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Review

Role of Spectrum-Light on Productivity, and Plant Quality over Vertical Farming Systems: Bibliometric Analysis

Cinthia Nájera [1,2,*], Victor M. Gallegos-Cedillo [3,4], Margarita Ros [2] and José Antonio Pascual [2]

[1] Department of Agronomy, University of Almería, 04120 Almería, Spain
[2] Department of Soil and Water Conservation and Organic Wastes Management, CEBAS-CSIC, 30100 Murcia, Spain
[3] Department of Engineering, CIAIMBITAL Research Centre, University of Almería, 04120 Almería, Spain
[4] Department of Agronomical Engineering, Technical University of Cartagena, 30203 Cartagena, Spain
* Correspondence: cnajera4@ual.es

Abstract: The growing demands for food with high quality standards and high nutritional value have caused agriculture to evolve towards agricultural innovation go hand in hand with technological development, as is the case of vertical farming (VF) development. VF is a competitive system for sustainable food production, reducing space, and natural and human resources for agricultural production, and it is a system that can be developed anywhere in the world and at any time, without seasonality being a factor that influences production. Light is the most important factor to consider when it comes to vertical farming, replacing sunlight with artificial light has had great advances in improving productivity, especially when using LED lighting. Despite the exponential growth of the system, there is a paucity of analysis on the research that has been carried out to date using a VF system, and on information on the most relevant parameters to be considered for optimum production. This review is a bibliometric analysis of 318 scientific articles taken from the SCOPUS database, where information from 109 papers published in relevant journals was used. During the last 10 years, the number of publications that have been carried out in a VF system has increased by 195%, with China standing out as the geographical location where field experiments are carried out. Lettuce crop predominates in the investigations, with a light intensity of 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and with a photoperiod of 16 $h \cdot day^{-1}$, using spectra between 450 and 495 nm, and a combination of blue and red (450–495 and 620–750 nm). The use of the research in the VF system for fresh, quality, local produce has increased in recent years, and has proven to be highly effective in productivity and quality. Conditions and management have been generalized, with more than 50% of researchers deciding to perform this cultivation method with similar photoperiod, spectrum, and intensity. Among the conclusions obtained by each researcher, it is also agreed that it is a potentially sustainable and controllable system that can be developed in urban locations, benefiting the social economy, food security, and the environment, while the conclusions on the cent per cent utilization of natural resources (such as energy from sunlight) in the system remain open and improving.

Keywords: spectrum; lighting-LED; energy efficiency; sustainability; agriculture; vegetables; food security; growing media; urban agriculture; vertical farming; plant factory; bioactive compounds

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1. Introduction

The constant threats of future food shortages as a result of the forecast increase in world population by 2050 (9 billion people), the loss of arable land area [1], or the increasing scarcity of natural resources, such as water [1,2], among other global issues closely interrelated, become worrisome. For this reason, alternatives have been sought to increase food production and also to ensure that the products have a high nutraceutical quality, nowadays demanded by consumers [3]. Technological innovation such as VF has changed the agriculture that is being produced in a traditional (open) way to be produced in closed and controlled (indoor) structures, where such change, is intended to be environmental and not genetic [4]. The construction of spaces for controlled indoor agriculture has a great competitive and comparative advantage over open agriculture. Vertical farming (VF) has the great potential to improve crops that can be produced locally, having fresh produce, without additives to increase long life and quality vegetables, eliminating food waste.

Kozai [5] described VF as “A multilayer indoor plant production system in which all growth factors, such as light, temperature, humidity, CO_2 concentration (CO_2), water, and nutrients, are precisely controlled to produce high quantities of high-quality fresh produce year-round, completely independent of solar light and other outdoor conditions”. Beacham et al. [6] remarked to the VF term has come to have a wide range of definitions that can provide confusion, although this system shares the same purpose, which is to reduce the use of traditional agricultural land incorporating soilless culture systems. It is particularly attractive for use in urban areas, as it is cultivated upwards rather than outwards. The origins of the VF date back to 600 BC with the construction of the Hanging Gardens of Babylon [7], the Chinese Floating Gardens in the fourth century, and the construction of the Aztec Chinampas in the twelfth century [8], which in its structure governed the optimization of natural resources and the use of urban spaces where successful obtained different vegetables for local production [9]. So, the VF system is not new, however, over the last few years, it has changed and improved its structure, its operation, and purpose [6,9].

Al-Kodmany [10] described these new systems as productive, economic, social, and environmentally advantageous because it includes: a reduction of food transportation, reduction of water and fertilizer consumption with the use of recirculation techniques, better plant pest and disease control, permitting the elimination or a maximum reduction of pesticides, no loss of production (caused by floods, droughts, and seasonal changes), local job creation, use and exploitation of renewable energies, and the reuse of buildings or use of buildings in the case of large cities. Despite these advantages, when comparing the indoor system with greenhouse production, energy consumption in indoor agriculture is higher, because the only source of light is through lamps that are supplied with electricity [11].

In Europe, the term “plant factories” has not been well adopted, as the term vertical farming has been preferred due to the description and characteristics that this system encompasses. This preference is cultural and may be because consumers and farmers themselves relate the word “factory” to a system of industrial pollution [12].

Vertical farming is increasingly becoming a necessity for agriculture, due to population growth, lack of agricultural space, and reduction of natural resources [9]. This technology has also demonstrated that it may be able to increase yields [13,14] and guarantee year-round production [5], e.g., the production of saffron bulbs [15], bell pepper [16,17], tomato [18], cucumber [19] and strawberry [20,21], which are crops of great economic and commercial interest worldwide; increase compounds naturally [22], and even increase plant defenses against pests and diseases thanks to the activation of genes or proteins produced by artificial light within the VF [23].

VF maximizes plant growth and increases vegetable consumption in winter, in northern European countries, America and China, where natural solar radiation is not sufficient. In addition, from the environmental point of view reducing the pollution emitted by transportation is a good reason for increasing production through VF, which reduces resources and pollution. It is estimated that, in the USA, for example, food from a supermarket travels 2000 km on average [24] without including the environmental costs to be assumed when the products need to be cooled during transportation in terms of generated CO_2 equivalent gas emissions.

There are some parameters to consider in VF agriculture focused on lighting that can affect plant production, such as light intensity, electromagnetic spectrum, photoperiod, photosynthetically active radiation (PAR) or daily light integral (DLI) (Table 1), and others that measure, plant production and productivity such as photosynthesis, Leaf Area (LA), plant productivity and Total Dry Matter (TDM) (Table 2).

Table 1. Relevant parameters related to lighting in VF systems.

Parameter	Description
Electromagnetic spectrum	It is the wavelength that determines the distribution of energy, including visible and non-visible wavelengths. In the case of the spectra emitted by lamps, a range of electromagnetic radiation detectable by the human eye is considered, from 380 nm to 780 nm, within the portion of the spectrum between ultraviolet and infrared, which are components of solar radiation. It has been demonstrated than approximately 95% of solar UV radiation at sea level is absorbed by plant photoreceptors, which are largely responsible for plant growth and development [25]. Some lamps include the above-mentioned entire range, such as fluorescent lamps, and others, such as LED luminaries, have more specific spectrum absorption peaks.
Photosyntenthically active radiation (PAR)	It consists of elementary, particles/wavelets, or photons and is the part of the radiation spectrum that plants use for photosynthesis corresponding to the range from 400 to 700 nm [26–28]. The measurement is done with PAR sensors, expressed as $\mu mol \cdot m^{-2} \cdot s^{-1}$.
Photosynthetic Photon Flux Density (PPFD)	Light intensity falling onto a surface measured as photosynthetic photon flux density (PPFD) with units of $\mu mol \cdot m^{-2} \cdot s^{-1}$. PPFD comprises about half the energy of solar radiation and scales well with the time at which photosynthesis responds to changes in light intensity [29]. Direct PPFD measurement, using PAR sensors.
Photoperiod	All living beings need a period of light and darkness to regulate their processes. These periods are regulated in a daily cycle of 24 h that results from the rotation of the Earth around its axis, where the greater or lesser perpendicular of the sun's rays varies depending on the latitude of the place, time of year and time of day [30]. Photoperiod plays an important role on plant growth and development, where being deficient in plants with high light requirements can induce stress and growth imbalance and can also significantly influence energy and economic efficiency in a VF system [31].
Daily Light Integral (DLI)	DLI is a measure of the total photosynthetic photon flux density (PPFD) delivered over the course of one day. It is a useful tool for assessing the irradiance delivered to various horticultural crops, therefore, it is of great importance in VF systems [32].
Radiation use efficiency (RUE) and Light use efficiency (LUE)	RUE is the efficiency with which a crop uses absorbed light energy for biomass production and is determined as the ratio of biomass accumulation per unit of photosynthetically active radiation (PAR) absorbed [33]. Unlike RUE, LUE, is the net CO_2 assimilation, which is the efficiency of plants to convert absorbed light into CO_2 absorption, LUE can be measured in a short time or quantified daily at the leaf level [34].

Table 2. Relevant parameter related to plant morphological and physiological in VF systems.

Parameter	Description
Photosynthetic parameters	It is one of the most widely used physiological parameters in crops and is non-destructive in nature, being used to accurately understand plant ecophysiology. It is the process where plants produce organic compounds by CO_2 and H_2O [35,36].
Leaf Area (LA)	It is a parameter that determines the amount of photoassimilates produced and affects who is growth, development, and productivity [37]. In general, it is assumed that LA and biomass accumulation in crops may be affected by some factors, such as light quality and radiation intensity, plant nutrition, substrate type, and container design and volume [38–41].
Plant productivity	It is determined by fresh weight, being of commercial interest in the market by edible fresh weight. However, every organ (stem, leaf, root, or fruit) is of research interest by dry weight, since biomass accumulation is the result of photosynthetic activity, CO_2 concentration [26] and is an indicator of long-term plant survival.
Total Dry Matter (TDM)	It represents the net gain in dry matter, and it is considered one of the best parameters for indicating plant quality [42]. Moreover, plants with a high TDM content show high growth potential and field yield.

Attending to reproduce the sunlight according to the spectrum, it has been different approaches since it was VF started. There is a record of research by Mangon [43], who used incandescent lighting in 1861 [44], Siemens [45] used coal-generated lighting in 1880, whose effectiveness was also analyzed from an economic point of view; and in 1985, Murdoch [46] used mercury vapor lamps as a light source, with fluorescent and high-pressure sodium lights being the standard lighting for many years. It was not until the 1990s that research began with light-emitting diodes (LEDs) for plant growth in the United States of America (USA) [47,48]. This caused a technological revolution due to its differences with respect to the previous lamps since LEDs are formed by the electroluminescence of the material when it is subjected to voltage. Currently, it was modified by adding one or more organic electrodes and gave rise to OLEDs (Organic light-emitting diodes) [49]. Both systems are sustainable and highly energy-efficient. These advances offer great opportunities in agriculture, as they have independent diode control allowing them to combine specific spectral composition with high light output at a low radiant temperature [47]. The vertical farming system is promising; however, it requires a significant economic investment in terms of electricity consumption and labor. Improvements are being sought to reduce these costs and even specific crops of higher market value have been identified to make the system competitive and profitable [50]. For example, short-cycle cultivation of sprouts or microgreens, whose, global economic value will increase by 175% from 2021 to 2030 [51], as well as linking other factors, such as renewable energy and waste heat reuse, is needed to further reduce system costs [52].

Currently, there are an increasing number of scientific experiments of production in VF systems that can be modified depending on the needs and objectives sought, obtaining yields equal to or greater than conventional production systems, with a higher content of bioactive compounds beneficial to health, e.g., to fruit (raspberry, camu-camu, tomato, and hot pepper) with a positive outcome effect in phenolics, anthocyanins, or ascorbic acid [53–56] and vegetables (tarragon, garlic, and broccoli) with a positive effect in carotenoids, polyphenols, ascorbic acid and phenolics [57–59], which are highly valued by consumers, as these compounds can reduce the risk of contracting chronic diseases [60]. From an ecological point of view, the increase in production in this system means an increase in demand for 0 km food, also benefiting food safety by having a more exhaustive environmental control.

This work aims to carry out a global bibliometric analysis of the current panorama and the prospects of the VF production system focusing on light as a potential tool to increase the productivity and bioactive compounds of grown plants.

2. Materials and Methods

A bibliometric analysis is carried out using the SCOPUS database to determine the evolution and development of vertical farming up to the present time, with the aim of providing guidance on the interest this system is taking in the scientific field. The work ends with an analysis of the results published by more than one hundred current research studies, showing the cultivation conditions, results obtained, and the most important conclusions of the use of the VF system.

The intelligent tools of Scopus and Boolean (AND, OR, and NOT) were used to review and analyzed the data for the period 2008–2022 in the Scopus database. The descriptor used as the central axis of the research was "Vertical farming" in the search field 'Article title, Abstract, and Keywords', and a total of 381 articles and 1578 keywords were obtained.

To visualize the research themes, the data were processed and mathematically analyzed using the clustering algorithm of the VOSviewer® software version 1.6.15 was used to produce a bibliometric map based on the keyword co-occurrence ratio and the similarity index [61]. The unit of analysis was considered as the set of keywords including author keywords and indexed keywords, establishing a keyword frequency equal to or greater than 8 (the number of times a keyword appears in the selected publications) according to the criteria established by Chen et al. [62]. As well as another overlay visualization map was performed to identify the most current trends of the keywords used in the set of articles analyzed in this study. To avoid repeated words or synonyms, a thesaurus file was made to increase confidence in the results.

A total sample of 381 articles was obtained from the search and a representative sample of 109 more current articles (2018–2022) was extracted and thoroughly analyzed in detail to collect data of interest exposing the importance of VF characteristics, including light, as a potential tool to increase the productivity of plants with a significant sample of horticultural, aromatic, and ornamental species. The number of data varies depending on the parameter and is specified in each case as *n*. The following were the main data considered of interest: the plant species studied, the growing medium, the growing method, the spectrum, the light intensity, the photoperiod, and the integral daily light (DLI). A short description of the studies with the characteristics of each crop and its efficacy is shown in Table 3.

3. Results and Discussion

3.1. Bibliometric Study: Clustering

Our network visualization map shows the 43 main descriptors used as keywords in the set of publications analyzed in this study (Figure 1). The different items were grouped into five clusters, represented by different colors on the map. Each cluster shows a set of closely related words from the same field of research. According to Chen et al. [62], 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 visualization map, due to their high occurrences and total link strength are vertical farming, crop production, agriculture, and urban agriculture, which highlight the main research topics in the studies due to their close relationship with the different lines of agricultural research. Furthermore, within the study period, the map shows a line of research with 10 items (cluster 1, red) that includes studies related to vertical farming, crop production, control environment agriculture, plant factory, led, photosynthesis energy efficiency, carbon dioxide, and greenhouse. Cluster 1 stands out for encompassing the current research trends in the agricultural sciences. The overlay visualization map (Figure 2) shows the evolution of keywords used to describe the main content of a research study, with the most recent and relevant terms, highlighted in yellow. These keywords are: Smart farming, Smart agricultures, Internet of Things, nutrients, decision making, humans, vegetables, control environment agriculture, environmental impact, and artificial intelligent.

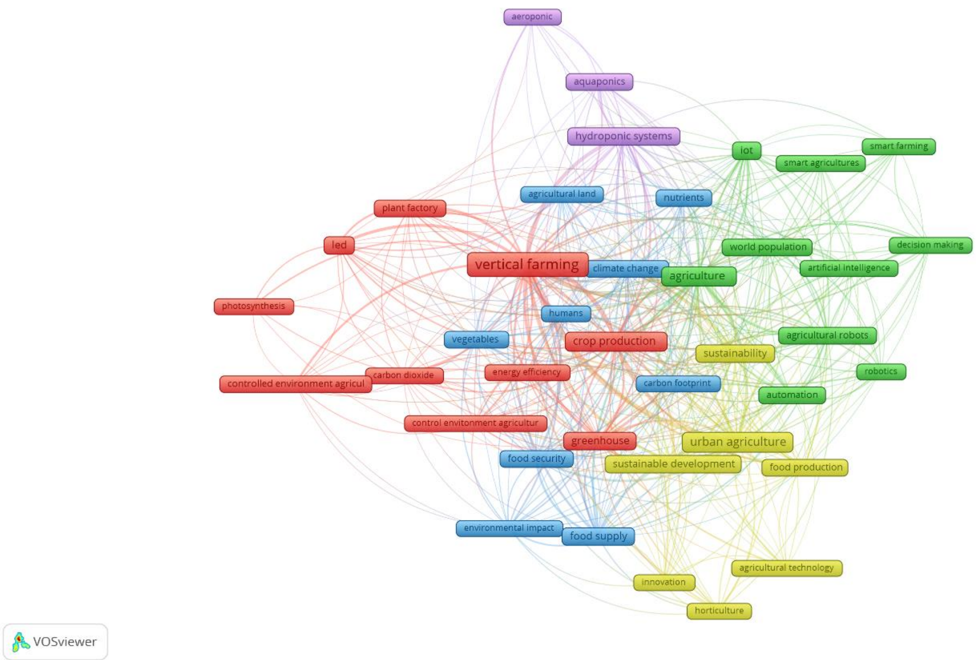


Figure 1. Bibliometric map generated from the analysis of the most repeated keywords in articles published during the period 2008–2022. Different colors represent the diversity of thematic clusters found and associated keywords. Red (cluster 1), green (cluster 2), blue (cluster 3), yellow (cluster 4), and purple (cluster 5). The data were processed and mathematically analyzed using the clustering algorithm of the VOSviewer® software version 1.6.15, Leiden, NL, USA.

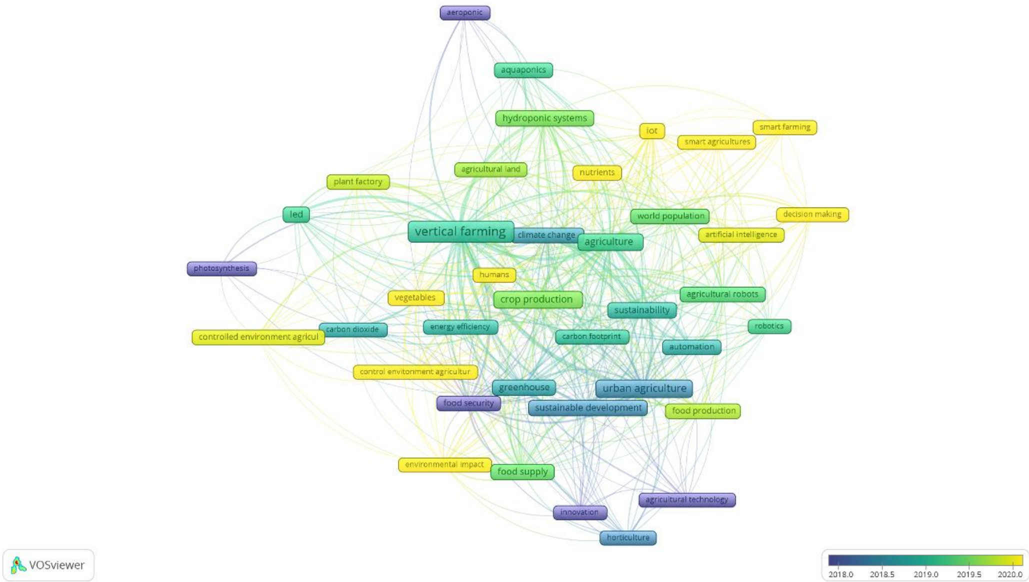


Figure 2. An overlay visualization map to identify the evolution of keywords used in the set of articles analyzed in this study. Different colors indicate the evolution of research keywords over time based on the average publication year. Earlier research topics are colored purple and more recent items are shown in yellow. The data were processed and mathematically analyzed using the clustering algorithm of the VOSviewer® software version 1.6.15.

3.2. Development of VF Systems

Agriculture has undergone several technological changes over the years, which have improved the agricultural systems, and the VF system has adapted these technologies to its benefit (Figure 3). The use of VF in scientific research to demonstrate their benefits shows a positive exponential trend (R^2 = 0.97) (Figure 4) indicating an increase of more than 195% in the number of articles published from 2008 to 2021. This increase may be due to the VF system being in synchrony with current sustainable production strategies and global development pacts to increase production efficiency and sustainability on the part of the Food and Agriculture Organization of the United Nations (FAO). The countries of higher research on VF are led by China (around 27.5% of the total), followed by Japan (24.8%), Korea (18.1%), and the USA (10.4%) (Figure 5), (also see Supplementary Material, Table S1). This may be due to the great interest on the part of developed countries to be at the forefront of innovations and technologies, being these countries among the most developed according to FAOSTAT [63] by their Gross Domestic Product.

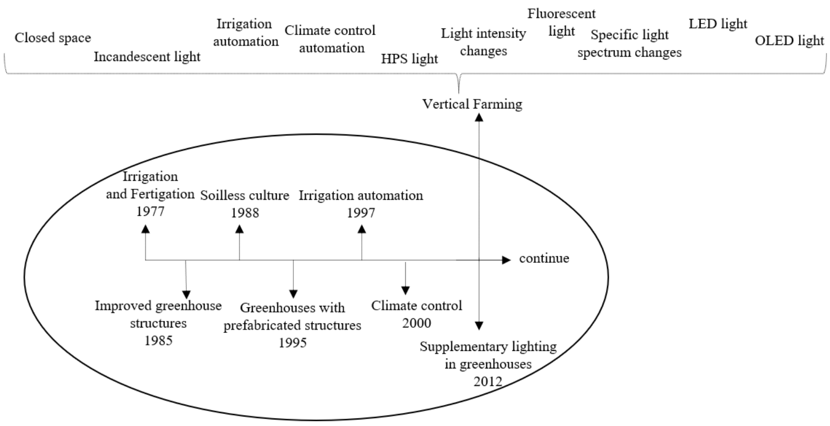


Figure 3. Schematic representation of innovations in intensive agriculture and major developments in vertical farming systems in line with the sustainability of agriculture.

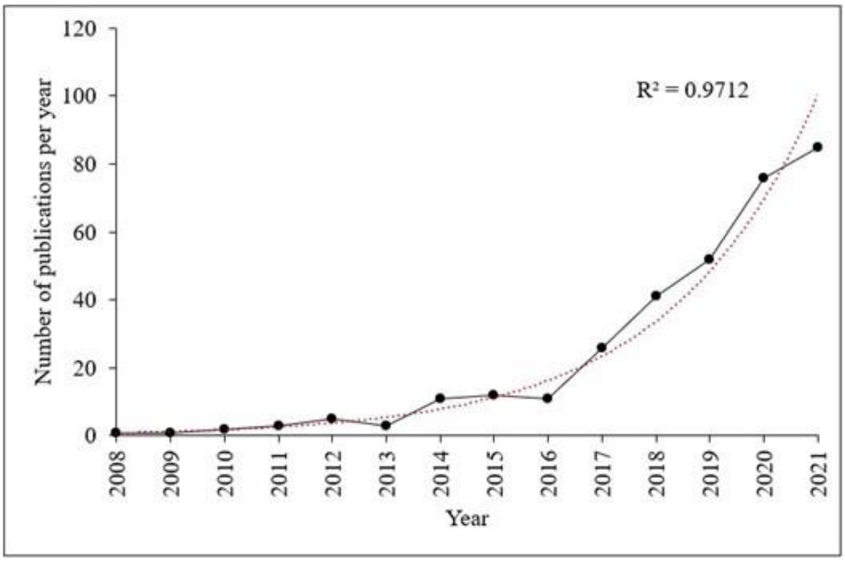


Figure 4. Trend in the number of published studies in which the vertical farming has been used. n = 381.

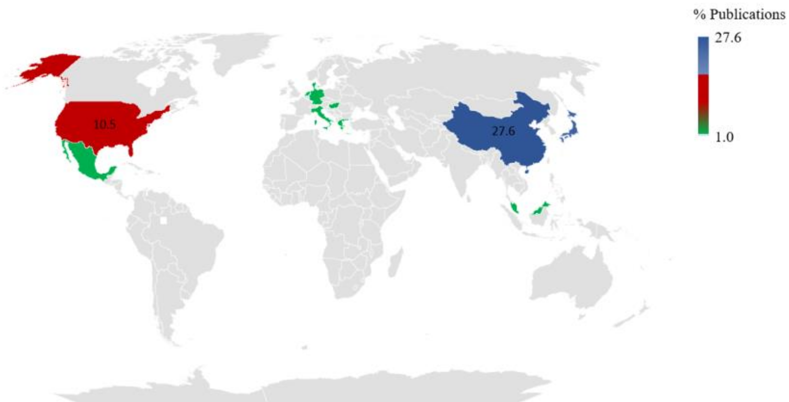
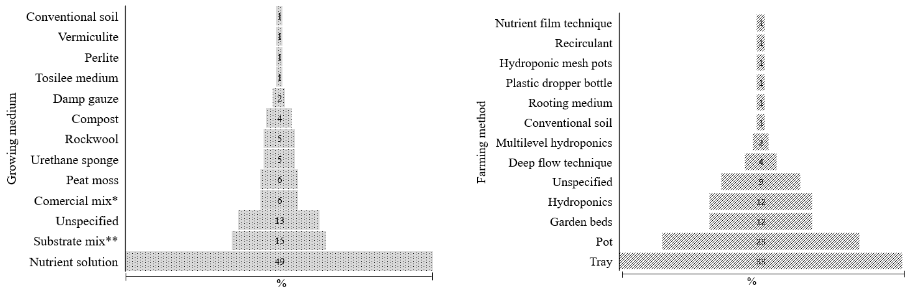


Figure 5. Geographical location where vertical farming systems were performed for researching. n = 105.

3.3. Characteristics of VF Systems

3.3.1. Methods and Culture Media

The limited space in the VF systems and the small amount of soil or substrate to be used has been reflected as an important advantage, opting for more sustainable and innovative cultivation methods. The articles analyzed in this work have used different types of culture media and culture systems (Figure 6A,B and see Supplementary Material, Table S1). The most growing media used is nutrient solutions (49%) followed by commercial substrate mixtures composed of peat moss, perlite, sand, vermiculite, coir, pumice stone, and pine bark (15%). In addition, the use of compost as an alternative substrate is gaining relevance in VF systems (4%), probably due to the different benefits on crop productivity and disease suppressive effects [64,65]. Wahome et al. [66] tested the effects of different hydroponics systems and growing media (vermiculite, sawdust, and river sand) on the vegetative growth of *Gypsophila*, and it was concluded that the highest plant height was obtained from plants grown in vermiculite, but the highest number of shoots/plant and cut flower stem length was obtained with sawdust, moreover the plants were grown using bag culture hydroponics system. Khandaker and Kotzen [67] studied vegetables (lettuce, basil, spinach, chicory, asparagus, mint, and tomato) with different substrates in vertical farming. better plant height results were obtained using mineral wool and vermiculite (14.7 and 13.7 cm, respectively) compared to coir substrate and pond algae (5 and 6 cm, respectively).



(**A**) (**B**)

Figure 6. Growing medium used (**A**) and type of farming methods (**B**) on vertical farming. * Unspecified mix; ** include peat moss, perlite, sand, vermiculite, coir, pumice stone, and pine bark.

On the other hand, soilless cultivation or hydroponics is the most used cultivation system in VF systems probably because it is a clean cultivation system, with zero residues in closed systems and because it allows a better adjustment of crop nutrition parameters, and the efficiency of water and nutrient use is higher per production cycle compared to other systems [68]. Frasetya et al. [69] showed that Nutrient Film Technique (NFT) hydroponic systems were 6–10% more efficient on lettuce growth compared to the floating system and deep flow technique system. Santos et al. [70] showed that Deep Flow Technique (DFT) or NFT hydroponic system does not cause significant changes in basil growth under saline stress (Supplementary Material, Table S1). These systems in VF seek to reduce damage to biodiversity through methods that allow efficient and respectful productivity of natural resources such as soil and water.

3.3.2. Cultivated Plant Species

Figure 7 shows the wide diversity of species cultivated in the VF system, with leaf crops being the most cultivated species, among which lettuce stands out as the model crop with more than 28%, followed by cabbage (7.5%) and basil (5.9%). Lettuce does not use large spaces and is tolerant to salinity [71] and light stresses [72]. Data from FAOSTAT [63] shows that the lettuce crop is one of the most stable and constant with respect to production and harvested area worldwide. For example, in the period from 2015 to 2020, there was 1.2 million cultivated hectares with 27 billion tons of fresh product worldwide. This fact, further it is worldwide spread, attracts interest in studying the cultivation of lettuce in indoor cropping systems. The use of VF for vegetables has also shown interest in various non-horticultural cultivars. Table 3 shows that in recent years this system has been used to study more than 40 species, obtaining as results improvements in productivity, and even identifying the physiological responses of the crops with the light stress supplied.

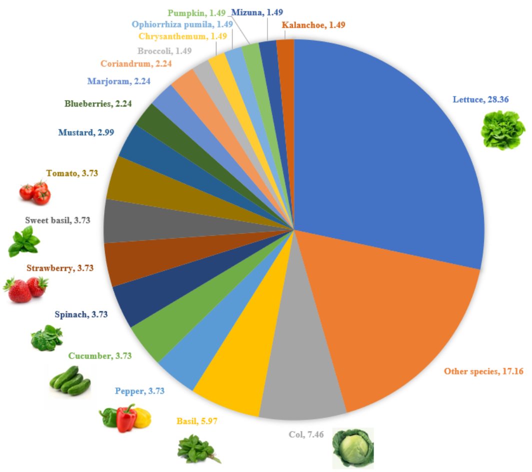


Figure 7. The pie chart shows the relative percentage of published research reported in the literature and used in this review for the different types of vegetables cropped on vertical farming.

3.4. Effect of Light in VF on Productivity, Quality, and Nutraceutical Values

3.4.1. Light Spectrum

Regarding the effect of spectrum in agronomy, the first scientific work was done in 1843 by John Draper [73], however, the increase in the number of publications on this subject has been reflected from 2010 onwards with a greater combination of spectrum colors and using LEDs of a specific spectrum. Figure 8 shows the wide diversity of spectra used in the investigations, where the specific spectrum-LED peak [450 nm (blue color)] was the most used (27%), followed by the combination of red + blue spectra [450–495 nm (blue) and 620–700 nm (red)] with 20%, the combined spectra red + white (11.8%) and red + blue + green (just over 10%). It can also be observed that there is still interest in evaluating other spectral combinations and their effect on crop growth and development (less than 10%), probably because of accelerated growth in VF systems and the improved quality of LED light implemented in the horticultural sector [74].

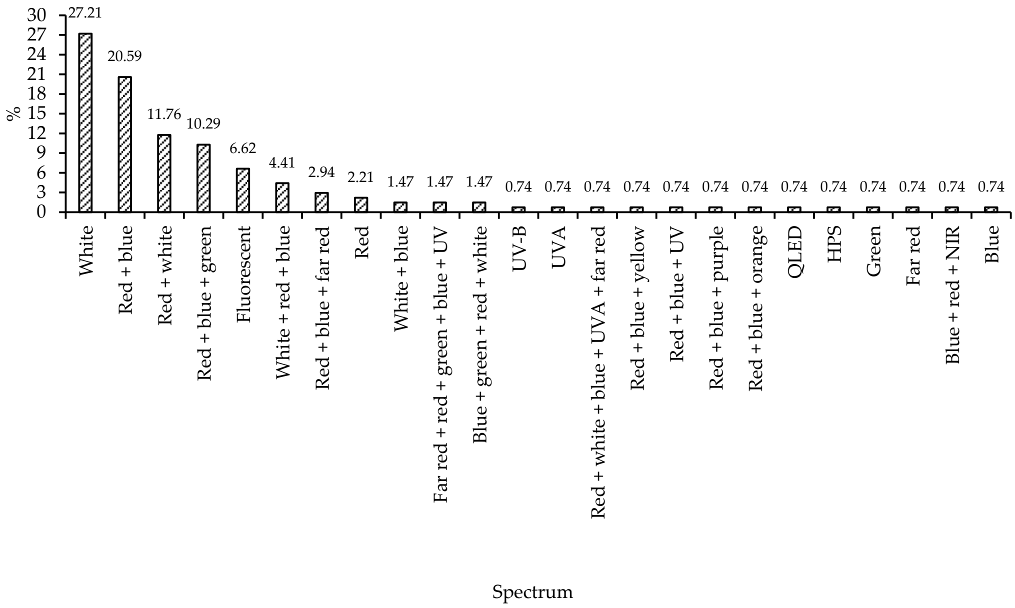


Figure 8. Illumination spectra used in vertical farming research for the growth and development of horticultural, ornamental, fruit, and aromatic plants. n = 136.

Table 3 and Supplementary Material shows some results about the types of lamps with the specific spectrum (lights red (R), blue (B), white (W), far red (FR), green (G), UVA, individual or combined) that have been used in different crops, and the effect in their productivity and antioxidant compounds. In basil cultivation, for example, Larsen et al. [75] or Pennisi et al. [76,77] studied spectral combinations that benefit growth (W/R) and phytochemical accumulation (R/W; G/R/W/B). For cabbage He et al. [78] found that the R/B/W/FR/UVA combination improved plant morphology and increased antioxidant compounds, compared to those growths without UVA light; Dou et al. [79] similarly obtained positive effects on phytochemical accumulation with a R/W/G spectral combination for basil, mustard, and kale crops, compared to those grown without the inclusion of G spectrum. Most of these spectral combinations are already given by default by the lamp manufactured (Supplementary Material, Table S1), and others are combined by researchers to see the effect on some parameters of interest.

Rihan et al. [80] in lemon balm plants obtained a positive effect on growth and yield with a value of 435 nm on photosynthetic activity, achieving this peak with the LED (B/G/R) combination. Combinations of spectra adding FR in lettuce cultivation have benefited weight gain [81]. The use of W/B spectra resulted in higher content of pigments, anthocyanins, vitamins C and A, phenolics, and total flavonoids in two lettuce cultivars (*Yanzhi* and *Red Butter*) [82]. For strawberry, most combinations were R/W which improved fruit development and propagation [21,83,84]. The positive effects of the red spectrum on plants are likely due to the fact that it coincides with the maximum absorption peak of the photosynthetic response recorded by McCree [28].

3.4.2. Light Intensity

The most used light intensity in VF is 100, 150, and 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Figure 9). When growing plants in VF, the aim is to simulate natural conditions light being one of the limiting resources in this system; therefore, light adaptation has been sought to efficiently optimize light, so studies are conducted with varying levels of intensity to test the effectiveness in different crops to increase the uniformity of leaf reflectance and avoid a lack of light or, on the contrary, light stress. The combined effect of photoperiod and intensity (PPFD) are parameters used to regulate plant growth and quality [85,86]. Low PPDF is associated with decreased plant quality [87]. In this sense, the optimal combination of PPFD, photoperiod, and spectrum quality can optimize energy use and plant quality [88]. In lettuce cultivation, Kim et al. [89] obtained adequate productivity with a PPFD 360 $\mu mol \cdot m^{-2} \cdot s^{-1}$. However, in cucumber, an optimum PPFD was 110 to 125 $\mu mol \cdot m^{-2} \cdot s^{-1}$ [19]. When plants have light needs, they tend to elongate to look for the necessary light on their own, which may explain the growth of stems and higher production. Simultaneously, insufficient light exposure stops the chlorophyll from working at peak performance, causing, leaves become yellow and died. Zou et al. [90] mentioned that spinach grown under an intensity of 150 $\mu mol \cdot m^{-2} \cdot s^{-1}$ is optimal to obtain better quality plants. In strawberry cultivation, Maeda and Ito [91] have found that illumination conditions of 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ higher anthocyanins are produced as a response to light stress protection [92], so perhaps 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ is a high value for strawberries crop, but that also provides additional nutritional value.

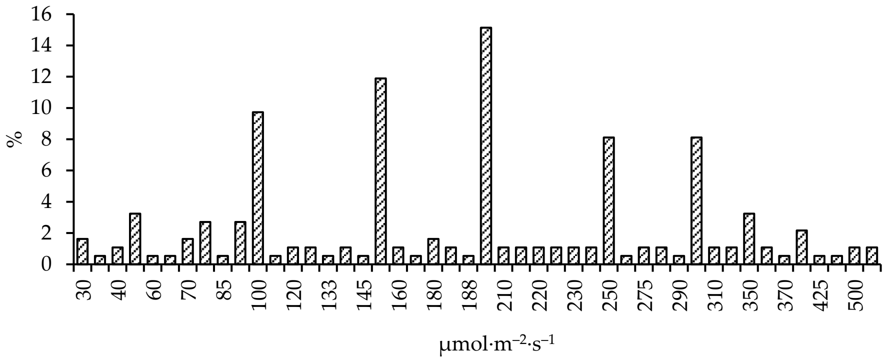


Figure 9. Intensities used in vertical farming systems. n = 185.

Therefore, depending on the species and the objectives to be achieved, the illumination conditions should be optimized, considering that the results obtained in this work had an adequate response between the range of 100 to 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for the studied species.

3.4.3. Photoperiod

There is a fundamental relationship between photoperiod and the produce enough photosynthate to plant development, especially for bloom [93]. The photoperiod varies according to the cultivars and the group to which it belongs, whether it is a short or long day. Therefore, finding the appropriate photoperiod is simple if we know the type of crop to study; however, this can be lengthened or shortened if the amount of light is modified, and thus find a balance between the light needed for the plants and saving electricity. The most frequently analyzed photoperiods in vertical farming were of 16 and 12 h light day, 50 and 20%, respectively, of the consulted studies (Figure 10).

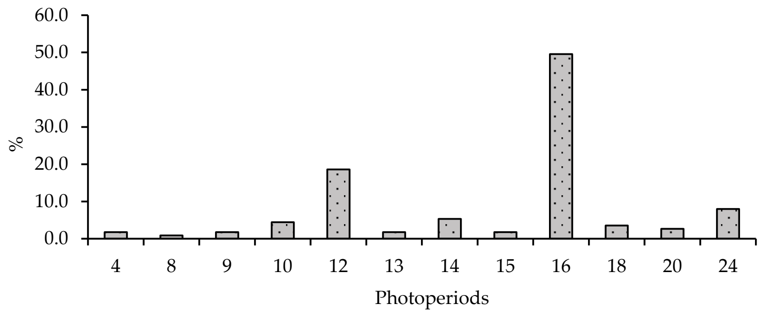


Figure 10. Photoperiods used in vertical farming systems. n = 113.

The most frequent use of these photoperiods may be due to the fact that is the time necessary for plant metabolism to maximize photosynthesis and produce sucrose and star synthesis [94]. Previous research suggests that an increase in dry weight showed positive relationships with photoperiod increased from 12 to 20 h·day^{-1}) in lettuce plants [95]. On the other hand, Ji et al. [96] found that the increase of photoperiod from 12 to 16 h·day^{-1}, significantly increased the plant height, stem diameter, and leaf area in three cucumber cultivars. Also, Yan et al. [86] observed an increase in cellulose content and improved mechanical strength at transplanting on cucumber plants subjected to a long photoperiod (16 to 20 h·day^{-1}). In crops such as watercress, Lam et al. [97] found that 20 h·day^{-1} could increase plant biomass. However, in spinach, Zou et al. [90] showed that 9 h·day^{-1} was sufficient to obtain higher quality plants.

3.4.4. Daily Light Integral (DLI)

One of the strategies to improve the productivity of a cultivation system with artificial lighting is through the optimization of the daily light integral (DLI). The most used range of DLI (more than 20%) for crops grown in artificially illuminated systems were 8.5 and 11.5 mol·m^{-2}·day^{-1} (Figure 11). These ranges are the result of the PPFD, and photoperiod used in the research and be adjusted to the crop and its age. Many experiments have evaluated the effect of different levels of DLI on growth, development, and plant quality on a wide range of crops [98,99] and the effect on consumption and energy-use efficiency in artificial lighting environment systems [100,101], where PPFD increased, but photoperiod is decreased or vice versa. Strawberry cultivation has been studied by Zheng et al. [84], where they concluded that a DLI between 11.5 and 17.3 mol·m^{-2}·day^{-1} helps the early propagation of plants because it is probably the right light intensity value and photoperiod value for the crop. Yan et al. [86] showed in hydroponic lettuce, with a DLI of 12.6 mol·m^{-2}·day^{-1} energy savings and carbohydrate accumulation; however, this value can be increased up to 14.4 mol·m^{-2}·day^{-1} and have a similar positive response in lettuce and chicory crops, with the increase of the amount of illumination in the plants [77]. Therefore, this parameter can help archive a reduction in energy consumption that is being demanded worldwide using the vertical farming system.

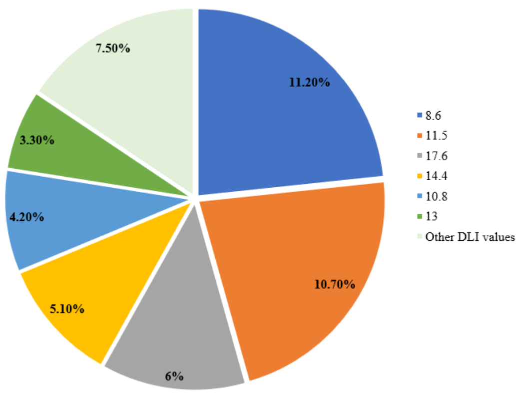


Figure 11. Daily Light Integral (DLI) (mol·m^{-2}·day^{-1}) values used in the studies. n = 215.

Table 3. Light and spectral characteristics of crops produced in vertical farming system and the effects produced.

Crop	Variety	Lamp Type	PPFD (µmol·m^{-2}·s^{-1})	Hours Per Day (h·day^{-1})	Best Results	Reference
Amaranth (*Amaranthus cruentus*)	Three-color cv. Red Aztec	LED R/B	180	16	Higher blue light, higher phenolic compounds. Chlorophyll decreases with R/B ratio 1:9.	Bantis [102]
Arabidopsis (*Arabidopsis thaliana*)	*	LED R/G/B	140	16	Red or blue light alone, they had opposite effects on tested parameters, but when of green light was mixed, mediate the effects caused, benefiting growth.	Zou et al. [90]
Asparagus (*Asparagus aethiopicus*)	Aethiopicus	LED B/R	*	8	Blue-red light combination improves yield by 1.5:1 ratio.	Rihan et al. [103]
Basil (*Ocimum basilicum*)	Dolly Emily	LED W/R; B	150; 300	16; 18	The plant fresh mass did not respond to the blue light while plant dry matter content was reduced at the combination high fraction of blue and a high PPFD.	Larsen et al. [75]
	Genovese	LED R/B	215; 250	16	Best growth with light intensity 250 µmol·m^{-2}·s^{-1}.	Pennisi et al. [76,77]
	Red Rubin	LED R/W; G/R/W/B	224	16	Green spectrum showed positive effects on phytochemical accumulation.	Dou et al. [79]
Blueberries (*Vaccinium sect. Cyanococcus*)	Emerald Snowchaser	LED W/R; W/UVA/FR	35; 70; 105; 140	20	Transplants under W/R produced higher shoot and root dry matter that W/UVA/FR demonstrating the important use of white light.	Gómez et al. [104]
Borage (*Borago officinalis*)	Blue	LED R/B	180	16	Higher blue light, higher phenolic compounds. Chlorophyll decreases with R/B ratio 1:9.	Bantis [102]
Broccoli (*Brassica oleracea*)	Italica cv. Lvhua	LED UVA	30	16	UVA treatment increased the contents of total chlorophylls, total soluble proteins, total phenolic compounds, and ferric reducing antioxidant power.	Gao et al. [105]
		LED G/B/R	30; 50; 70; 90	12	50 µmol·m^{-2}·s^{-1} (red: green: blue = 1:1:1:1) optimum light intensity and spectrum for growth. 70 µmol·m^{-2}·s^{-1} optimal for phytochemical accumulation.	Gao et al. [106]

Table 3. *Cont.*

Crop	Variety	Lamp Type	PPFD (μmol·m^{-2}·s^{-1})	Hours Per Day (h·day^{-1})	Best Results	Reference
Canola (*Brassica napus*)	Kizakino-natane	Fluorescent W	200	16	200 μmol·m^{-2}·s^{-1} was not sufficient illumination to reach the entire canopy.	Saito et al. [107]
		LED W/UVB	200	16 + 0.25; 16 + 0.5; 16 + 1; 16 + 2; 16 + 5; 16 + 8; 16 + 12; 16 + 16; 16 + 24 additional UV-B light	At 200 μmol·m^{-2}·s^{-1} the concentrations of all antioxidants increased Short-term UV-B irradiation could augment antioxidant biosynthesis without sacrificing crop yield or quality.	Lee et al. [72]
Capica (*Stylosanthes Capitata*)	*	LED R/W/B	150.89	16	Light R and FR improve reproductive responses.	Park et al. [108]
Choy Sum (Brassica *rapa*)	Parachinensis	LED W	50 to 500	12	Optimum illumination range is 400 μmol·m^{-2}·s^{-1} for greater leaf area, stem thickness, root system and photosynthesis	Huang et al. [109]
Chrysanthemum (*Chrysanthemum*)	Gaya Yellow Radost	LED W	180	4; 9; 10; 13	Supplementing with light B for 4 h·day^{-1} promoted flowering and increased the number of flower buds.	Park and Jeong [110]
Col (*Brassica alboglabra*)	Bailey	LED W; R/W/B/UVA/FR	300	10 (W); 12	LED R/B/W/UVA/FR improved biomass, morphology, antioxidant compounds and tender leaf production.	He et al. [78]
	Capitata	LED G		0; 24; 48	Chlorophyl concentration increased with intensity 50 μmol·m^{-2}·s^{-1} with green light spectrum at 48 h·day^{-1}.	Amagai et al. [111]
	Chinensis	LED R; W	200	16	Increased growth and development with red LED.	Harun et al. [88]
	Lvbao	LED R/W + UVA	250	12	UVA was benefited to produce functional substances, while FR was conducive to a significant increase in crop yield.	He et al. [78]
	Pabularia Scarlet	FR LED R/W; R/W/G	224	16	Inclusion of G wavelengths decreased shoot biomass compared to that of plants grown under combinations of R and B light.	Dou et al. [79]

Table 3. *Cont.*

Crop	Variety	Lamp Type	PPFD ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Hours Per Day ($h \cdot day^{-1}$)	Best Results	Reference
Coriandrum (*Coriandrum sativum* L.)	Green Aroma	LED R/B; R/B/G	150	16	Increasing the spectral range increases the concentration coriander aromatics E-(2)-decenal and E-(2)-hexenal. Plants grown under LED R acquired the greatest biomass in the same period.	McAusland et al. [112]
	*	LED R/B	*	8	The combination of blue-red light improves yield.	Rihan et al. [103]
	*	LED W	300	16	Growing coriander at 15 °C for 6 days increases the amount of dry biomass, antioxidant capacity, and a high content of secondary metabolites.	Nguyen et al. [113]
Cucumber (*Cucumis sativus* L.)	Joeunbaegdadagi	LED W	50; 100; 150; 200; 250	12; 16; 20	PPFD 150 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 16 $h \cdot day^{-1}$ improved plant growth and energy efficiency.	An et al. [114]
	Heukjong	LED W; FR	200	16	FR light positively supports plant morphological growth compared to light W.	Hwang et al. [115]
	Yuexiu No.3	LED R/B		12 to 16	Optimal PPFD of 110 to 125 $\mu mol \cdot m^{-2} \cdot s^{-1}$, in 14 to 16 $h \cdot day^{-1}$.	Cui et al. [19]
Garlic (*Alium schoenoprasum*)	Thick sheet	LED R/B	180	16	Higher blue light, higher phenolic compounds. Chlorophyll decreases with R/B ratio 1:9.	Bantis [102]
Gingeng (*Panax ginseng*)	Meyer	LED R/G/B	80	16	R light improved growth and photosynthesis, and B-light had a positive effect on bioactive compounds.	Kim et al. [89]
Kalanchoe (*Kalanchoe blossfeldiana*)	Lipstick Spain	LED W	250	160	Night Interruption Light affects morphogenesis and flowering depending on the cultivar.	Kang et al. [116]
Lemon balm (*Melissa officinalis*)	*	LED B/G/R/W	*	16	For blue spectra, the development and yield were lower despite having a significant impact on the photosynthesis activity. White and red-light spectra gave the best outputs in terms of impact on the growth and yield.	Rihan et al. [103]

Table 3. *Cont.*

Crop	Variety	Lamp Type	PPFD ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Hours Per Day ($h \cdot day^{-1}$)	Best Results	Reference
Lettuce (*Lactuca sativa* L.)	Batavia Othilie	*	200; 400; 750	16	Dry mass increased with increasing photon flux to a PPFD of 750, but the highest fresh weight efficiency was achieved at 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$.	Carotti et al. [117]
					Best growth effect with LED W without combination.	Nguyen et al. [118]
	Butterhead cv. Asia Cherokee	LED W; W/R; W/B	150	12	Addition of constant FR increased weight and growth and reduced chlorophyll.	Meng and Runkle [81]
	Rex	LED B/R; B/R/FR	180	24	Optimal PPFD at 360 $\mu mol \cdot m^{-2} \cdot s^{-1}$ with LUE 6.5 g MJ^{-1}.	Kim et al. [89]
	Romaine cv. Asia	LED R/B	200	16	Tipburn showed positive relationship with light intensity and the relative growth rate occurred during 23~27 days after sowing.	Xu et al. [119]
	Romaria Summer Surge	LED W LED W/R/B	85; 125; 187 80; 120	16 12	Increased growth under alternating R/B lights. The R/B combination is recommended for short-cycle crops to reduce autotoxin secretion and guarantee yields.	Ohtake et al. [120]
	Tiberius	LED W; R/B	200	16	Light quality with different R/B ratios showed pronounced effects on organic carbon and autotoxin secretion.	Zhou et al. [121]
	Yanzhi	LED W; W/FR; W/B	250	10	W/B produced higher contents of pigments, anthocyanins, vit C-A, phenolics and total flavonoids. With W/FR increase in fresh and dry weight.	Li et al. [122]
Lychnis coronaria (*Silene coronaria*)	*	LED R/B	*	8	The combination of blue-red light improves yield.	Rihan et al. [103]
Marjoram (*Origanum majorana*)	*	LED W/FR; W; W/B	362	4	W/FR and W LEDs increased plant growth, dry matter, and light use efficiency.	Wittmann et al. [123]
Mentha (*Mentha spicata*)	*	LED R/W	*	8	B/R light combination improves yield.	Rihan et al. [103]

Table 3. *Cont.*

Crop	Variety	Lamp Type	PPFD (µmol·m^{-2}·s^{-1})	Hours Per Day (h·day^{-1})	Best Results	Reference
Mizuna (*Brassica rapa*)	Japonica Little Gem	LED R + B pulses LED W	154 444; 370; 318; 278; 247; 222	Various 10; 12; 14; 16; 18; 20	Environmental stress in low light, higher water use efficiency. Biomass increased 16% in response to increasing the photoperiod from 10 to 20 h. Extending the photoperiod and reducing PPFD increased plant growth and reduced the instantaneous heat generated by the lamps.	Park et al. [124] Palmer et al. [125]
Mustard (*Brassica juncea*)	Red Lion	LED R/B	180	16	Increasing the blue light portion caused less phenolic compounds and total antioxidants.	Bantis [102]
Nasturtium (*Tropaeolum majus* L.)	*	LED W	200; 300	16; 24	24 h improved dry weight, antioxidant capacity and total phenolic content.	Xu et al. [126]
Onion (*Allium cepa*)	Victory	LED R/G/B	69–77	*	Light R promoted leaf width and area, starch accumulation in shoots, but reduced concentrations of flavonoids and total saponins.	Zhou et al. [127]
Pea (*Pisum sativum*)	Dun	LED R/B	180	16	Increasing the blue light portion caused less phenolic compounds and total antioxidants.	Bantis [102]
Pepper (*Capsicum annuum* L.)	Serrano	LED W; R/B pulses	50; 110; 180	*	No difference between continuous and LED pulsed in production or capsaisinoid is shown.	Olvera-Gonzalez et al. [16]
	Shinhong Tantan	LED W; FR	200	16	FR-enriched supplemental lighting for improved plant growth and morphology.	Hwang et al. [115]
Pumpkin (*Cucurbita mostacha*)	Bulrojangsaeng	LED W; FR	200	16	Supplemental lighting enriched with FR improved plant growth and plant morphology.	Hwang et al. [115]
	Heukjong	LED W	150	16	Scion and rootstock production in a Plant Factory with Artificial Light improves productivity and uniformity.	An et al. [128]
Radish (*Raphanus raphanistrum*)	Saxa	LED R/B	180	16	Increasing the blue light portion caused less phenolic compounds and total antioxidants.	Bantis [102]
Saffron (*Crocus sativus*)	*	LED W	*	*	Decreases starch content.	Natsuhara et al. [15]

Table 3. *Cont.*

Crop	Variety	Lamp Type	PPFD ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Hours Per Day ($h \cdot day^{-1}$)	Best Results	Reference
Sesame (*Sesamum indicum*)	Gomazou	Fluorescent	235	12	At 28 °C leaf browning was induced. At 15°C the fresh weight of shoots was higher.	Date et al. [129]
Spinach (*Spinacia oleraciea* L.)	BJC009	LED W/B/R	145	14	Increase productivity by 160%.	Fernández-Cabanás et al. [130]
	Disease-resistant 388	LED R/B/G	100; 150	9; 13	150 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 9 h is optimal for best quality.	Zou et al. [90]
	Geant D Hiver	LED FR/R/G/B/UV	150	16	Photosynthesis developed best with a high ratio of R or FR light with B.	Bantis et al. [131]
Ssamchoo (*Brassica Lee*)	Namai	LED W	300	14	Causes stunted growth due to photorespiration.	Noh and Jeong [132]
Strawberry (*Fragaria × ananassa* Duch.)	Benihoppe	LED R/W	30; 90; 150; 210	16	PPFD 90 is recommended at the rooting stage and 210 at the seedling stage.	Zheng et al. [83]
		LED R/W	200; 250; 300; 350	12; 16	DLI 11.5–17.3 $mol \cdot m^{-2} \cdot day^{-1}$ is beneficial for propagation.	Zheng et al. [84]
	Elan	LED W	200; 300; 400; 500	16; 24	At 24 h and 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ higher anthocyanin and productivity.	Maeda and Ito [91]
	Maehyang	Fluorescent	230	16	VF is a suitable method to improve the propagation system.	Park and Jeong [110]
	Sachinoka	Fluorescent LED W	65 150	10 10	High potential to produce flowers and fruits. Method and conditions suitable for growth.	Le et al. [21]
Sweet basil (*Ocimum basilicum*)	Compact	LED W/R	90	16	Increased light B increased the content of pigments and phenolic compounds.	Azad et al. [133]
Tomato (*Solanum lycopersicum* L.)	Dongfeng	Fluorescent; LED W; W/R	50; 100; 150	14	LED light showed 110% energy saving, promote dry matter, leaf thickness Increase growth and production.	Zheng et al. [134]
	Ingar F1	LED W/B/G/A/R/FR	210	15	The combination of plant and architecture and spectrum-dependent photosynthesis results in the highest rate of crop photosynthesis under red light in plants initially grown under green light.	Dieleman et al. [135]
Watercress (*Nasturtium officinale* L.)	Brassicaceae	LED R/B	133; 160; 200; 266	12; 16; 20; 24	20 h with PPFD 160 enhanced glucosinolate and plant biomass.	Lam et al. [97]

* Unspecified.

4. Conclusions

The increasing need for more vegetable production worldwide and the energy reduction needs of lighting by using LED has led to an exponential increase in vertical farming. The 195% increased VF research in 12 years is important to help address several of the current handicaps due to the great variability of the effects of the spectra supplied on horticultural crops.

Our bibliographic analysis in VF has helped to quantify the information and results of the research carried out. For example, the control of photoperiod, spectrum quality, and comprehensive daily illumination to optimize morphological and physiological parameters of crops to obtain sustainable and profitable crop production and improve crop productivity and energy efficiency. Leafy vegetables were the most produced crops in VF, predominantly lettuce. In most of the research for most of the species analyzed LED lights were used with specific spectrum peaks between 450–490 nm and 620–700 nm, while the optimal photoperiod was (12 and 16 $h \cdot day^{-1}$), the intensity (PPFD) (100, 150 and 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$) and DLI (8.5 and 11.5 $mol \cdot m^{-2} \cdot day^{-1}$).

However, there is still great interest in VF systems for further optimizing these parameters to achieve specific objectives that improve each plant yield and quality, as well as the increase of bio-compounds (such as phenolic compounds, anthocyanin, ascorbic acid, carotenoids, polyphenols, etc.) that have been improved by the use of LED lights.

Currently and in the short term, there will surely be more interdisciplinary advances that can help the potential growth of this system, both at a business and research level, finding more profitable crops that help offset the economic cost, such as short-cycle crops that are very important due to their high demand (e.g., microgreens), and the use of solar panels for the use of LEDs. Although we can say that the gains at the environmental level are tangible, through the resources use efficiency (RUE) and with a great potential demonstrated on the quality of the products, although there are still future perspectives to be defined in the economic, social, and energetic area.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae9010063/s1, Table S1: Characteristics, agronomic and lighting conditions used in the scientific research that practiced vertical farming.

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