed to the study conception and design. The first draft of the manuscript was written by J.K and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Conflict of Interest

The authors do not have any conflicts of interest to declare.

Ethical Approval

For this type of study, formal consent is not required.

REFERENCES

Abdel-Ghany, A., Al-Helal, I., Alkoaik, F., Alsadon, A., Shady, M., & Ibrahim, A. (2019). Predicting the cooling potential of different shading methods for greenhouses in arid regions. *Energies*, *12*(24), 4716. https://doi.org/10.3390/en12244716

Ahmed, H. A., Yu-Xin, T., & Qi-Chang, Y. (2020). Lettuce plant growth and tipburn occurrence as affected by airflow using a multi-fan system in a plant factory with artificial light. *Journal of thermal biology*, *88*, 102496.10.1016/j.jtherbio.2019.102496

Aires, A. (2018). Hydroponic Production Systems: Impact on Nutritional Status and Bioactive Compounds of Fresh Vegetables. In M. Asaduzzaman, & T. Asao (Eds.), Vegetables - Importance of Quality Vegetables to Human Health. IntechOpen. https://doi.org/10.5772/intechopen.73011.

Albright, L. D., Both, A. J., & Chiu, A. J. (2000). Controlling greenhouse light to a consistent daily integral. *Transactions of the ASAE*, *43*(2), 421. https://doi.org/10.13031/2013.2721

Baeza E, van Breugel AJ, Swinkels G, Hemming S, Stanghellini C. (2018) The perfectly smart greenhouse cover: a simulation study: *Wageningen University & Research*,*76*. https://doi.org/10.18174/451812

Barthel, S., Isendahl, C., Vis, B. N., Drescher, A., Evans, D. L., & van Timmeren, A. (2019). Global urbanization and food production in direct competition for land: Leverage places to mitigate impacts on SDG2 and on the Earth System. *The Anthropocene Review*, *6*(1-2), 71-97. https://doi.org/10.1177/2053019619856672

Botero-Valencia, J. S., Mejia-Herrera, M., & Pearce, J. M. (2022). Low cost climate station for smart agriculture applications with photovoltaic energy and wireless communication. *HardwareX*, *11*, e00296. https://doi.org/10.1016/j.ohx.2022.e00296

Brechner, M., & Both, A. J. (2013). Controlled Environment Agriculture-Hydroponic Lettuce Handbook. Retrieved on June 9, 2022, from https://cea. cals. cornell. edu/attachments/Cornell CEA Lettuce Handbook. pdf

Chen, P., Zhu, G., Kim, H. J., Brown, P. B., & Huang, J. Y. (2020). Comparative life cycle assessment of aquaponics and hydroponics in the Midwestern United States. *Journal of Cleaner Production*, *275*, 122888. https://doi.org/10.1016/j.jclepro.2020.122888

Chinchilla, S., Izzo, L. G., Van Santen, E., & Gómez, C. (2018). Growth and physiological responses of lettuce grown under pre-dawn or end-of-day sole-source light-quality treatments. *Horticulturae*, *4*(2), 8. https://doi.org/10.3390/horticulturae4020008

Climate Data (2019). *KLIMA KAIRO*. Retrieved on June 9, 2022, from de.climate-data.org/afrika/aegypten/gouvernement-al-qahira/kairo-3392/

Dai, A., Zhao, T., & Chen, J. (2018). Climate change and drought: a precipitation and evaporation perspective. *Current Climate Change Reports*, *4*(3), 301-312. https://doi.org/10.1007/s40641-018-0101-6

CDC. (2022). *Climate Data Center, Deutscher Wetterdienst*. Retrieved on June 9, 2022, from https://cdc.dwd.de/portal/.

Dzakovich, M. P., Gómez, C., & Mitchell, C. A. (2015). Tomatoes grown with light-emitting diodes or high-pressure sodium supplemental lights have similar fruit-quality attributes. *HortScience*, *50*(10), 1498-1502. https://doi.org/10.21273/HORTSCI.50.10.1498

Feng, L., Qin, W., Wang, L., Lin, A., & Zhang, M. (2018). Comparison of artificial intelligence and physical models for forecasting photosynthetically-active radiation. *Remote Sensing*, *10*(11), 1855. https://doi.org/10.3390/rs10111855

Fu, W., Li, P., and Wu, Y., (2012) 'Effects of different light intensities on chlorophyll fluorescence characteristics and yield in lettuce', *Scientia Horticulturae*, Vol. 135, 2012. https://doi.org/10.1016/j.scienta.2011.12.004

Ge, S., Smith, R. G., Jacovides, C. P., Kramer, M. G., and Carruthers, R. I., Ge, S., Smith, R. G., Jacovides, C. P., Kramer, M. G., & Carruthers, R. I. (2011). Dynamics of photosynthetic photon flux density (PPFD) and estimates in coastal northern California. *Theoretical* *and Applied Climatology*, *105*(1), 107-118. https://doi.org/10.1007/s00704-010-0368-6

Gómez, C., & Mitchell, C. A. (2015). Growth responses of tomato seedlings to different spectra of supplemental lighting. *HortScience*, *50*(1), 112-118. https://doi.org/10.21273/HORTSCI.50.1.112

Hamed, Y., Hadji, R., Redhaounia, B., Zighmi, K., Bâali, F., & El Gayar, A. (2018). Climate impact on surface and groundwater in North Africa: a global synthesis of findings and recommendations. *Euro-Mediterranean Journal for Environmental Integration*, *3*(1), 1-15. https://doi.org/10.1007/s41207-018-0067-8

Ilić, S. Z., Milenković, L., Dimitrijević, A., Stanojević, L., Cvetković, D., Kevrešan, Ž., ... & Mastilović, J. (2017). Light modification by color nets improve quality of lettuce from summer production. *Scientia horticulturae*, *226*, 389-397. https://doi.org/10.1016/j.scienta.2017.09.009

Jiang, J., Mohagheghi, A., & Moallem, M. (2019). Energy-efficient supplemental LED lighting control for a proof-of-concept greenhouse system. *IEEE Transactions on Industrial Electronics*, *67*(4), 3033-3042. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8701607

Kang, J. H., KrishnaKumar, S., Atulba, S. L. S., Jeong, B. R., & Hwang, S. J. (2013). Light intensity and photoperiod influence the growth and development of hydroponically grown leaf lettuce in a closed-type plant factory system. *Horticulture, Environment, and Biotechnology*, *54*(6), 501-509. https://doi.org/10.1007/s13580-013-0109-8

Khalil, S. A., & Shaffie, A. M. (2016). Attenuation of the solar energy by aerosol particles: A review and case study. *Renewable and Sustainable Energy Reviews*, *54*, 363-375. https://doi.org/10.1016/j.rser.2015.09.085

Kozai, T. (2016). Why LED Lighting for Urban Agriculture?. In: T. Kozai, K. Fujiwara, E. S. Runkle (Eds.), *LED Lighting for Urban Agriculture* (pp. 3-18). Springer, Singapore. https://doi.org/10.1007/978-981-10-1848-0_1

Leng, G., Tang, Q., & Rayburg, S. (2015). Climate change impacts on meteorological, agricultural and hydrological droughts in China. *Global and Planetary Change*, *126*, 23-34. https://doi.org/10.1016/j.gloplacha.2015.01.003

Mahato, A. (2014). Climate change and its impact on agriculture. *International Journal of Scientific and Research Publications*, *4*(4), 1-6. https://www.nswai.org/docs/Climate_change_impact_on_Agriculture.pdf

Materska, M., Olszówka, K., Chilczuk, B., Stochmal, A., Pecio, Ł., Pacholczyk-Sienicka, B., ... & Masullo, M. (2019). Polyphenolic profiles in lettuce (Lactuca sativa L.) after CaCl2 treatment and cold storage. *European Food Research and Technology*, *245*(3), 733-744. https://doi.org/10.1007/s00217-018-3195-0

Mattson, N. S. (Ed.). (2015). Tipburn of Hydroponic Lettuce *e-Gro Alert (4)*. https://www.e-gro.org/pdf/2015_431.pdf

McCree, K. J. (1971). The action spectrum, absorptance and quantum yield of photosynthesis in crop plants. *Agricultural Meteorology*, *9*, 191-216. https://doi.org/10.1016/0002-1571(71)90022-7

Michelon, N., Pennisi, G., Myint, N. O., Dall'Olio, G., Batista, L. P., Salviano, A. A. C., & Gianquinto, G. (2020). Strategies for improved yield and water use efficiency of lettuce (Lactuca sativa L.) through simplified soilless cultivation under semi-arid climate. *Agronomy*, *10*(9), 1379. https://doi.org/10.3390/agronomy10091379

Namgyel, T; Khunarak, C; Siyang, S; Pobkrut, T; Norbu, J and Kerdcharoen T. (2018) Effects of supplementary LED light on the growth of lettuce in a smart hydroponic system, 10th *International Conference on Knowledge and Smart Technology (KST)*, Thailand, pp. 216-220. https://doi.org/ 10.1109/KST.2018.8426202.

Nhut, D.T., Huy, N.P., Tung, H.T., Luan, V.Q., Nam, N.B. (2017). LEDs and Their Potential in Somatic Embryogenesis of *Panax vietnamensis* Ha *et* Grushv.. In: S. Dutta Gupta (Ed.), *Light Emitting Diodes for Agriculture*. Springer, Singapore. https://doi.org/10.1007/978-981-10-5807-3_14

Paulescu, M., Stefu, N., Calinoiu, D., Paulescu, E., Pop, N., Boata, R., & Mares, O. (2015). Ångström–Prescott equation: Physical basis, empirical models and sensitivity analysis. *Renewable and Sustainable Energy Reviews*, *62*, 495-506. https://doi.org/10.1016/j.rser.2016.04.012

Pinho, P., Hytönen, T., Rantanen, M., Elomaa, P., & Halonen, L. (2013). Dynamic control of supplemental lighting intensity in a greenhouse environment. *Lighting Research & Technology*, *45*(3), 295-304. https://doi.org/10.1177/1477153512444064

Javadinejad, S., Dara, R., & Jafary, F. (2021). Analysis and prioritization the effective factors on increasing farmers resilience under climate change and drought. *Agricultural research*, *10*(3), 497-513. https://doi.org/10.1007/s40003-020-00516-w

Sahdev, R.K., Kumar, M. & Dhingra, A.K. A comprehensive review of greenhouse shapes and its applications. *Front. Energy* 13, 427–438 (2019). https://doi.org/10.1007/s11708-017-0464-8

Searchinger, T., Waite, R., Hanson, C., Ranganathan, J., Dumas, P., Matthews, E., & Klirs, C. (2019). Creating a sustainable food future: A menu of solutions to feed nearly 10 billion people by 2050. Final report. *World Resources Report*, https://agritrop.cirad.fr/593176/1/WRR_Food_Full_Report_0.pdf

Sharma, N., Acharya, S., Kumar, K., Singh, N., & Chaurasia, O. P. (2018). Hydroponics as an advanced technique for vegetable production: An overview. *Journal of Soil and Water Conservation*, *17*(4), 364-371. https://doi.org/ 10.5958/2455-7145.2018.00056.5

Shimizu, H., Saito, Y., Nakashima, H., Miyasaka, J., & Ohdoi, K. (2011). Light environment optimization for lettuce growth in plant factory. *IFAC Proceedings Volumes*, *44*(1), 605-609. https://doi.org/10.3182/20110828-6-IT-1002.02683

Song, J., Huang, H., Hao, Y., Song, S., Zhang, Y., Su, W., & Liu, H. (2020). Nutritional quality, mineral and antioxidant content in lettuce affected by interaction of light intensity and nutrient solution concentration. *Scientific reports*, *10*(1), 1-9. https://doi.org/10.1038/s41598-020-59574-3

Spencer, J. W. (1971)."Fourier series reprensentation of the position of the sun." *Search* 2 (5), 162-172.

Stagnari, F., Galieni, A., & Pisante, M. (2015). Shading and nitrogen management affect quality, safety and yield of greenhouse-grown leaf lettuce. *Scientia Horticulturae*, *192*, 70-79. https://doi.org/10.1016/j.scienta.2015.05.003

Statuto, D., Abdel-Ghany, A.M., Starace, G., Arrigoni, P., Picuno, P. (2020). Comparison of the Efficiency of Plastic Nets for Shading Greenhouse in Different Climates. In A. Coppola, G. Di Renzo, G. Altieri & P. D'Antonio, (Eds.), *Innovative Biosystems Engineering for Sustainable Agriculture, Forestry and Food Production.* MID-TERM AIIA 2019. Lecture Notes in Civil Engineering, vol 67. Springer, Cham. https://doi.org/10.1007/978-3-030-39299-4_33

Svanera, L., Ghidesi, G., & Knoche, R. (2021). Agrovoltaico®: 10 years design and operation experience. In *AIP Conference Proceedings* (Vol. 2361, No. 1, p. 090002). AIP Publishing LLC. https://doi.org/10.1063/5.0055869

Udo, S. O., & Aro, T. O. (2000). New empirical relationships for determining global PAR from measurements of global solar radiation, infrared radiation or sunshine duration. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *20*(10),1265-1274. https://doi.org/10.1002/1097-0088(200008)20:10<1265::AID-JOC530>3.0.CO;2-C

United Nations Department of Economic and Social Affairs, Population Division (2022). World Population Prospects, the 2015 Revision. Retrieved on June 9, 2022, from https://population.un.org/wpp/

Viršilė, A., Brazaitytė, A., Vaštakaitė-Kairienė, V., Miliauskienė, J., Jankauskienė, J., Novičkovas, A., & Samuolienė, G. (2019). Lighting intensity and photoperiod serves tailoring nitrate assimilation indices in red and green baby leaf lettuce. *Journal of the Science of Food and Agriculture*, *99*(14), 6608-6619.https://doi.org/10.1002/jsfa.9948

Westermann, Diercke (Ed.) (2022). Atlas. Retrieved on June 9, 2022, from https://diercke.westermann.de/

Zhang, X., He, D., Niu, G., Yan, Z., & Song, J. (2018). Effects of environment lighting on the growth, photosynthesis, and quality of hydroponic lettuce in a plant factory. *International Journal of Agricultural and Biological Engineering*, *11*(2), 33-40. https://doi.org/10.25165/j.ijabe.20181102.3420

Zhou, C., Zhang, Y., Liu, W., Zha, L., Shao, M., & Li, B. (2020). Light quality affected the growth and root organic carbon and autotoxin secretions of hydroponic lettuce. *Plants*, *9*(11), 1542. https://doi.org/10.3390/plants9111542