UNIVERSITI PUTRA MALAYSIA

INDOOR PRODUCTION OF BRASSICACEAE MICROGREENS USING LED LIGHT AND DIFFERENT LIGHT INTENSITIES

NURSYAFIQAH BINTI IBRAHIM

FP 2022 10

INDOOR PRODUCTION OF BRASSICACEAE MICROGREENS USING LED LIGHT AND DIFFERENT LIGHT INTENSITIES

By

NURSYAFIQAH BINTI IBRAHIM

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

November 2020

© COPYRIGHT UPM

COPYRIGHT

All material contained within the thesis, including without limitation text, logos, icons, photographs, and all other artwork, is copyright material of Universiti Putra Malaysia unless otherwise stated. Use may be made of any material contained within the thesis for non-commercial purposes from the copyright holder. Commercial use of material may only be made with the express, prior, written permission of Universiti Putra Malaysia.

Copyright © Universiti Putra Malaysia

© COPYRIGHT UPM

DEDICATION

This thesis is dedicated to myself, my beloved parents and siblings, my thoughtful supervisor and colleagues for giving and offering me with so much kindness, knowledge, love and affection.

© COPYRIGHT UPM

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

INDOOR PRODUCTION OF BRASSICACEAE MICROGREENS USING LED LIGHT AND DIFFERENT LIGHT INTENSITIES

By

NURSYAFIQAH BINTI IBRAHIM

November 2020

Chairman : Associate Professor Yahya Awang, PhD
Faculty : Agriculture

A study was conducted to assess the effect of different regimes of irradiance generated by LEDs with cool white fluorescent (CWF) on the growth and nutritional contents of four species of *Brassica* microgreens (Chinese kale, Pak Choy, mustard and radish). The objective of this study was to determine the effects of different combination of light quality (red and blue LED with CWF) and intensity (120, 150, 180 and 210 µmol m^{-2} s^{-1}), sowing density and nutrient concentration in influencing growth and phytochemical compound of *Brassica* microgreens. Light regime had insignificant effect on yield, however, vegetative features such as hypocotyl elongation, cotyledon area and stem thickness varied significantly under different light treatment. While yield was insignificant, combination of red, blue LEDs with CWF (150 µmol m^{-2} s^{-1}) produced visually pleasing microgreens. Radish produced higher yield and higher concentration of phenolic and flavonoid compound than the other species. In second experiment, effects of light regime and sowing density (3.5 and 7.0 g seeds per container) on radish microgreens were determined. Higher sowing density, produced higher fresh weight due to increase in number of emerging shoots per area in response to higher seeds number, however, individual shoot weight decreased by 15%. Lower sowing density promoted higher individual fresh weight, nutrients, phenolic and DPPH activity. Five levels of nutrients concentration was used (1.0, 1.5, 2.0, 2.5 and 3.0 mS cm^{-1}) in the subsequent study. Results indicated that microgreens fresh weight increased gradually by 6%, 17%, 27% and 31% with increasing concentration (1.5, 2.0, 2.5 and 3.0 mS cm^{-1}) compared to microgreens grown with EC1.0. Total phenolic gradually increase by 28%, 47%, 65% and 81% as nutrient concentrations increased. Flavonoid content was highest when grown using EC2.5 but decreased by 57% when treated with EC 3.0. Nitrate accumulation in microgreens under EC2.5 was lower with 16% reduction compared to EC3.0. In conclusion, light regime did not affect final yield of microgreens, but the distribution of vegetative part of microgreens was largely affected by the combination of light spectrum and intensity. Increased in nutrients concentration with proper sowing rate help to enhance microgreens growth and increased yield.

© COPYRIGHT UPM

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENGELUARAN MIKROGREEN BRASSICACEAE DI DALAM BANGUNAN MENGGUNAKAN CAHAYA LED DAN INTENSITI CAHAYA BERBEZA

Oleh

NURSYAFIQAH BINTI IBRAHIM

November 2020

Pengerusi : Profesor Madya Yahya Awang, PhD
Fakulti : Pertanian

Satu kajian dilakukan untuk menilai kesan pelbagai jenis pancaran cahaya yang dihasilkan oleh LED dengan pendarfluor putih sejuk (CWF) pada pertumbuhan dan kandungan nutrien dari empat spesies *Brassica* microgreens (Kailan, Pak Choy, sawi dan lobak putih). Matlamat kajian ini adalah untuk mengetahui kesan kombinasi kualiti cahaya yang berbeza (LED merah dan biru dengan CWF) dan keamatan (120, 150, 180 dan 210 µmol m^{-2} s^{-1}), kadar penyemaian dan kepekatan nutrien dalam mempengaruhi pertumbuhan dan sebatian fitokimia mikro hijau Brassica. Rejim cahaya mempunyai kesan yang tidak ketara terhadap hasil, namun, ciri vegetatif seperti pemanjangan hipokotil, luas kotiledon dan ketebalan batang berbeza dengan ketara disebabkan oleh rawatan yang digunakan. Walaupun hasilnya tidak ketara, gabungan LED merah dan biru dengan CWF (150 µmol m^{-2} s^{-1}) menghasilkan microgeens yang menarik dari segi rupa bentuk. Lobak putih menghasilkan hasil tinggi dan kepekatan kandungan fenolik dan flavonoid yang lebih tinggi daripada spesies lain. Dalam kajian berikut, kesan rejim cahaya dan kadar penyemaian (3. 5 dan 7.0 g biji setiap bekas) pada microgreens lobak putih ditentukan. Kadar penyemaian yang lebih tinggi, menghasilkan berat basah yang lebih tinggi kerana peningkatan jumlah pucuk yang muncul di setiap kawasan sebagai tindak balas kepada jumlah biji yang lebih tinggi, namun, berat pucuk individu menurun sebanyak 15%. Kadar penyemaian yang lebih rendah mendorong peningkatan berat badan, nutrien, fenolik dan aktiviti DPPH individu yang lebih tinggi. Lima tahap kepekatan nutrien digunakan (1.0, 1.5, 2.0, 2.5 dan 3.0 mS cm-1) dalam kajian seterusnya. Hasil kajian menunjukkan bahawa berat microgreens meningkat secara beransur-ansur sebanyak 6%, 17%, 27% dan 31% dengan peningkatan kepekatan (1.5, 2.0, 2.5 dan 3.0 mS cm-1) berbanding dengan microgreens yang tumbuh dengan EC1.0. Jumlah fenolik secara beransur-ansur meningkat sebanyak 28%, 47%, 65% dan 81% apabila kepekatan nutrien meningkat. Kandungan flavonoid adalah tertinggi ketika ditanam menggunakan

© COPYRIGHT UPM

EC2.5 tetapi menurun sebanyak 57% apabila dirawat dengan EC 3.0. Pengumpulan nitrat dalam microgreens di bawah EC2.5 adalah lebih rendah dengan pengurangan sebanyak 16% berbandingkan dengan EC3.0. Sebagai kesimpulan, rejim cahaya tidak mempengaruhi hasil akhir microgreens, tetapi pengagihan bahagian vegetatif microgreens banyak dipengaruhi oleh gabungan spektrum cahaya dan keamatan. Peningkatan kepekatan nutrien dengan kadar penyemaian biji benih yang sewajarnya membantu meningkatkan pertumbuhan microgreens dan peningkatan hasil.

© COPYRIGHT UPM

ACKNOWLEDGEMENTS

Alhamdullilah, I offer my sincerest gratitude to ALLAH S.W.T. for the blessing and guidance He had granted me throughout my thesis study. First and foremost, I offer my sincerest gratitude to my supervisor, Assoc. Prof. Dr. Yahya Bin Awang, who has supported me throughout my thesis with his patience and knowledge whilst allowing me the room to work in my own way.

I would like to express my gratitude to my supervisor committee, Dr. Mohd. Hakiman Mansor for the valuable guidance and encouragement. I would also like extend my thanks to Mr. Mazlan Bin Bangi for helping me in the various laboratories works and equipment handling.

My sincere thanks also goes to my fellow colleagues, Zurafni Binti Mat Daud and Fatin Izzati Binti Mislani for their helps and motivation. Without their precious support it would not be possible to conduct this research. Last but not least, I would like to thank my family: my parents and to my brothers and sister for supporting me spiritually throughout writing this thesis and my life in general.

Sincerely,

NURSYAFIQAH IBRAHIM

© COPYRIGHT UPM

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

Yahya bin Awang, PhD
Associate Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Chairman)

Mohd. Hakiman bin Awang@Mansor, PhD
Senior Lecturer
Faculty of Agriculture
Universiti Putra Malaysia
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 9 June 2022

© COPYRIGHT UPM

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

Signature: ________________________________
Name of Chairman of Supervisory Committee: Associate Professor Dr. Yahya bin Awang

Signature: ________________________________
Name of Member of Supervisory Committee: Dr. Mohd. Hakiman bin Awang@Mansor

© COPYRIGHT UPM

TABLE OF CONTENTS

© COPYRIGHT UPM

© COPYRIGHT UPM

© COPYRIGHT UPM

© COPYRIGHT UPM

LIST OF TABLES

© COPYRIGHT UPM

© COPYRIGHT UPM

LIST OF FIGURES

© COPYRIGHT UPM

© COPYRIGHT UPM

© COPYRIGHT UPM

LIST OF APPENDICES

© COPYRIGHT UPM

© COPYRIGHT UPM

LIST OF ABBREVIATIONS

µmol	micromole
AA	Ascorbic acid
ADI	Acceptable daily intake
ANOVA	Analysis of variance
ARS	Agricultural Research Service
cm	Centimetre
cm^2	Square centimeter
DRV	Dietary reference values
DW	Dry weight
EFSA	European Food Safety Authority
FW	Fresh weight
FP	Fresh products
g	Gram
GA	Gibberellic acid
GAE	Gallic acid equivalent
GLDH	L-galactono-1,4-lactone dehydrogenase
H_2O_2	Hydrogen peroxide
H_2SO_4	Sulphuric acid
HPSL	High pressure sodium lamp
LED	Light emitting diodes
LHC	Light harvesting complex
MH	Metal halide
mg/L	Milligram per litre

© COPYRIGHT UPM

mS	millisiemen
NFT	Nutrient film technique
PAR	Photosynthetically active radiation
PET	Polyethylene terephthalate
PPFD	Photosynthetic photon flux
RDA	Recommended dietary allowance
ROS	Reactive oxygen species
SCF	The Scientific Committee on Food

© COPYRIGHT UPM

CHAPTER 1

INTRODUCTION

Microgreens are young, tiny versions of vegetables or herbs, loaded with phytonutrients and antioxidants. Microgreens can be grown by a combination of hydroponics and sole-source (SS) lighting in multilayer vertical growing system by using light-emitting diodes (LEDs) or conventional lighting. LEDs are known for its advantage of producing specific light wavelengths to influence plant morphology and phytochemical contents. LEDs has become an important device in many areas and applications including horticultural lighting. LED is defined as a solid-state semiconductor that emits light when a current is applied through the device. They are discovered for its functionality around the year 1897, however the development of LED technology and industry did not begin until the late year of 1960 (Shubert, 2003).

The primary role of LED in horticultural sector is to provide supplemental light source for the plant that are grown inside laboratory, greenhouse and structure house. LED is a type of semiconductor diode that can produce specific wavelength and able to control the spectral composition, thus allowing the adaption of light to be matched with the plant requirement. It is also high in energy efficiency. Most of the power supplied to LED is converted into radiation in the desired form. Efficiency of LEDs is not affected by the shape and size of the bulbs or tubes (Gupta et al, 2013). LEDs are also known for their long operational lifetime which ranged from 30,000 to 50,000 h and even beyond that. Heat generation of LEDs is relatively low compare to fluorescence light.

Plant or any culture can be placed close to the light source without damaging the plant or causing photo-stress. It has been reported that different lights are widely used to study the effects of spectral quality on plant growth and it has been proven to induce excellent growth of plants by adjusting the spectral quality. Previous study had showed that by combining the spectra of both conventional lighting sources with LED wavelengths, it is possible to not only optimize the spectral quality for various plant and different physiological processes (growth, flowering, photosynthetic efficiency), but also to create economically efficient lighting system (Li & Kubota, 2009; Lin et al., 2013).

As stated before, the blue and red zone of the visible light spectrum are the most beneficial for plant growth. The absence of one of the two (red or blue) light wavelengths creates photosynthetic inefficiencies that affect plant growth and development. It has also been reported that red light is important for shoot/stem elongation, phytochrome responses and changes in plant anatomy (Schuerger et al., 1997). In contrast, blue light is important in chlorophyll biosynthesis, stomatal opening, enzyme synthesis, maturation of chloroplast and photosynthesis (Tibbitts et al., 1983). Sowing density and nutrient concentration are among the important

© COPYRIGHT UPM

factor that generally affect plant growth. Optimal sowing rate is crop-specific, based on average seed weight, germinability and desired shoot population density.

Currently, there are no standardize sowing rate for specific species. Growers usually measure the sowing rate based on their field trial by using their own seeds. This is because the size of the seeds can differ among varieties of the same species or due to different methods of seed production. However, Di Gioia & Santamaria, (2015) recommended general sowing density for microgreens ranging from 1 seed per cm^2 in large-seeded species such as pea, chickpea and sunflower, up to 4 seeds per cm^2 in small-seeded species like arugula, watercress, mustard. Murphy & Pill (2010) observed a linear increase in fresh yield per unit area with increasing sowing rate, but also a decrease in mean shoot weight in arugula microgreens. Increasing sowing rate to maximize yield will reflect on the cost of production, while excessive stand density may produce undesirably elongated shoots and limited air circulation which can promotes development of fungal diseases.

Microgreens can be grown in conventional bench-top production or hydroponically. Plastic flats with drainage holes at the bottom are generally used for microgreen production. The trays are either lined with a sterile fiber-like seeding mat or partially filled with a peat-based soilless germinating media. Hydroponic producers may utilize aggregate culture with rockwool as the inert growing medium (Yildiz & Wiley, 2017). As microgreens are usually grown with soil or other soilless media (peat and peat-based media) containing nutrients, not much information was obtained regarding nutrient solution concentration that is suitable for microgreens production. Abad et al. (2001) recommended that growing media should have a pH of 5.5-6.5, low electrical conductivity (<500 mS/cm) and optimal water holding capacity (55-70% v/v) and aeration (20-30% v/v). Information regarding possible interaction between light treatment with sowing rate and nutrient concentration in microgreens is too little.

Microgreens have been claimed as nutritionally beneficial crop and various type of studies were carried out to enhance the nutritional value and increase the production yield of microgreens. It was known that each spectral band of light can induce certain responses in plants from various past studies. LEDs offers an advantage of producing specific light wavelengths to influence plant morphology and phytochemical contents. Thus, by manipulating the spectra and intensity and other factors such as sowing rate and nutrient concentration, it is possible to manipulate plant growth and improve phytochemical contents. In justification, this study will examine the interaction between LED lightings on different mirogreens growth performance, beneficial nutrition and yield. Thus, the objectives of this study are:

i) To measure the effects of intensity levels and spectra produced by LEDs on growth and phytochemical content in different Brassicaceae microgreens.

© COPYRIGHT UPM

ii) To determine the interactive effect between different LED light regime and sowing density on growth and phytochemical contents of selected microgreens.

iii) To determine the interactive effect between different LED light regimes and different EC nutrient solutions on growth and phytochemical content of microgreens.

© COPYRIGHT UPM

REFERENCES

Abad, M., Noguera, P., & Bures, S. (2001). National inventory of organic wastes for use as growing media for ornamental potted plant production: Case study in Spain. Bioresource Technology, 77, 197-200.

Agati, G., Azzarello, E., Pollastri, S., & Tattini, M. (2012). Flavonoids as antioxidants in plants: Location and functional significance. Plant Science, 196, 67–76.

Albornoz, F. & Lieth, J.H. (2015). Over fertilization limits lettuce productivity because of osmotic stress. Chilean J Agric Res, 75, 284–290.

Arrigoni, O. & De Tullio, M.C. (2002). Ascorbic acid: Much more than just an antioxidant. Biochimica et Biophysica Acta - General Subjects, 1569, 1-3.

Bach, C.E. & Hruska, A.J. (1981). Effects of Plant Density on the Growth, Reproduction and Survivorship of Cucumbers in Monocultures and Polycultures. The Journal of Applied Ecology, 18(3), 929.

Bagale, K.V. (2018). The effect of electrical conductivity on growth and development of strawberries grown in deep tank hydroponic systems, a physiological study. J Pharmacogn Phytochem, 7(1), 1939-1944

Barku, V.Y.A., Opoku-Boahen, Y., Owusu-Ansah, E. & Mensah, E.F. (2013). Antioxidant activity and the estimation of total phenolic and flavonoid contents of the root extract of *Amaranthus spinosus*. Asian Journal of Plant Science and Research, 3, 69–74.

Bian, Z.H., Yang, Q.C. & Liu, W.K. (2015). Effects of light quality on the accumulation of phytochemicals in vegetables produced in controlled environments: A review. Journal of the Science of Food and Agriculture, 95, 869-877.

Björkman, M., Klingen, I., Birch, A.N.E., Bones, A.M., Bruce, T.J.A., Johansen, T.J., Meadow, R., Mølmann, J., Seljåsen, R., Smart, L.E. & Stewart, D. (2011). Phytochemicals of *Brassicaceae* in plant protection and human health—influences of climate, environment and agronomic practice. Phytochemistry, 72, 538–556

Brown, C., Shuerger, A.C., & Sager, J.C. (1995). Growth and photomorphogenesis of pepper plants under red light-emitting diodes with supplemental blue or far-red lighting. J Am SocHortic Sci, 120, 808–813.

Bulgari, R., Baldi, A., Ferrante, A. & Lenzi, A. (2016). Yield and quality of basil, Swiss chard, and rocket microgreens grown in a hydroponic system. New Zealand Journal of Crop and Horticultural Science, 45(2), 119–129.

© COPYRIGHT UPM

Cataldo, D.A., Maroon, M., Schrader, L.E. & Youngs, V.L. (1975). Rapid colorimetric determination of nitrate in plant tissue by nitration of salicylic acid. Communications in Soil Science and Plant Analysis, 6(1), 71–80.

Chang, D.C., Cho, I.C., Suh, J.T., Kim, S.J. & Lee, Y.B. (2011). Growth and yield response of three aeroponically grown potato cultivars (*Solanum tuberosum* L.) to different electrical conductivities of nutrient solution. American Journal of Potato Research, 88(6), 450–458.

Chen, X.L., Guo, W.Z., Xue, X.Z., Wang, L.C. & Qiao, X.J. (2014). Growth and quality responses of "Green Oak Leaf" lettuce as affected by monochromic or mixed radiation provided by fluorescent lamp (FL) and light-emitting diode (LED). Scientia Horticulturae, 172, 168–175.

Cheynier, V., Comte, G., Davies, K.M., Lattanzio, V. & Martens, S. (2013). Plant phenolics: Recent advances on their biosynthesis, genetics, and ecophysiology. Plant Physiology and Biochemistry, 72, 1–20.

Chloupek, O., Forster, B. P. & Thomas, W.T.B. (2006). The effect of semidwarf genes on root system size in field-grown barley. Theor. Appl. Genet, 112, 779–786.

Chory, J. (2007). Howard Hughes Medical Institution. Retrieved from: http://www.hhmi.org/research/investigators/chory_bio.html. [Accessed on 20 February 2021]

Claussen, W., Brückner, B., Krumbein, A. & Lenz, F. (2006) Long-term response of tomato plants to changing nutrient concentration in the root environment - the role of proline as an indicator of sensory fruit quality. Plant Science, 171, 323–331.

D'Anna, F., Miceli, A. & Vetrano, F. (2003). First results of floating system cultivation of *Eruca sativa* L. Acta Horticulturae, 609, 361–364.

De Pascale, S., Maggio, A., Fogliano, V., Ambrosino, P. & Ritieni, A. (2001). Irrigation with saline water improves carotenoids content and antioxidant activity of tomato. J. Hortic. Sci. Biotechnol, 76, 447–453.

Di Gioia, F., Renna, M., & Santamaria, P. (2017). Sprouts, Microgreens and "Baby Leaf" Vegetables. Minimally Processed Refrigerated Fruits and Vegetables. Food Engineering Series, 403–432.

Ding, X., Jiang, Y., Zhao, H., Guo, D., He, L., Liu, F., Zhou, Q., Nandwani, D., Hui, D. & Yu, J. (2018). Electrical conductivity of nutrient solution influenced photosynthesis, quality, and antioxidant enzyme activity of pakchoi (*Brassica campestris* L. ssp. Chinensis) in a hydroponic system. PLOS ONE, 13(8), e0202090.

© COPYRIGHT UPM

Dou, H., Niu, G., Gu, M. & Masabni, J.G. (2018). Responses of sweet basil to different daily light integrals in photosynthesis, morphology, yield, and nutritional quality. HortScience, 53, 496–503.

European Food Safety Authority (2017). Dietary reference values for nutrients: Summary report. EFSA supporting publication, 14(12), 48-68.

European Union (2013) Commission Implementing Regulation (EU) no 208/2013 of 11 March 2013 on traceability requirements for sprouts and seeds intended for the production of sprouts. Off J Eur Union, 56, 16–18.

Fallovo, C., Rouphael, Y., Rea, E., Battistelli, A. & Colla, G. (2009). Nutrient solution concentration and growing season affect yield and quality of *Lactuca sativa* L. var. acephala raft culture. Journal of Food Science and Agriculture, 89, 1682-1689.

Farnia, A., Aminbaygi, A. & Fard, A. N. (2014). The effect of plant density on comparison forage yield of spring barley cultivar. Int. J. Farming Allied Sci., 3, 244–250.

Fu, Y., Li, H., Yu, J., Liu, H., Cao, Z., Manukovsky, N.S. & Liu, H. (2017). Interaction effects of light intensity and nitrogen concentration on growth, photosynthetic characteristics and quality of lettuce (*Lactuca sativa* L. Var. youmaicai). Scientia Horticulturae, 214, 51–57.

Gent, M.P.N. (2003). Solution electrical conductivity and ratio of nitrate to other nutrients affect accumulation of nitrate in hydroponic lettuce. HortScience, 38, 222–227.

Gerovac, J.R., Craver, J.K., Boldt, J.K. & Lopez, R.G. (2016). Light intensity and quality from sole-source light-emitting diodes impact growth, morphology and nutrient content of *Brassica* microgreens. Hortscience, 51(5), 497-503.

Ghasemzadeh, A., Jaffar, H.Z. & Rahmat, A. (2010). Synthesis of phenolics and flavonoids in ginger (*Zingiber officinale Roscoe*) and their effects on photosynthesis rate. International Journal of Molecular Science, 11(11), 4539-4555.

Gorbe, E. (2009). Study of nutrient solution management in soilless rose cultivation, through the analysis of Physiological parameters and nutrient absorption. Doctoral thesis, Valencia.

Gupta, S.D. & Jatothu, B. (2013). Fundamentals and applications of light-emitting diodes (LEDs) in in vitro plant growth and morphogenesis. Plant Biotechnology Reports, 7, 211-220.

Hammer, G.L., Dong, Z., McLean, G., Doherty, A., Messina, C. & Schussler, J. (2009). Can changes in canopy and/or root system architecture explain historical maize yield trends in the U.S. Corn Belt?. Crop Sci., 49 (1) 299-312.

© COPYRIGHT UPM

Hecht, V.L., Temperton, V.M., Nagel, K.A., Rascher, U. & Postma, J.A. (2016). Sowing Density: A Neglected Factor Fundamentally Affecting Root Distribution and Biomass Allocation of Field Grown Spring Barley (*Hordeum Vulgare* L.). Frontiers in Plant Science, 7, 944-958.

Herbst, S.T. (2001). The New Food Lover's Companion: Comprehensive Definitions of Nearly 6,000 Food, Drink, and Culinary Terms. Barron's Cooking Guide. Hauppauge, NY: Barron's Educational Series.

Jacobo-Velázquez, D., & Cisneros-Zevallos, L. (2013). An Alternative Use of Horticultural Crops: Stressed Plants as Biofactories of Bioactive Phenolic Compounds. Agriculture, 3(3), 596–598.

Jagota, S.L. & Dani, H.M. (1982). A new colorimetric techniques for the estimation of vitamin C using Folin phenol reagent. Anal. Biochem., 127,178-182

Kaiser, C. & Ernst, M. (2012). Microgreens. CCD-CP-104. Lexington, KY: Center for Crop Diversification, University of Kentucky College of Agriculture, Food and Environment.

Kałużewicz, A., Lisiecka, J., Gąsecka, M., Krzesiński, W., Spiżewski, T., Zaworska, A. & Frąszcza, B. (2017). The effects of plant density and irrigation on phenolic content in cauliflower. Hortic. Sci. (Prague), 44(4), 178–185.

Kang, J.G. & Van Iersel, M.W. (2004). Nutrient Solution Concentration Affects Shoot: Root Ratio, Leaf Area Ratio, and Growth of Subirrigated Salvia (*Salvia splendens*). HortScience, 39, 49-54.

Karimi, E., Jaafar, H.Z.E., Ghasemzadeh, A. & Ibrahim, M.H. (2013). Light intensity effects on production and antioxidant activity of flavonoids and phenolic compounds in leaves, stems and roots of three varieties of *Labisia pumila* benth. Aust. J. Crop. Sci., 7 (7), 1016-1023.

Kazuo, Y. & Nobutoshi, S. (1998). Effect of temperature and light intensity on the growth and flowering of *Odontoglossum* intergeneric hybrids J. Jpn. Soc. Hort. Sci., 67(6), 1925-1933.

Khan, K.A., Yan, Z. & He, D. (2018). Impact of Light Intensity and Nitrogen of Nutrient Solution on Nitrate Content in Three Lettuce Cultivars Prior to Harvest. Journal of Agricultural Science, 10(6), 99-104.

Klamkowski, K. & Treder, W. (2006). Morphological and Physiological Responses of Strawberry Plants to Water Stress. Agriculturae Conspectus Scientificus (ACS), 71(4), 159-165.

© COPYRIGHT UPM

Kopsell, D.A., Pantanizopoulos, N.I., Sams, C.E. & Kopsell, D.E. (2012). Shoot tissue pigment levels increase in 'Florida Broadleaf' mustard (*Brassica juncea* L.) microgreens following high light treatment. Scientia Horticulturae, 140, 96-99.

Krauss, S., Schnitzler, W.H., Grassmann, J. & Woitke, M. (2006). The Influence of Different Electrical Conductivity Values in a Simplified Recirculating Soilless System on Inner and Outer Fruit Quality Characteristics of Tomato. Journal of Agricultural and Food Chemistry, 54(2), 441–448.

Kyriacou, M.C., Rouhael, Y., Di Gioia, F., Kyratzis, A., Serio, F., Renna, M., De Pascale, S. & Santamaria, P. (2016). Micro-scale vegetable production and the rise of microgreens. J. Food Science and Technology, 57, 103-115.

Le Bot, J., Adamowicz, S. & Robin, P. (1998). Modelling plant nutrition of horticultural crops: a review. Sci.Hortic., 74, 47-82.

Lee, J.S., Pill, W.G., Cobb, B.B. & Olszewski, M. (2004). Seed treatments to advance greenhouse establishment of beet and chard microgreens. Journal of Horticultural Science and Biotechnology, 79(49), 565-70.

Li, Q. & Kubota, C. (2009). Effects of supplemental light quality on growth and phytochemicals of baby leaf lettuce. Environ Exp Bot, 67, 59–64.

Lin, K.H., Huang, M.Y., Huang, W.D., Hsu, M.H., Yang, Z.W. & Yang, C.M. (2013). The effects of red, blue, and white light-emitting diodes on the growth, development, and edible quality of hydroponically grown lettuce (*Lactuca sativa* L. var. capitata). SciHortic, 150, 86–91.

Lobiuc, A., Vasilache, V., Oroian, M., Stoleru, T., Burducea, M., Pintilie, O. & Zamfirache, M.M. (2017). Blue and Red LED Illumination Improves Growth and Bioactive Compounds Contents in Acyanic and Cyanic *Ocimum basilicum* L. Microgreens. Molecules, 22(12), 2111.

Machado, R.M.A., Alves-Pereira, I., & Ferreira, R.M.A. (2018). Plant growth, phytochemical accumulation and antioxidant activity of substrate-grown spinach. Heliyon, 4(8), e00751.

Maisarah, A.M., Amira, N.B., Asmah, R. & Fauziah, O. (2013) Antioxidant analysis of different parts of *Carica papaya*. International Food Research Journal 20(3), 1043–1048.

Makus, D.J., Lester, G. (2002). Effect of soil type, light intensity, and cultivar on leaf nutrients in mustard greens. Subtrop. Plant Sci. 54, 23–28.

Mir, S., Shah, M.A. and Mir, M.M. (2016). Microgreens: Production, shelf life and bioactive components. Critical Reviews in Food Science and Nutrition, 57(12), 2730-2736.

© COPYRIGHT UPM

Mizuno, T., Amaki, W. & Watanabe, H. (2011). Effects of Monochromatic light irradiation by led on the growth and anthocyanin contents in leaves of cabbage seedlings. Acta Horticulturae, 907, 179–184.

Munson, R.D. (1998). Principles of plant analysis, in Y.P. Kalra, Ed., Handbook of Reference Methods for Plant Analysis, CRC Press, Boca Raton, FL, 1-24.

Murphy, C.J. & Pill, W.G. (2010). Cultural practices to speed the growth of microgreen arugula (roquette; *Eruca vesicaria* subsp. sativa). Journal of Horticultural Science and Biotechnology, 85(3), 171-176.

Nemali, K.S. & Van Iersel, M.W. (2004). Light Intensity and Fertilizer Concentration: I. Estimating Optimal Fertilizer Concentrations from Water-use Efficiency of Wax Begonia. HortScience, 39(6), 1287–1292.

Nishio, J.N. (2000). Why Are Higher Plants Green? Evolution of the Higher Plant Photosynthetic Pigment Complement. Plant, Cell and Environment, 23, 539-548.

Nolan, D.A. (2018). Effects of seed density and other factors on the yield of microgreens grown hydroponically on burlap. Master, Virginia Tech., U.S.A.

Olle, M., & Viršile, A. (2013). The effects of light-emitting diode lighting on greenhouse plant growth and quality. Agricultural and Food Science, 22(2), 223-234.

Ohashi-Kaneko, K., Takase, M., Kon, N., Fujiwara, K. & Kurata, K. (2007). Effect of light quality on growth and vegetable quality in leaf lettuce, spinach and komatsuna. Environmental Control Biology, 45, 189-198.

Paciolla, C., Fortunato, S., Dipierro, N., Paradiso, A., De Leonardis, S., Mastropasqua, L. & de Pinto, M. C. (2019). Vitamin C in Plants: From Functions to Biofortification. Antioxidants, 8(11), 519.

Park, S.Y., Oh, S.B., Kim, S.M., Cho, Y.Y. & Oh, M.M. (2016). Evaluating the effects of a newly developed nutrient solution on growth, antioxidants, and chicoric acid contents in *Crepidiastrum denticulatum*. Horticulture, Environment, and Biotechnology, 57(5), 478–486.

Pollastri, S. & Tattini, M. (2011). Flavonols: old compounds for old roles. Annals of Botany, 108(7), 1225–1233.

Price, A.H. & Hendery, G.A.F. (1991). Iron-catalysed oxygen radical formation and its possible contribution to drought damage in nine native grasses and three cereals. Plant, Cell and Environment, 14(5), 477–484.

Rajashekar, C.B., Carey, E.E., Zhao, X. & Oh, M.M. (2009). Health-promoting phytochemicals in fruits and vegetables: Impact of abiotic stresses and crop production practices. Functional Plant Science and Biotechnology, 3, 30-38.

© COPYRIGHT UPM

Reilly, K., Valverde, J., Finn, L., Rai, D.K., Brunton, N., Sorensen, J.C., Sorensen, H. & Gaffney, M. (2014). Potential of cultivar and crop management to affect phytochemical content in winter-grown sprouting broccoli (*Brassica oleracea* L. var. italica). Journal of the Science of Food and Agriculture, 94, 322-330.

Riad, G., Ghoname, A., Ahmed, A., El-Baky, M.A. & Hegazi, A. (2009). Cabbage nutritional quality as influenced by planting density and nitrogen fertilization. Fruit, Vegetable and Cereal Science and Biotechnology, 3, 68-74.

Ricuarte, J., Michelangeli, J.A.C., Sinclair, T. R., Rao, I.M. & Beebe, S.E. (2016). Sowing Density Effect on Common Bean Leaf Area Development. Crop Science, 56, 2713–2721.

Romero-Aranda, R., Soria, T. & Cuartero, J. (2001). Tomato plant-water uptake and plant-water relationships under saline growth conditions. Plant Science, 160(2), 265–272.

Rousseaux, M.C., Ballare, C.L., Jordan, T.E. & Vierstra, R.D. (1997). Directed overexpression of PHYA locally suppresses stem elongation and leaf senescense responses tofar-red radiatin. Plant Cell and Environment, 20, 1551-1558.

Saied, A.S., Keutgen, A.J. & Noga, G. (2005). The influence of NaCl salinity on growth, yield and fruit quality of strawberry cvs. '*Elsanta*' and '*Korona*'. Scientia Horticulturae, 103(3), 289–303.

Sakamoto, M. & Suzuki, T. (2020). Effect of Nutrient Solution Concentration on the Growth of Hydroponic Sweetpotato. Agronomy, 10(11), 1708.

Samarakoon, U.C, Weerasinghe, P.A & Weerakkody, A.P. (2006) Effect of Electrical Conductivity [EC] of the Nutrient Solution on Nutrient Uptake, Growth and Yield of Leaf Lettuce (*Lactuca sativa* L.) in Stationary Culture. Trop Agric Res, 18, 13-21.

Samuoliene, G., Brazaityte, A., Sirtautas, R., Sakalauskiene, S., Jankauskiene, J. & Duchovskis, P. (2012). The impact of supplementary short-term red led lighting on the antioxidant properties of microgreens. Acta Horticulturae, 956, 649-655.

Samuoliene, G., Brazaityte, A., Jankauskiene, J., Virsile, A., Sirtautas, R. & Novickovas, A., et al. (2013). LED irradiance level affects growth and nutritional quality of Brassica microgreens. Central European Journal of Biology, 8(12), 1241-1249.

Savvas, D. (2003). Hydroponics: A modern technology supporting the application of integrated crop management in greenhouse. J. Food Agric. Environ., 1, 80–86.

© COPYRIGHT UPM

Schmid, V. H. (2008). Light-harvesting complexes of vascular plants. Cell Mol. Life Sci., 65, 3619-3639

Schmitt, J. & Wulff, R. D. (1993). Light spectral quality, phytochrome and plant competition. Trends in Ecology & Evolution, 8(2), 47-51.

Schuerger, A.C., Brown, C.S. & Stryjewski, E.C. (1997). Anatomical features of pepper plants (Capsium annuum L.) grown under red light emitting diodes supplemented with blue or far-red light. Ann Bot, 79, 273–282.

Singh, D., Basu, C., Meinhardt-Wollweber, M. and Roth, B. (2015). LEDs for Energy Efficient Greenhouse Lighting. Renewable and Sustainable Energy Reviews, 49, 139-147.

Sobko, O., Hartung, J., Zikeli, S., Claupein, W. & Gruber, S. (2019). Effect of sowing density on grain yield, protein and oil content and plant morphology of soybean (*Glycine max* L. Merrill). Plant Soil Environ, 65, 594-601.

Soengas, P., Cartea, M. E., Francisco, M., Sotelo, T., & Velasco, P. (2012). New insights into antioxidant activity of Brassica crops. Food Chemistry, 134(2), 725–733.

Soleymani, A., Shahrajabian, M. H. & Naranjani, L. (2011). Determination of the suitable planting date and plant density for different cultivars of barley (*Hordeum vulgare* L.) in Fars. Afr. J. Plant Sci., 5, 284–286.

Sudhakar, P., Latha, P., & Reddy, P. V. (2016). Plant pigments. Phenotyping Crop Plants for Physiological and Biochemical Traits, 121–127.

Sultana, B., Anwar, F. & Ashraf, M. (2009). Effect of Extraction Solvent/Technique on the Antioxidant Activity of Selected Medicinal Plant Extracts. Molecule, 2167–2180.

Sun, J., Kou, L., Geng, P., Huang, H., Yang, T. & Luo, Y. (2015). Metabolomic assessment reveals an elevated level of glucosinolate content in $CaCl_2$ treated broccoli microgreens. Journal of Agricultural and Food Chemistry, 63, 1863-1868.

Taârit, M.B., Msaada, K., Hosni, K. & Marzouk, B. (2012). Physiological changes, phenolic content and antioxidant activity of *Salvia officinalis* L. grown under saline conditions. J. Sci. Food Agric., 92, 1614–1619

Tabata K., Takaoka, T. & Esaka, M. (2002). Gene expression of ascorbic acid-related enzymes in tobacco. Phytochemistry 61, 631–635.

Tassoni, A., Franceschett, M. & Bagni, N. (2008) Polyamines and salt stress response and tolerance in *Arabidopsis thaliana* flowers. Plant Physiology and Biochemistry, 46, 607–613.

© COPYRIGHT UPM

Teixeira, J. & Pereira, S. (2007). High salinity and drought act on an organ-dependent manner on potato glutamine synthetase expression and accumulation. Environmental and Experimental Botany, 60(1), 121–126.

Tessema, L., Chindi, A., Giorgis, G.W., Solomon, A., Shunka, E. & Seid, E. (2017). Determination of nutrient solutions for potato (*Solanum tuberosum* L.) seed production under aeroponics production system. Open Agriculture, 2(1), 155–159.

Tibbitts, T.W., Morgan, D.C. & Warrington, I.J. (1983). Growth of lettuce, spinach, mustard, and wheat plants under four combinations of high-pressure sodium, metal halide, and tungsten halogen lamps at equal PPFD. J. Amer. Soc. Hort. Sci., 168, 622–630.

Treadwell, D., Hochmuth, R., Landrum, L., & Laughlin, W. (2010). Microgreens: A new specialty crop (p. HS1164). University of Florida, IFAS Extension.

Tripathy, B.C. & Brown, C.S. (1995). Root-shoot interaction in the greening of wheat seedlings grown under red light. Plant Physiology, 107, 407–411.

Usami, T., Mochizuki, N., Kondo, M., Nishimura, M. & Nagatani, A. (2004). Cryptochromes and phytochromes synergistically regulate Arabidopsis root greening under blue light. Plant Cell Physiol., 45, 1798–1808.

U.S. Department of Agriculture, Agricultural Research Service (2019). FoodData Central: USDA Survey Foods. Retrieved from: https://fdc.nal.usda.gov/. [Accessed on 01 March 2021].

Van Iersel, M. W. & Kang, J.G. (2002). Nutrient solution concentration affects growth of subirrigated bedding plants. Journal of Plant Nutrition, 25(2), 387–403.

Vaštakaitė, V., Viršilė, A., Brazaitytė, A., Samuolienė, G., Jankauskienė, J., Sirtautas, R., et al. (2015). "The effect of UV-A supplemental lighting on antioxidant properties of *Ocimum basilicum* L. microgreens in greenhouse" in Proceedings of the 7th International Scientific Conference Rural Development 2015. 1–7.

Viršilė, A., Samuolienė, G., Miliauskienė, J., & Duchovskis, P. (2019). Applications and Advances in LEDs for Horticulture and Crop Production. Ultraviolet LED Technology for Food Applications, 35–65.

Wang, W. J., Sun, X.T., Wang, G.C., Xu, P., Wang, X.Y. & Lin, Z. L. (2010). Effect of blue light on indoor seedling culture of *Saccharina japonica* (Phaeophyta). J. Appl. Phycol., 22, 737–744.

Weiner, J. & Freckleton, R.P. (2010). Constant final yield. Annu. Rev. Ecol. Evol. Syst., 41, 173–192.

© COPYRIGHT UPM

Wojciechowski, T., Gooding, M.J., Ramsay, L. & Gregory, P.J. (2009). The effects of dwarfing genes on seedling root growth of wheat. J. Exp. Bot., 60, 2565–2573.

Wu, L., Deng, Z., Cao, L., & Meng, L. (2020). Effect of plant density on yield and Quality of perilla sprouts. Scientific Reports, 10(1).

Xiao, Z., Lester, G.E., Luo, Y. & Wang, Q. (2012). Assessment of vitamin and carotenoid concentrations of emerging food products: edible microgreens. Journal of Agricultural and Food Chemistry, 60, 7644–7651.

Yadav, V., Kundu, S., Chattopadhyay, D., Negi, P., Wei, N., Chattopadhyay, S. & Deng, X.W. (2002). Light regulated modulation of Z-box containing promoters by photoreceptors and downstream regulatory components, COP1 and HY5, in Arabidopsis. The Plant Journal, 31, 741–753.

Yeh, N. & J., Chung. (2009). High-brightness LEDs—Energy efficient lighting sources and their potential in indoor plant cultivation. Renew. Sustain. Energy Rev., 13, 2175– 2180.

Yildiz, F. & Wiley, R.C.W. (2017). Minimally processed refrigerated fruits and vegetables, 2nd Edition. Springer. Food Engineering Series, 403-422.

Zhou, J., Li, P., Wang, J. & Fu, W. (2019). Growth, Photosynthesis, and Nutrient Uptake at Different Light Intensities and Temperatures in Lettuce. HortScience horts, 54(11), 1925-1933.

Zhou, W. L., Liu, W. K., & Yang, Q. C. (2013). Reducing nitrate content in lettuce by pre-harvest continuous light delivered by red and blue light-emitting diodes. J. Plant Nutr., 36, 481-490.

© COPYRIGHT UPM