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Review

Vegetable Production in PFALs: Control of Micro-Environmental Factors, Principal Components and Automated Systems

Filippos Bantis [1,*], Ioanna Chatzigeorgiou [2], Michail Sismanis [3], Georgios K. Ntinas [2] and Athanasios Koukounaras [4]

[1] Department of Agriculture, University of Patras, 30200 Messolonghi, Greece
[2] Institute of Plant Breeding and Genetic Resources, Hellenic Agricultural Organization DIMITRA (ELGO-Dimitra), 57001 Thermi, Greece; ichatzigeorgiou@elgo.gr (I.C.); gntinas@elgo.gr (G.K.N.)
[3] Green Blue Modern Solutions P.C., 55534 Thessaloniki, Greece; gbm.solutions@outlook.com
[4] Department of Horticulture, Aristotle University, 54124 Thessaloniki, Greece; thankou@agro.auth.gr
* Correspondence: fbantis@upatras.gr

Abstract: Plant factories with artificial lighting (PFALs) are indoor crop production systems aiming at the growth of high-value products in terms of yield and quality, while maximizing resource use efficiency. The emergence of PFALs opened a new world for crop production and offered an option to tackle problems related to climate change, land availability, and urban/peri-urban farming. This was made possible upon major technological advancements and extensive research in the field of controlled environment agriculture, which paved the way for the establishment of such cost-efficient and climate-unaffected modules of vegetable and other crops' production. In the present review, we have examined the recent research achievements regarding the micro-environmental factors, the principal components, as well as the automated systems used for plant production in PFALs. Ultimately, we provide the reader with a number of future perspectives that can be considered for indoors cultivation in the following years.

Keywords: plant factory with artificial lighting; growth chamber; vertical farming; soilless cultivation systems; light quality; IoT systems

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Citation: Bantis, F.; Chatzigeorgiou, I.; Sismanis, M.; Ntinas, G.K.; Koukounaras, A. Vegetable Production in PFALs: Control of Micro-Environmental Factors, Principal Components and Automated Systems. *Agriculture* **2024**, *14*, 642. https://doi.org/10.3390/agriculture14040642

Academic Editor: Phillip Wadl

Received: 9 February 2024
Revised: 15 March 2024
Accepted: 20 April 2024
Published: 22 April 2024

1. Introduction

1.1. Review Objectives

During the last decade, the field of research on plant factories with artificial lighting (PFAL) has yielded technologies that make such systems increasingly efficient, thus multiplying its benefits to the research and industrial sectors, and ultimately to consumers. The present article reviews the scientific literature on PFAL systems and provides a critical examination of the micro-environmental factors that can affect horticultural crop growth and productivity, as well as the principal components and automated systems at hand. In addition, the role of artificial lighting regarding plant–light spectra interaction is examined, along with the use of soilless systems and the control of nutrient solution. Figure 1 depicts the configuration of PFAL, including the principal components, the renewable sources, and the connection with automated systems.

1.2. The Emergence of PFALs

Nowadays, the agricultural sector and global supply chain have to address new challenges such as food safety, food security, increased bioactive compounds, and food sustainability [1]. Major issues include the expected increase in world population by 25% at 2050; the urban population, which is estimated to reach 6.3 billion in 2050 and be 65% of the total [2]; agricultural land loss; consumers' demand for food with high nutritional value; pressure for using renewable energy resources, as well as climate change [3]. Recently, the COVID-19 pandemic placed the food supply chain and the food industry in the spotlight, since a severe pandemic could cause significant food shortages throughout the world due to social and economic constrains, as well as labor availability [4,5]. Possible answers to the above, among other practices, are local production and short supply chains that are less affected by international restrictions, and are in close proximity to the stakeholders (supermarkets, restaurants, catering companies, etc.).

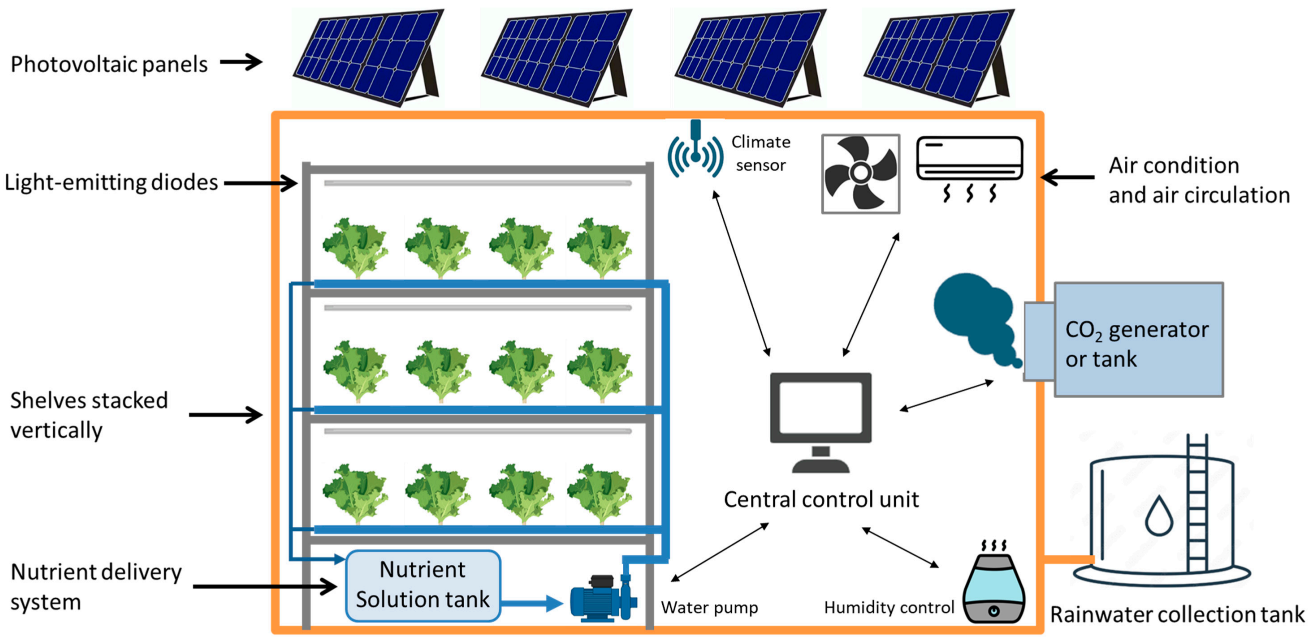

Figure 1. Configuration of plant factory with artificial lighting depicting the principal components, the renewable sources at hand, and the connection with the automated systems.

A wide range of vegetables are cultivated worldwide, which are essential for a healthy diet since they offer a plethora of bioactive compounds such as vitamins, phenolics, and carotenoids, among other antioxidants providing a means of controlling oxidative stress in humans [6], and therefore the WHO recommends the daily consumption of 400 g fruits and vegetables. Vegetable cultivation takes place on various scales of farms, which require good and marginal land, in both urban and rural areas [7], although the productivity of vegetable farming is not increasing at the required rate [8]. Moreover, vegetables are characterized by a wide range of sizes and shapes, taking up different volumes, thus some of them are better suited to growth in PFALs than others. The appropriate morphological and physiological characteristics of plants required to make them suitable for cultivation in PFALs are discussed later in this section.

Urban agriculture is characterized by benefits such as fresh products with extended storage potential and improvements in the city environment. The most common spaces that could be used are rooftops, fallow land, roadsides and private balconies [9], characterized by proportionally small available space, and mainly used in a manner supplementary to other agricultural systems in urban areas [10]. Therefore, alternative systems without the use of land or acreage for farming have been proposed under the term Zero-Acreage Farming (Z-farming), based on alliance between agriculture and urban constructions, providing the benefits of circularity and bio-economy [11,12].

Among Z-farming systems, nowadays, PFALs are gaining a lot of attention from researchers, growers and stakeholders due to their several important benefits. They represent a vertical indoor hydroponic growing system, allowing the development of unused buildings (e.g., abandoned warehouses, railway wagons, old containers) into plant production environments isolated from undesirable environmental conditions [12–14]. Such PFALs can also be established in schools and community centers for educational purposes, in order for students and residents to familiarize themselves with cultivation practices and sustainable crop production, as well as to enjoy freshly produced vegetables. A similar approach may be followed for rooftop plant production on top of residential and other buildings in urban areas. The latter is an ideal practice in densely populated cities where space for crops is scarce and resource use efficiency is imperative for sustainable vegetable production. Greenhouses also offer a significant option to tackle some of the abovementioned issues, but environmental control and land-use efficiency are considerably less controlled, while the growth cycle duration is reportedly increased compared to PFALs [15].

Plant-growing in specialized substrates and in a decontaminated environment greatly limits incidents of plant pathogen infections, subsequently leading to the avoidance of agrochemical use [16]. Also, the use of mainly closed hydroponic systems (i.e., systems where the same nutrient solution is recirculated), such as deep water culture (DWC) and the nutrient film technique (NFT), among others, provides the opportunity to increase nutrient and water use efficiency [17]. Besides this, PFALs can be established almost anywhere, with an emphasis on urban and periurban spaces in order to reduce "food miles" to the absolute minimum, since the production center can be in close proximity to the market and even the consumer's plate. For the same reason, the products have higher safety, since fewer people will be involved in the supply chain, and the shelf-life will be increased due to the lower time needed to reach the market [18]. Furthermore, a closed-circuit monitoring system (i.e., an interconnected network of sensors, where all components capture and transmit data to a central control unit) ensures the constant monitoring of the environmental conditions, while it facilitates visual observation of the crops' status. Precise environmental control is a crucial parameter separating PFALs from other growing systems. Here, micro-environmental conditions, which are factors that are unique to a single plant or to a group of plants within their growing spaces, can efficiently be controlled according to specific crops' requirements and with a view to enhancing the yield and production quality. For comparison, conditions in the broader environment are common over a larger location at a given time. Moreover, PFALs, as indoor farming units, offer the advantage of reduced environmental impact while achieving higher production. The implementation of innovative technologies in PFALs can help establish a positive balance in energy production/consumption during its operation, and can characterize this system as a unit of double production (vegetables and energy). To achieve the above, appropriate methods seek the maximum possible exploitation of energy intake. The smart use of solar energy in PFALs provides opportunities for new industries, strengthens local economies of urban and rural areas, reduces dependence on fossil fuels, and reduces greenhouse gas emissions, leading to sustainable food production.

A plethora of crop types and species are suitable for cultivation in PFAL systems, depending on a number of specifications. Today, in most cases, vertical farming is characterized by multilayer plant production, where layers are separated by a short vertical distance from each other (about 50 cm) in order to maximize land use efficiency; thus, crops must not exceed 30 cm in height. However, some PFALs are established with a view to producing crops typically grown using high-wire, such as tomatoes. In addition, plants should be able to grow well under relatively low light intensity and high planting density, while they must also provide a high-value product that can be regulated according to the customers' needs [18]. To that end, the following crop types and plant species are suitable for PFAL systems: (a) leafy vegetables and (b) baby leaf vegetables such as lettuce, spinach, rocket, and kale; (c) sprouts and microgreens such as Brassica spp., radish, basil, and garlic chives; (d) fruit crops such as tomatoes and strawberries, and rooted crops such as carrots; (e) edible flowers such as pansies; and (f) any kind of transplant such as vegetable seedlings, flowers and tree cuttings. Before now, leafy vegetables and microgreens have been the most commonly produced plants in PFALs, while trials are in progress on the production of other products, such as medicinal plants, edible flowers and other fruits and vegetables [19–22].

2. Principal Components and Automated Systems

2.1. Environmental Control Systems

A controlled environment offers benefits regarding production efficiency, plant yield and product quality. Therefore, microclimate management is fundamental to guaranteeing proper plant development [23]. When it comes to PFALs, continuous dehumidification is required to avoid relative humidity level increases related to several factors, such as plant transpiration rate, irrigation strategy and lack of natural ventilation [24,25]. Natural ventilation is not preferable due to the reduction in CO_2 efficiency, and the possible contamination caused by pests and microorganisms from the outside [26]; heat pumps and adsorption methods are used instead [24].

In closed environments, the CO_2 concentration can rapidly drop below the ambient level, requiring supplemental injection to avoid limitations to photosynthesis and plant growth [27]. Carbon dioxide (CO_2) enrichment systems are commonly used to increase CO_2 concentration from 800 to 2000 µmol mol^{-1}, promoting both photosynthesis and plant growth [23]. Indoor CO_2 concentration can be increased as needed, according to plant species, environmental control strategies for light, ambient temperature and humidity, and the cost and source of CO_2 injection [27], by releasing pure gas or by producing CO_2 via fuel combustion [28].

Temperature is another environmental factor that influences all stages of plant growth cycles. Thus, not only are heating and cooling systems required, but a uniform spatial air temperature distribution in the PFAL cultivation room is also necessary in order to obtain homogenous plant growth. Besides this, artificial lighting systems may produce heat, which should be removed by heat pumps [29], or homogenously recirculated using air fans [30].

Finally, another necessary input in PFAL systems is lighting. In horticulture and especially in controlled environment production systems, the use of light-emitting diodes (LEDs) has rapidly grown [31], offering many advantages such as the ability to select light wavelengths, and change the intensity and quantity, thus influencing plant growth [32]. Blue and red light have the highest photon efficiency, so they are more effectively absorbed by chlorophylls than the light of other wavelengths in the visible spectrum [32,33].

Even though LEDs are used instead of fluorescent light to reduce electricity consumption, electricity costs still represent a large part of the production cost [34]. Generally, artificial lighting systems, along with the electricity needs associated with heat pumps and air fans, were estimated to account for around 30-45% of the total operation costs of a PFAL [29]. In comparison to open-field cultivation, though, PFAL cropping saves on storage, refrigeration, transportation fuel, and pest and weed management. The high energy costs can be ameliorated with the use of renewable energy sources such as photovoltaic panels, which can be installed on the roof, or even adjacent to the sun-facing walls, of the establishment [35]. Additionally, the yield is higher, and production is profitable in all seasons [24]. Ultimately, the reduction in energy used for environmental control conditions' management can help to reduce operational costs [29].

New technological phenomena, such as scientific and technical inventions including artificial intelligence (AI), Information and Communication Technologies (ICTs), Automated Design (AD) and Big Data, are correlated with the design of PFALs. Nowadays software constitutes an extremely important design factor, which gives PFALs added value both in engineering design via computer systems and in terms of economic weight [36]. An adaptive artificial intelligence (AI) algorithm model can be combined with visual devices and a variety of environmental sensors to examine plants' growth state and adjust the control strategy in place for plant growth online. This requires careful configuration and custom programming in the application of such devices [37]. An open Internet of Things (IoT) platform can be used to store and display the system's parameters and graphical interface for remote access. The designed system can maintain healthy growing parameters for the plants with minimal user input [38].

2.2. Soilless Cultivation Systems

Cultivation systems in PFALs usually consist of a soilless culture, with the use of an organic or inorganic substrate, and the active application of water and fertilizer in a diluted nutrient solution [39]. Hydroponic cultivation is a type of soilless culturing method whereby plant roots are suspended in a static nutrient solution, or in a continuous flow or mist [39]. Specifically, the most common hydroponic systems include the following:

- NFT, wherein a thin film of nutrient solution flows (either continuously or intermittently) over the roots;
- DWC, which consists of crops grown with their roots continuously submerged in a nutrient solution;
- The aggregate culturing of growing crops in bagged substrates (e.g., rockwool or coconut coir slabs) or containers (e.g., Dutch/Bato buckets) with the nutrient solution applied via drip emitters.

NFT and DWC are typically used for short-term, non-fruiting crops such as leafy greens and herbs, while long-term fruiting crops are usually grown in aggregate culture [23].

An aeroponic system is another type of soilless culture methodology in which plant roots are suspended in a fine mist of nutrient solution applied continuously or intermittently [40], this being a viable and promising option in terms of water reduction [41].

Finally, to further reduce nutrient inputs, hydroponic and aquaculture system combinations are suggested. Here, fish and vegetables are produced alongside each other. Aquaculture products, such as decomposed fish feed and fish dejection, are use as inputs for plant development in a hydroponic unit for the action of nitrifying bacteria, which transform the ammonia produced by fish into nitrates that can be easily absorbed by roots [42]. The abovementioned soilless cultivation systems can be combined with rainwater from the roof, which can be collected using pipes leading to tanks adjacent to the PFAL establishment [43].

2.3. Design of the Artificial Lighting System

One of the principal components of any PFAL system is the lighting system, a multi-tier or multi-layer system consisting of lighting devices, almost exclusively LEDs, positioned above culture panels. The light sources are placed in a relatively thick array in order to maximize the light-use efficiency, since PFALs are systems based on intensive crop cultivation. The cost for lighting accounts for 20% of the total production cost, and a greater portion of the total electricity cost (roughly 70–80%) [44,45]. Light use efficiency is critical for both plant growth and for the economic and environmental sustainability of the PFAL system. Changing or improving the hardware of the lighting system after construction is not considered cost-effective, making it essential for a good hardware design to be put in place from the beginning [46]. LEDs are normally preferred over fluorescent lamps, due to the fact that their consumption is significantly lower, and they generate less heat [47], further lowering electricity costs by improving energy use efficiency [40]. This is especially important when taking into account other factors of PFAL systems, such as the high cultivation density, the limited area volume, the reliance upon artificial ventilation methods, etc., which all tend to increase demand, and thus the cost of temperature regulation/cooling [48]. LEDs also have a higher coefficient of conversion from electric energy to photosynthetically active radiation [26], making them ideal for use in indoor plant factories. However, one of the most critical drawbacks when using LED lighting technology is the initial cost [49], which tends to be significantly higher than that of conventional lamps [50]. Finally, while still in its early stages of development, plasma lighting is a promising new technology that could be potentially utilized for both supplementary lighting and as the sole light source in plant factories [51].

LEDs should be placed appropriately above the culture beds, creating a multi-tier system with vertical distances depending on the height of the cultivated crop (usually about 30–40 cm between shelves). Further improvements can be made in order to maximize the ratio of the light energy received by the leaves. Among others, improvements can be made via the selection of LEDs with well-designed light reflectors, reductions in the vertical distance between the plant canopy and the lights, and increases in inter-plant distances to allow more room for growth [26]. For example, through simulations, the photosynthetic photon flux density (PPFD) has been found to increase by 38% when using a white reflector, compared to a similar light source without one [52].

The recommended photoperiod for lettuce is 16 to 20 h of light, which improves the LUE when taking into account the electric energy use efficiency and the photosynthetically active radiation use efficiency [40]. An alternating 16 h light period and 8 h dark period is the most commonly used regime. Several tests have been performed to find the optimal photoperiod (primarily for lettuce), reaching up to a 24 h photoperiod [53,54]. However, electricity costs are ultimately what defines the photoperiod in PFALs, and an effective balance has to be reached between lowering power costs and maximizing yield [55]. Control of the lighting schedule can be achieved using a Programmable Logic Controller (PLC), which is a technology widely used in industrial automation applications, or using an open-source microcontroller, i.e., Arduino. The use of a microcontroller or microcomputer for the control of the lighting system can work synergistically with automation and IoT applications, since the use of such a device is a critical part of a PFAL system, handling the load of data and the processing.

2.4. Automation and IoT Systems

Wireless sensor networks (WSNs) have shown great advances over the past few years. The capabilities and the degree of flexibility offered from a multitude of different devices, sensors and communication protocols have greatly benefited plant production in PFAL systems, both in terms of monitoring and automation. The ZigBee wireless protocol is one of the most recent protocols to have been developed, and is regarded as one of the best alternatives for agriculture and closed plant production systems. ZigBee devices have low power consumption, can be used over a long range (i.e., 100 m with the use of a router node), and can be combined in great numbers to create topologies, covering wide areas and requirements. Bluetooth and Bluetooth low-energy (BLE) are also popular protocols used in small devices to aid communication, and have been extensively used to develop solutions in agriculture [56]. One of the main limitations of Bluetooth and BLE is the short communication distance (10 m) [57]. WiFi is one of the most widely used wireless communication technologies, with communication distances ranging from 20 m to 100 m. Diverse capacities for connections, messaging, and remote access are offered, with the main drawback being the very high power consumption [56], making it less than ideal for use in small devices and many agricultural applications.

PFALs can greatly benefit from the constantly increasing capacity for automation provided by advances in technology. Vast wireless sensor networks and complex monitoring systems are not only means of automating closed plant production systems, but they can also significantly lower production costs, especially compared with more traditional controlling schemes [58,59]. Optimizing production in such a way and enhancing plant quality [26] can greatly aid in improving PFAL sustainability and viability.

For example, Chen et al. (2016) [60] proposed an automated, non-destructive plant weight measurement system for the monitoring of plant growth and weight in closed plant production systems, comprising a weight measurement device and an imaging system. Another plant weight estimation system has been proposed by Jiang et al. [61]. This real-time image processing and spatial mapping system can calculate the weight of plants with an acceptable level of accuracy, and also give an estimation of future plant yield ahead of harvesting. An innovative approach in estimating plant growth and yield has also been proposed by Nagano et al. [62]. By processing a time series of leaf movements using optical flow analysis, the team was able to derive a good estimation of the plant weight at harvest time.

Montoya et al. [63] proposed a plant factory monitoring system for the measurement of air temperature, humidity, temperature, pH, electrical conductivity, dissolved oxygen and nutrient solution temperature. The system was based on an Arduino microcontroller, and all the data were stored and were accessible wirelessly via Bluetooth. When compared to well-established industrial-grade monitoring systems, this low-cost system presented a good alternative in terms of both data accuracy and cost. In another experiment, Spinelly et al. [64] proposed a new low-cost system for water use monitoring that produces similar results to state-of-the-art industrial solutions, while at the same time being less than a quarter of the regular cost.

An implementation proposed by Chowdhury et al. [38] offered the design and integration of a completely automated vertical hydroponics plant factory. The automatic monitoring and control system integrates a series of IoT environmental sensors (pH, EC, water level, humidity and temperature) that transmit their information via Wi-fi, using an Arduino microcontroller, to an IoT cloud platform. The IoT platform serves not only as a medium for storing and visualizing the information, but also as a medium for controlling all the subsystems to optimal conditions, under a predefined schedule or in a corrective way. This degree of control of all the subsystems involved greatly benefits plant production, in terms of enhancing growth rate and minimizing costs. The team of Cai et al. [65] presented an implementation aimed specifically at the real-time automatic regulation of nutrient solution pH in hydroponic plant factories.

Ijaz et al. [66] created a prototype of a PFAL with a remote control system, leveraging the capacities of ZigBee technology. The system proposed uses environmental and power sensors for data acquisition, and a ZigBee wireless mesh network to transfer the information and enable remote monitoring and control via the internet. Most of the plant factories opt for multi-shelf racks, maximizing production while at the same time minimizing costs and area extent. Part of the automation scheme is not only controlling the environmental variables to optimize plant growth, but also controlling the cultivation and transferring the plants throughout the whole process. Ohara et al. [67] proposed a new system and an automatic transfer unit, a robot, to fully automate the process and completely omit manual labor. Plants are placed on the racks, and the robot, placed between the multi-shelf racks, performs all the transferring via a predefined (and efficient) system based on the cultivation needs. This system is completely flexible and programmable, and is able to adapt to a multitude of different cultivation schemes. Sensors are placed on the automatic transfer unit to ensure the correct execution of all the movements and actions. The system as described was made fully functional at the Plant Factory Research Center of Osaka Prefecture University, and operated for more than a year with an average production rate of 250 plants (lettuces) each day [67].

3. Control of Micro-Environmental Factors for Vegetable and Food Production

3.1. Control of the Nutrient Solution

The properties of the nutrient solution provided (i.e., the composition of fertilizers, the pH, the final electrical conductivity) should be optimized for each crop, since plant nutrition in PFALs completely relies on it. It should be noted that electrical conductivity is a measure of the total inorganic salts (i.e., fertilizers) dissolved in the nutrient solution. According to most of the findings in the literature, an electrical conductivity of about 2.0–4.0 dS m^{-1} has proven beneficial for the development and quality of most vegetable crops. In a study involving sowthistle (*Ixeris dentata*) grown in a PFAL with different nutrient solutions, shoot fresh and dry weight, chlorophyll content, and leaf photosynthetic rate were enhanced under the highest electrical conductivity of 2.0 dS m^{-1} [68]. Moreover, Cho et al. [69] reported greater total and individual phenolic contents in carrots grown in a nutrient solution with an electrical conductivity of 2.0 dS m^{-1}, while fresh and dry weights were enhanced at 3.0 dS m^{-1}. This experiment was conducted in a controlled environment, under an NFT system. In another study on Korean mint (*Agastache rugosa*), the authors determined that electrical conductivities of 2.0 and 4.0 dS m^{-1} maximized all plant growth, physiological (Fv/Fm and gas exchange) and biochemical (phenolics) parameters compared to lower and higher (up to 8.0 dS m^{-1}) values [70].

High salinity is one of the major problems met by out-field cultivations, leading to diminished crop development and suboptimal yields. However, if applied properly, mild salinity has the potential to enhance the quality of specific crops by imposing controlled stress on plants. For example, in a study with spinach assessing both salinity levels and light quality treatments, it was shown that including 40 mM NaCl in the nutrient solution along, with a red and far-red rich light (low red/far-red ratio), enhanced the photosynthetic apparatus as well as the total phenol content and soluble sugar content in a PFAL system [71]. Red leaf lettuce cultivated with saline nutrient solution (either using seawater or NaCl) accumulated greater amounts of chlorophylls, carotenoids, sugars, and anthocyanins, thus achieving higher nutritional value [72]. Moreover, an electrical conductivity (EC) of 4.0 dS m^{-1} (higher than the typical Hoagland solution EC of about 2.0 dS m^{-1}) was found to be optimal, in Korean mint (*Agastache rugosa*), to promote bioactive compound accumulation without sacrificing plant growth [70].

3.2. Control of Light Properties

The most important environmental factors, such as temperature and relative humidity, are more or less well-established for several crops grown in closed plant production systems. For example, a recent study with lettuce (cv. Batavia Othilie) demonstrated that a combination of a 24 °C air temperature, a 28 °C root zone temperature, and a PPFD of 200 μmol m^{-2} s^{-1} was the most efficient with regard to photon conversion, even though a PPFD of 750 μmol m^{-2} s^{-1} accelerated biomass production [14]. This section deals with the effects of light used in fully controlled environments for plant production. In particular, the following paragraphs summarize recent findings related to light's effects on microgreens, baby-leaf vegetables, seedlings, and other vegetable types with a view to enhancing their yield, physiological and molecular status, and nutritional quality. Special attention has been given to plants' responses to the different spectral zones (i.e., UV, blue, green, red, and far-red), as well as their combinations.

Light is a unique factor that is absolutely essential in PFALs. The control of light quality for scientific purposes, in particular, has only recently been made technologically possible with the development of semiconductors mainly emitting red and far-red lights. The development of high-brightness blue LED (2014 Nobel Prize in Physics) paved the way for further research [73]. Red (600–700 nm) and blue (400–500 nm) lights are considered as the major wavebands enhance photosynthesis and controlled photomorphogenesis. Mustard (*Brassica juncea*) and kale (*Brassica napus*) microgreens were found to be less elongated and accumulated greater amounts of macro- and micronutrients with increases in blue light, while species dependency was reported for growth parameters (i.e., leaf area, fresh and dry mass) and optical leaf indices (i.e., chlorophyll, flavonol, anthocyanin, and carotenoid reflectance) [32]. Moreover, a red:blue ratio of 3 units was found to promote the growth, physiology, metabolic functions, and resource use efficiency of basil "Genovese" plants compared to fluorescent lamps and other red:blue ratios ranging from 0.5 to 4 units [74]. Besides this, morphological and phytochemical responses to different red:blue ratios are species-dependent, as demonstrated in a study involving seven vegetables grown as microgreens [75].

Green light (500–600 nm) is generally considered an unused part of the visible radiation spectrum, but this is hardly the case. In a review by Smith et al. [76], it was demonstrated that green light regulates plants' physiological responses and anatomical traits. In another study, cucumber seedlings treated with saturating (1000 μmol m^{-2} s^{-1}) red-green or monochromatic green had a greater photosynthetic capacity compared to monochromatic red light, proving the importance of green light for the remediation of the photosynthetic apparatus, while monochromatic blue enhanced morphological parameters such as leaf area, height, and stem thickness [77].

Apart from red and blue, non-visible wavelengths have been demonstrated to be significantly influential over plant development and phytochemical content. In particular, regardless of light dose, applying far-red reduced the accumulation of glucosinolates and increased the levels of 22 types of free amino acids in Chinese kale, while the authors reported that five down-regulated PHYTOCHROME INTERACTING FACTORs (*PIF3-like*, *PIF4-like*, *PIF5*, *PIF6*, and *PIF7*) appeared to be involved in the far-red-regulated biosynthesis of glucosinolates [78]. As regards the other side of the non-visible-light spectrum, supplemental UV-A irradiation (10 μmol m^{-2} s^{-1}) enhanced the functional properties (i.e., soluble protein and sugar, vitamin C, flavonoids, anthocyanins, and DPPH scavenging activity) of two lettuce cultivars, while supplemental far-red promoted leaf expansion, but the responses varied depending on the cultivar [79].

Nowadays, broad-spectra (i.e., white) light sources tend to be used in place of monochromatic and biochromatic lights, mainly due to the facilitation of scouting without compromising crop production and quality. The color rendering index (CRI) is a light parameter that denotes the ability of a light source to reveal the actual color of an object compared to natural light, as perceived by the human eye. The CRI depends on the spectral distribution of the light source, and reaches values up to 100 units. Narrow-band red or blue and bichromatic red-blue lights have negative or very low CRI values, while values above 50 units are considered favorable for application in PFAL systems. In a study involving green onion, white light supplemented with blue (3:1 ratio; 500 μmol m^{-2} s^{-1}) promoted morphological characteristics (i.e., leaf area, plant height, and stem thickness), relative growth rate and pigment content, and enhanced the photosynthetic capacity compared to 3:1 ratios of white light supplemented with red, yellow or green [80]. In another study, baby rocket leaves cultivated under a white light with elevated levels of red showed a greater expression of genes encoding photosynthesis components, as well as a greater expression of *SUS1* genes, which are related to the biosynthesis of soluble solids, including sugars [81]. Moreover, red and green Oakleaf lettuce grown under a sun-simulating white light exhibited similar dry mass per yield photon flux (YPF), but the plants were inferior with respect to their phenolic, anthocyanin, and chlorophyll contents compared to red-blue treatments [82]. Seedlings are ideal candidates given their adherence to the technical specifications of PFAL systems. Seedlings from two cucurbits, watermelon and squash, reached a higher quality when irradiated with broad-spectra light including 56–67% red, 8–11% blue, and a red/far-red ratio of about 3 units [83].

Another capability offered by PFAL systems is the application of light treatments for the regulation of postharvest quality in vegetables. For example, warm white with supplemental green light induced greater plant growth, chlorophyll content, and antioxidant activity (DPPH) in baby lettuce leaves compared to supplemental UV-A, red, or blue lights, while UV-A and blue promoted the secondary metabolism [84]. Moreover, the authors examined the postharvest storage quality, and concluded that supplemental red light enhanced the phytochemical preservation of lettuce.

4. Conclusions and Future Perspectives

Today, PFALs represent a means of the production of high-quality seedlings and crops, unaffected by the seasons and climatic constraints that prevail outdoors. This is particularly important given that environmental conditions are expected to severely deteriorate year by year due to the ongoing issue of climate change, which is also leading to reduced cultivated land availability. The present review provides a comprehensive analysis of the recent achievements made in the field of indoors horticultural production. Specifically, we have compiled a great amount of information related to the impact of micro-environmental factors on crop production in a PFAL, as well as the recent advances regarding the principal components and available automated systems employed in PFALs.

Ongoing technological advancements are expected to further enhance the yield and product quality, while also reducing production costs. More research could provide valuable information on the aforementioned goals, while also contributing to preserving the ecological environment by reducing inputs and increasing resource use efficiency. Special focus should be directed towards the plants' health and nutrition, which are greatly affected by the adjustments to environmental factors made possible in PFALs, such as via temperature, relative humidity, light, CO_2, and nutrient control. Research can also offer valuable insight into the pre- and postharvest factors that affect crop quality and shelf-life. Besides this, experiments in PFALs can offer robust conclusions, given that the growth conditions therein are fully controlled, and they can be effectively repeated by changing one or more of the parameters. Moreover, the growth cycle of most crops cultivated in PFALs is typically short, ranging from a few days (i.e., sprouts and microgreens) to a few weeks, offering the opportunity to perform many cultivation cycles in a short period of time.

Furthermore, research efforts are already being made by breeders towards the development of cultivars with better performance under certain lighting conditions, with a view to increasing the yield and quality achieved in PFALs and greenhouses [85]. This is due to the fact that several anatomical, morphophysiological, and metabolic characteristics are regulated by different light spectra. Today, the available information is vast, and this means that breeding companies can concentrate on the most important attributes for every plant species, as well as the most critical environmental parameters, in order to generate efficient genotypes for indoor production.

Another conclusion here is that most research efforts have been focused on a rather small number species, while other species have been left understudied or even not tested at all. We should also keep in mind that land use efficiency is key in order for PFALs to be profitable; thus, only compact crops can be cultivated in these systems that use such modern technology. For example, commonly grown leafy vegetables, such as baby leaves including arugula (*Eruca sativa*) and rocket (*Diplotaxis tenuifolia*), mustard (*Brassica juncea*), beet (*Beta vulgaris*), and valeriana (*Valeriana officinalis*), are mainly addressed in articles studying microgreens indoors. The same observation can be made about aromatic herbs, such as parsley, dill, and mint. We also suggest the inclusion of underutilized crops commonly known as "weeds", such as common sowthistle (*Sonchus oleraceus*), milk thistle (*Sylibum marianum*), common brighteyes (*Reichardia picroides*), and several other species with high nutritional quality, the cultivation of which is also addressed in the European Union's policies (e.g., Farm to Fork Strategy New Green Deal) set out to increase biodiversity and enhance consumer nutrition.

Author Contributions: Literature review and writing—original draft preparation: F.B., I.C., M.S., G.K.N. and A.K. Revision: F.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

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