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Proceeding Paper

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

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Abstract: One of the greatest challenges of modern agriculture is to produce more with less, to produce 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 cultures. 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 and 300 µmol m^{-2} 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 as, 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, as one hundred percent of the research was carried out on crops that utilized 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 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. This solution is the creation of indoor or vertical farming, which 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 that the crops suffer changes, improvements, or damages that cause the increase or decrease of nutritional compounds in the crops [12,13]. 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

The period between 2013–2022 was considered to search the Scopus database for articles of interest to be analysed, using Boolean operators (AND and OR) [14]. Quantitative analyses were performed for the keywords "vertical agriculture" and "led" by searching by "Article title, Abstract, and Keywords", resulting in 64 articles and 476 keywords in total.

To visualize the most relevant research topics, a bibliometric map was made based on the co-occurrence of the resulting keywords, where author keywords and indexed keywords were considered, and greater than or equal to 5 frequency keywords (number of times a keyword appears in the selected publications) were established according to the criteria established by Chen et al. [15]. To identify the evolution of keywords, a visualization map was made using a methodology similar to the previous one. To eliminate repeated data, a thesaurus file with synonyms was constructed to increase the consistency of the main research topics [14]. These data were processed and analysed using VOSviewer® version 1.6.15 software (Centre for Science and Technology Studies, Leiden University, The Netherlands).

From the total number of articles obtained (n = 64), a random and representative sample (47 articles) was extracted and analysed in the Scopus database for the period 2018-2022. 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 (*Ocimum basilicum* L.) [19–21]	"Genovese"	Marjoram (*Origanum majorana*) [22]	*
Broccoli (*Brassica oleracea* var. italica) [9,11]	"lvhua"	Mizuna (*Brassica rapa nipposinica*) [23]	*
Canola (*Brassica napus* L.) [1]	"Kizakino-natane"	Nasturtium (*Tropaeolum majus* L.) [12]	*
Chicory (*Cichorium intybus*) [21]	"Bionda a foglie larghe"	*Ophiorrhiza pumila* [24]	*
Chinese kale (*Brassica alboglabra* Bailey) [5]	*	*Panax ginseng* [25]	*
Coriander (*Coriandrum sativum* L.) [26]	*	Pepper (*Capsicum annuum* L.) [27]	"Shinhong"
Cucumber (*Cucumis sativus*) [13,23,28]	"Yuexiu No.3"		"Tantan"
	"Joenbaekdadagi"	Platostoma palustre (*Mesona chinensis*) [29]	*
	"Heukjong"	Pumpkin (*Cucurbita ficifolia* Bouché) [6,27]	"Heukjong"
	"Joeunbaegdadagi"		"Bulrojangsaeng"
Kalanchoe (*Kalanchoe blossfeldiana*) [23,24,30,31]	"Lipstick"	Rocket (*Eruca vesicaria* ssp. sativa) [8,27,32]	"Coltivata"
	"Spain"	Spinach (*Spinacia oleraciea* L.) [8,31,33,34]	"Geant D' Hiver"
	"Romaine"		"BJC009"
Lettuce (*Lactuca sativa* L.) [2,3,8,10,16–18,20,21,23,32–45]	Butterhead "Asia Butter Head"		"Disease-resistant 388"
	Romaine "Asia Heuk Romaine"	Ssamchoo (*Brassica* Lee ssp. namai) [46]	*
	"Yidali"	Strawberry (*Fragaria × ananassa*) [47,48]	Duch. "Elan"
	"Romaine"		"Benihoppe"
	"Little Gem"	Sweet basil (*Ocimum basilicum*) [46]	*
	"Red butter"	Tomato (*Lycopersicon esculentum* Mill.) [6,13]	"Zhezhan No.1"
	"Green butter"		"Dongfeng No.1"
	"Tiberius"		"Dotaerangdia"
	"Lollo rosso"		"B-blocking"
	"Rebelina"	Watercress (*Nasturtium officinale* L.) [7]	
	"Capitata"	Watermelon (*Citrullus vulgaris* L.) [27]	"Sambokkul"
	"Lvdie and Ziya"		
	"Longifolia"		
	"Rex"		
	"Cherokee"		
	"Ziwei"		
	"Greenwave"		
	"Red Romaine"		
	"Crispa"		
	"Summer Surge"		
	"Red Oak"		

* n.d.

3.2. Clustering

Figure 1 shows the visualization map of the main descriptors used as keywords in the publications analysed in this study. The elements were grouped into three different clusters, represented by colours on the map. Each cluster (colour) shows a set of closely related words belonging to the same field of research. Authors such as Chen et al. [15] performed a bibliometric study based on the analysis of keywords, size, and number of clusters, and have indicated differences between research lines.

The results show that the keywords most frequently visualized in the network are vertical agriculture, plant factory, light emitting diodes, artificial lighting, sustainability, and agriculture, which show that these are the main research topics in the studies due to their close relationship. In addition, within the study period, the map shows a line of research with 4 items (cluster 1; red) that includes studies related to vertical agriculture including terms such as sustainability, plant factory, light-emitting diode, artificial lighting, and agriculture.

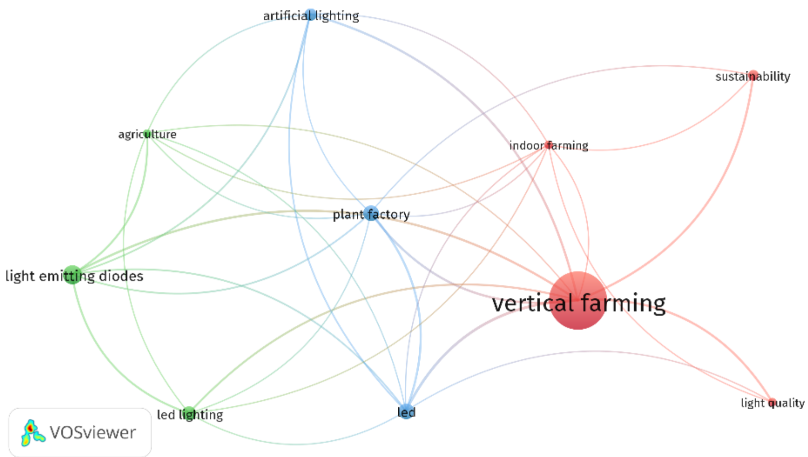

Figure 1. Bibliometric map generated from an analysis of the most repeated keywords in articles published during period 2013–2021. The different colours represent the diversity of thematic clusters found and the associated keywords: red (cluster 1), green (cluster 2), and blue (cluster 3).

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.

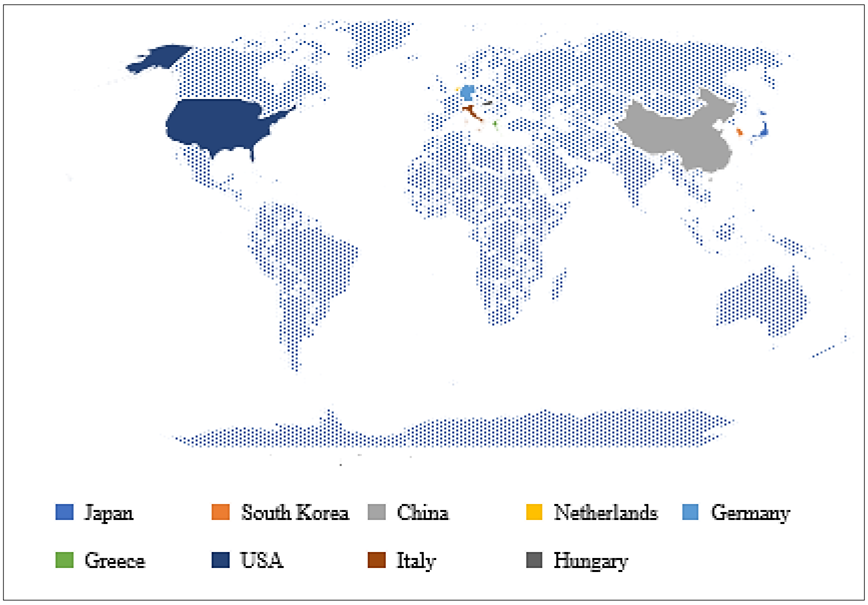

Figure 2. Global distribution of the main countries in which researchers have used the vertical farming and bioactive compounds in vegetables crops studies.

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 [49], 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 of age is especially worrisome according to the European Food Safety Authority [50], as 75% of the nitrates consumed are supplied by vegetables [51].

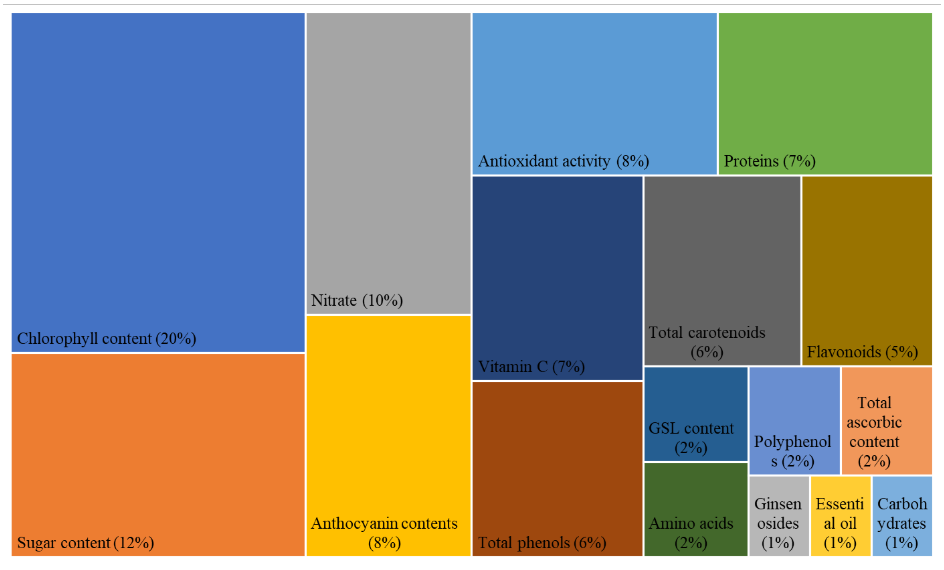

Figure 3. Research topics in the vertical farming on nutritional parameters. Values are expressed as percentages (n = 100).

3.4. Light and Spectral Parameters

The results showed that the most commonly used spectrum-LED peaks are between 450–495 nm (blue colour) (Figure 4A). In addition, 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 light is one of the best performing spectra for crop growth and development [52].

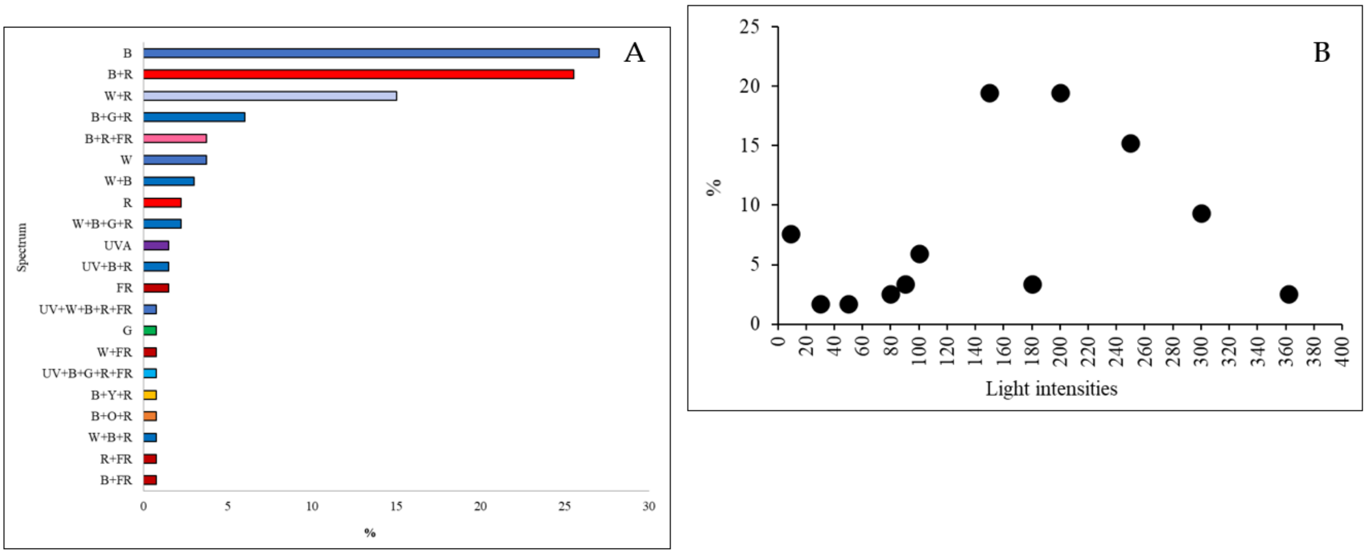

Figure 4. Type of spectra and colour (**A**) and light intensity (μmol m^{-2} s^{-1}) (**B**) used in the analysed research. Data are expressed as percentage (n = 118). B (blue 450–495 nm); R (red 620–700 nm); FR (far-red 700–800 nm); G (green 500–560 nm); O (orange 600-620).

The intensity of reflected light is an element 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 µmol m^{-2} s^{-1} for their experiments, which have given them clear and significant results.

The use of specific spectra fitting within the ranges of maximum photosynthetic efficiency significantly enhances the nutraceutical quality of a wide range of vegetable 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 µmol m^{-2} 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.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/IECHo2022-12514/s1.

Author Contributions: C.N., M.R. and J.A.P. conceived and designed the review; C.N. and V.M.G.-C. did the bibliographic research and analysed the data; C.N. wrote the paper. All authors have read and agreed to the published version of the manuscript.

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