

LED Lighting in Vertical Farming Systems Enhances Bioactive Compounds and Productivity of Vegetables Crops [†]

Cinthia Nájera ^{1,2,*}, Victor M. Gallegos-Cedillo ^{3,4}, Margarita Ros ⁵ and José Antonio Pascual ²

¹ University of Almeria

² CEBAS-CSIC, Murcia, Spain; email1@gmail.com (J.A.P.)

³ Universidad de Almería, Spain; email1@gmail.com (V.M.G.-C.)

⁴ Universidad Politécnica de Cartagena, Spain;

⁵ CEBAS-CSIC, Murcia, Spain; email1@gmail.com (M.R.)

* Correspondence: cnajera4@ual.es

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Abstract: One of the greatest challenges of modern agriculture is to produce more with less, to producing healthier, safer food under sustainable systems, this includes a focus on increasing the efficiency of finite resources such as water and nutrients and increasing the sustainable productivity of crops under innovative systems with LED lights on soilless culture. The aim of this research was to perform a bibliometric analysis on the benefits of vertical farming production systems on the nutraceutical quality parameters of horticultural crops, additionally, the main parameters used to evaluate the quality and productivity of crops were identified. The methodology and results were analysed over a period of 5 years using the different quality parameters of lighting-LED as the main light source. The main plant species studied were lettuce, cabbage, cucumber, and spinach. The results showed that use of 16 h light photoperiods increased nutritional compounds such as antioxidants, phenols, and total sugar concentration, but in general, a moderately positive effect on plant growth and development was observed. The most used light intensities were between the range of 150 to 300 $\mu\text{mol m}^{-2} \text{s}^{-1}$, and the specific spectrum-LED peaks between 450–495 nm (blue) and 620–700 nm (red). Therefore, the use of LED lights on vertical farming systems as an alternative to increase the nutritional parameters of horticultural plants is a viable option since, in a short period of time and without geographical differentiation, it contributes to the production of nutraceutical compounds. It also contributes to a reduction of natural resource use, such as water, since one hundred percent of the research was carried out on the crops through hydroponic systems, which have the capacity to reuse water and nutrients.

Keywords: led; vertical-farming; bibliometric analysis; photoperiod; light

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1. Introduction

Trends in agriculture have been increasing in recent years, mainly due to the need to improve growing conditions with few natural resources [1]. In recent years, agriculture has faced major challenges, e.g., pollution caused by leachate from irrigation of crops and, in turn, the increasingly limited space available for production [2]. The climate change crisis has become a threat to agricultural sustainability, with rising temperatures, droughts and floods [3]. In addition, consumers are increasingly demanding healthier and more sustainable food. This is why farmers themselves have seen the need to make drastic changes in the way they produce, and to look for solutions to make more efficient use of natural resources. However, concerns about food shortages are growing [4–7].

To cover all these external needs of the crop, alternatives must be sought that also cover the photosynthetic needs of the plants. Solar energy, therefore, is an indispensable

tool to take into account for the growth, development and reproduction of plants, not only because of the intensity of light it provides to crops, but also because of the spectral quality it emits [8]. Natural light conditions vary depending on geographical location, which is another constraint to having more sustainable vegetables because of the cost of importing food to certain places that are not able to have the ideal natural conditions to activate the plants' photoreceptors.

Recently, a solution has been found to curb the constraints on the development of sustainable agriculture and food supply worldwide, irrespective of geographical location, the creation of indoor or vertical farming, include technologies such as temperature control, light, and the automation of irrigation and supply of nutrient solutions [2–9]. These systems always depend on artificial light (light intensity, photoperiod, and light quality), which controls the photosynthetic process, plant physiology, biochemistry, and morphology [4,9–11]. LED lighting has become allied to these systems, as they are energy efficient and can have a specific spectrum for each agricultural need. However, it has been shown that not only the development and growth of the plants is solved by this system, but also the crops suffer changes, improvements or damages that cause the increase or decrease of nutritional compounds in the crops [12]. Therefore, the aim of this research was to perform a bibliometric analysis on the benefits of vertical farming production systems on the nutraceutical quality parameters of horticultural crops, additionally, the main parameters used to evaluate the quality and productivity of crops were identified.

2. Materials and Methods

Data from the 2013–2022 period were reviewed and analysed in the Scopus database using Scopus smart tools and Boolean (AND, OR, and NOT) and proximity (PRE/and W/) operators [14]. Quantitative analyses of key- or co-words 'vertical farming' AND led were performed using the search field 'Article title, Abstract, and Keywords', resulting in a total of 64 articles and 476 keywords.

To visualize the research topics, a bibliometric map was developed based on the keyword co-occurrence ratio, where the unit of analysis was the set of keywords that includes the author's keywords and indexed keywords, establishing a keyword frequency equal to or greater than 5 (number of times that a keyword appears in the selected publications) according to the criteria established by Chen et al. [15].

Following a similar procedure, an overlay visualization map was drawn to identify the evolution of keywords used in the set of articles analyzed in this study. A thesaurus file was constructed with synonyms or repeated concepts to increase the consistency of the main research topics [14]. The data were processed and mathematically analyzed using the clustering algorithm of the VOSviewer® software version 1.6.15.

From the total sample of articles ($n = 64$), a representative and random sample of 47 articles was extracted and analysed by relevance in the Scopus database from the 2018–2022 period. A quantitative, detailed, and meticulous analysis of the 47 articles was performed to collect the data of interest, such as plant species under study, the main goal of each study. In addition, the nutritional parameters, spectra, light intensity, photoperiod and conclusions of each article were identified, described and quantified.

3. Results

3.1. Crops

Table 1 shows the varieties used in the literature in vertical crops. It can be seen that lettuce is the most demanded for use in this type of cultivation (more than 20 different varieties). Therefore, lettuce is a crop for which there may be clearer data on its performance in vertical farming. This high demand for lettuce crops in vertical farming can be attributed to the fact that it is a species with short cycles, in which a quick response to its performance can be obtained, as well as the fact that it is an economically and agronomically viable crop [16–18].

Table 1. Crops used in vertical farming

Crops	Variety	Crops	Variety
Basil (<i>Ocimum basilicum</i> L.) [19,34,49]	"Genovese"	Marjoram (<i>Origanum majorana</i>) [42]	
Broccoli (<i>Brassica oleracea</i> var. italica) [9,11]	"Ivhua"	Mizuna (<i>Brassica rapa nipposinica</i>) [43]	
Canola (<i>Brassica napus</i> L.) [1]	"Kizakino-natane"	Nasturtium (<i>Tropaeolum majus</i> L.) [12]	
Chicory (<i>Cichorium intybus</i>) [49]	"Bionda a foglie larghe"	<i>Ophiorrhiza pumila</i> [28]	
Chinese kale (<i>Brassica alboglabra</i> Bailey) [5]		<i>Panax ginseng</i> [45]	
Coriander (<i>Coriandrum sativum</i> L.) [32]		Pepper (<i>Capsicum annum</i> L.) [47,50]	"Shinhong"
Cucumber (<i>Cucumis sativus</i>) [13,20,43]	"Yuexiu No.3"		"Tantan"
	"Joenbaekdadagi"	Platostoma palustre (<i>Mesona chinensis</i>) [48]	
	"Heukjong"	Pumpkin (<i>Cucurbita ficifolia</i> Bouché) [6,50]	"Heukjong"
	"Joenbaekdadagi"		"Bulrojangaeng"
Kalanchoe (<i>Kalanchoe blossfeldiana</i>) [35,43,44]	"Lipstick"	Rocket (<i>Eruca vesicaria</i> ssp. sativa) [8,47,49]	"Coltivata"
	"Spain"	Spinach (<i>Spinacia oleracea</i> L.) [8,24,26,44]	"Geant D' Hiver"
	"Romaine"		"BJC009"
	Butterhead "Asia Butter Head"		"Disease-resistant 388"
Lettuce (<i>Lactuca sativa</i> L.) [2-3,8,10,16-18,21,23,25,27,29-31,33-34,37-41,43,49]	Romaine "Asia Heuk Romaine"	Ssamchoo (<i>Brassica Lee</i> ssp. namai) [46]	
	"Yidali"	Strawberry (<i>Fragaria × ananassa</i>) [22,36]	Duch. "Elan"
	"Romaine"		"Benihoppe"
	"Little Gem"	Sweet basil (<i>Ocimum basilicum</i>) [46]	
	"Red butter"	Tomato (<i>Lycopersicon esculentum</i> Mill.) [6,13]	"Zhezhan No.1"
	"Green butter"		"Dongfeng No.1"
	"Tiberius"		"Dotaerangdia"
	"Lollo rosso"		"B-blocking"
	"Rebelina"	Watercress (<i>Nasturtium officinale</i> L.) [7]	
	"Capitata"	Watermelon (<i>Citrullus vulgaris</i> L.) [47]	"Sambokkul"
	"Lvdie and Ziya"		
	"Longifolia"		
	"Rex"		
	"Cherokee"		
	"Ziwei"		
	"Greenwave"		
	"Red Romaine"		
	"Crispa"		
	"Summer Surge"		
	"Red Oak"		

3.2. Clustering

Our network visualisation map shows the main descriptors used as keywords in the set of publications analysed in this study (Figure 1). The different items were grouped into three clusters, represented by different colours on the map. Each cluster shows a set of closely related words from the same field of research. According to Chen et al. [15], who conducted a bibliometric study based on keyword analysis, cluster size and number may indicate variations in lines of research. The keywords that stand out most in the network visualisation map, due to their high occurrences and total link strength are vertical farming, plant factory, light emitting diodes, artificial lighting, sustainability and agriculture, which highlight the main research topics in the studies due to their close relationship. Furthermore, within the study period, the map shows a line of research with 4 items (cluster 1; red) that includes studies related to vertical farming including sustainability.

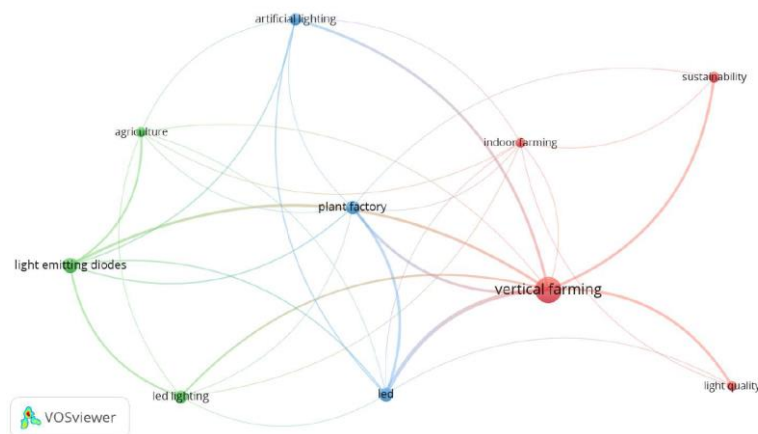


Figure 1. Bibliometric map generated from an analysis of the most repeated keywords in articles published during period 2013–2021. Different colours represent the diversity of thematic clusters found and the associated keywords: Red (cluster 1), green (cluster 2) and blue (cluster 3).

Figure 2 shows the world distribution of research studies conducted by country in which the vertical farming has been used as a method of production and have also conducted nutritional research under this system. Studies conducted in China, South Korea and Japan are the countries where more than 60% of the research on nutritional quality of vegetables grown in vertical farming.

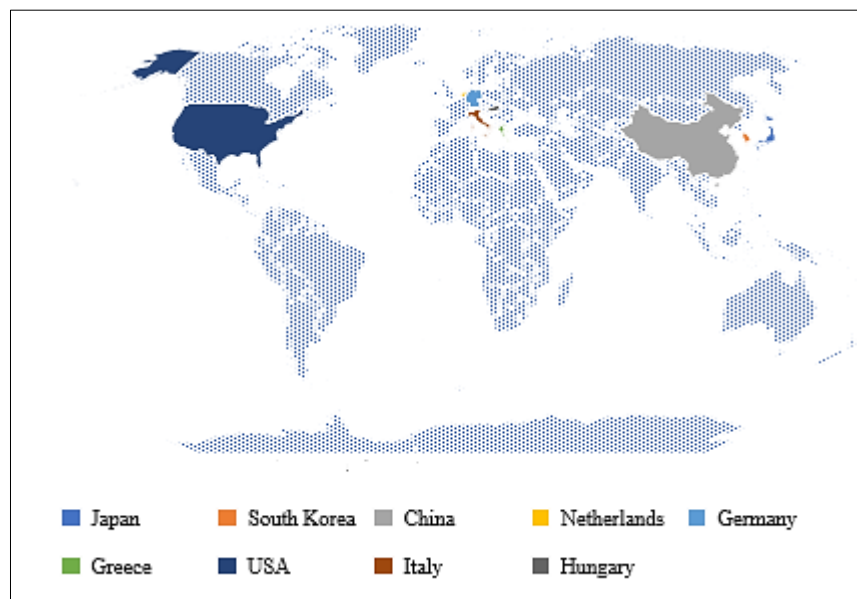


Figure 2. Global distribution of the main countries in which researchers have used the vertical farming and bioactive compounds in vegetables crops studies.

These countries correspond to the countries with the highest socio-economic level and technological development in agriculture according to the FAO.

3.3. Nutritional Parameters

Among the main parameters, chlorophyll content was the main evaluated in than 20% of the article samples analysed in this study (Figure 3). In addition, 12% of the articles focused on the effect of LED lights on sugar content and 10% on the effect of nitrate content. Nitrate is highly correlated with chlorophyll content in plants. According to the Agency for Toxic Substances and Disease Registry [50], nitrate is a source of carcinogenic nitrosamines via nitrites [8], which can seriously compromise human health; moreover, the consumption of nitrate-accumulating vegetables in children under 6 years old is especially worrisome according to the European Food Safety Authority [51], because 75% of the nitrates consumed are supplied by vegetables [52].

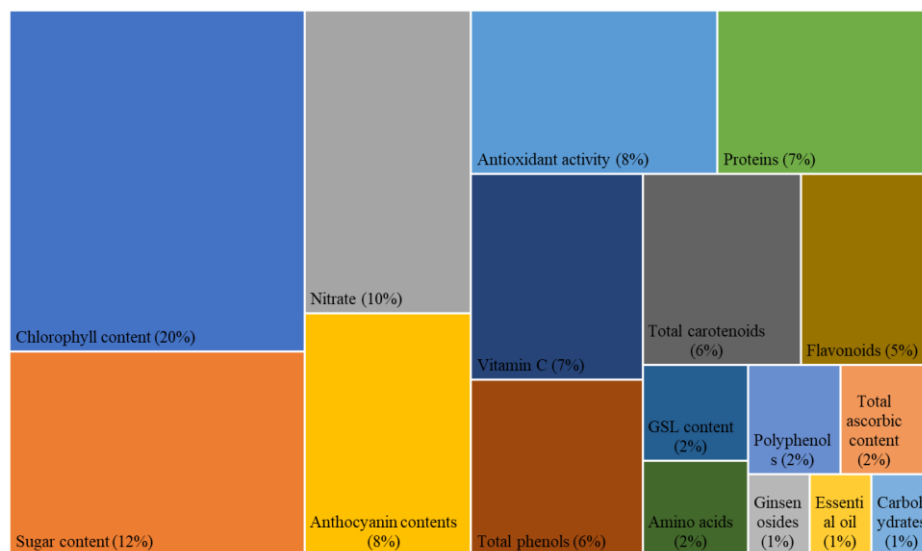


Figure 3. Research topics in the vertical farming on nutritional parameters. Values are expressed as percentages (n = 100).

3.4. Light and Spectral Parameters

The results showed that the most commonly used spectrum-LED peaks is between 450–495 nm (blue color) (Figure 4A), besides, this wavelength was considered an element essential element in all spectral combinations evaluated. On the other hand, blue spectrum peak has been shown to increase the content of antioxidants and total phenols, however, it also increases chlorophyll and nitrate. With respect to productivity, blue spectrum is one of the best performing spectra for crop growth and development [53].

The intensity of reflected light which is a parameter to take into account when research is concerned with analysing nutritional parameters, and in plant production. Figure 4B shows that 40% of the researchers have considered intensities of 150 and 200 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for their experiments, which have given them clear and significant results.

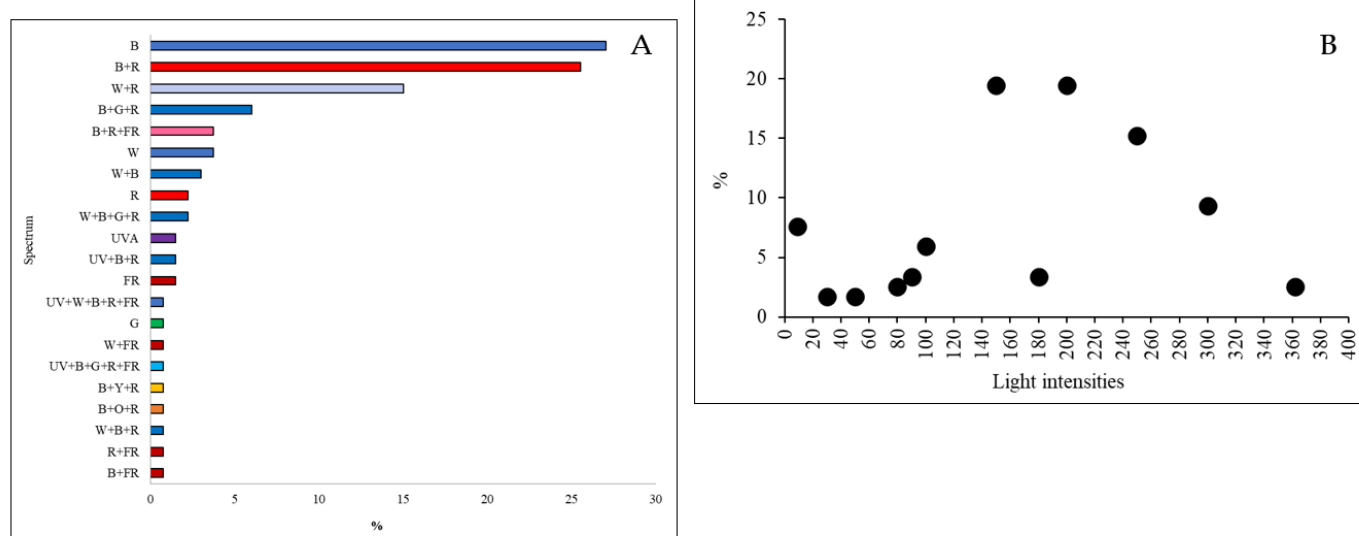


Figure 4. Type of spectra and color (A) and light intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) (B) used in the analyzed research. Data are expressed as percentage (n = 118). B (Blue 450–495 nm); R (Red 620–700 nm); FR (Far-red 700–800 nm); G (Green 500–560 nm); O (Orange 600–).

The use of specific spectra fitting within the ranges of maximum photosynthetic efficiency significantly enhances the nutraceutical quality of a wide range of vegetables species. This review has gathered the reference values of light intensity for more than 25 species of agronomic interest. The recommended intensity light for vegetables crops is in the range of 150 and 200 $\mu\text{mol m}^{-2} \text{s}^{-1}$.

The combined effect of LED lighting through vertical farming systems is an alternative to increase the nutritional parameters and productivity of vegetables crops and optimising the raw resource use, such as water and energy.

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