AI

Review

A Systematic Literature Review on Parameters Optimization for Smart Hydroponic Systems

Umar Shareef, Ateeq Ur Rehman and Rafiq Ahmad *

Aquaponics 4.0 Learning Factory (All Factory), Department of Mechanical Engineering, University of Alberta, 9211 116 St., Edmonton, AB T6G 2G8, Canada; ushareef@ualberta.ca (U.S.); ateequr@ualberta.ca (A.U.R.)
* Correspondence: rafiq.ahmad@ualberta.ca

Abstract: Hydroponics is a soilless farming technique that has emerged as a sustainable alternative. However, new technologies such as Industry 4.0, the internet of things (IoT), and artificial intelligence are needed to keep up with issues related to economics, automation, and social challenges in hydroponics farming. One significant issue is optimizing growth parameters to identify the best conditions for growing fruits and vegetables. These parameters include pH, total dissolved solids (TDS), electrical conductivity (EC), light intensity, daily light integral (DLI), and nutrient solution/ambient temperature and humidity. To address these challenges, a systematic literature review was conducted aiming to answer research questions regarding the optimal growth parameters for leafy green vegetables and herbs and spices grown in hydroponic systems. The review selected a total of 131 papers related to indoor farming, hydroponics, and aquaponics. The review selected a total of 123 papers related to indoor farming, hydroponics, and aquaponics. The majority of the articles focused on technology description (38.5%), artificial illumination (26.2%), and nutrient solution composition/parameters (13.8%). Additionally, remaining 10.7% articles focused on the application of sensors, slope, environment and economy. This comprehensive review provides valuable information on optimized growth parameters for smart hydroponic systems and explores future prospects and the application of digital technologies in this field.

Keywords: hydroponic; IoT; AI; growth parameters; optimal growth

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1. Introduction

World Population and Food Insecurity

The world population is growing at an alarming rate, exerting tremendous pressure on the development of sophisticated and sustainable agricultural and food production systems and necessitating increased food production to adequately feed everyone. Unsustainable growth of the world population is causing resource and food scarcity globally [1]. Today, there are more than three times as many people in the world as there were in the mid-1900s. By mid-November 2022, the global human population had reached 8.0 billion, a significant increase from approximately 2.5 billion in 1950. This number is projected to rise to 8.5 billion by 2030 and 9.7 billion by 2050. Such sustained population growth presents substantial challenges to sustainable development, making accurate population data crucial for effective development planning [2].

As of 2024, the world's population is increasing by approximately 0.91% annually. This rate is slightly higher than the 0.88% rate in 2023, but lower than the 0.98% in 2020 and 1.06% in 2019, with around 73 million people being added each year [3].

The scarcity of land and water resources is pushing traditional agriculture to the limits [4]. To meet the growing need for food, global production will need to increase by approximately 70% from 2007 levels [5]. As more people move to cities, it is estimated that 75% of the world's population will live in urban areas. Currently, cities occupy just 3% of the Earth's land, but they consume 60–80% of the energy, produce 75% of the carbon emissions, and are home to 56% of the population [5]. In 2015, the United Nations General Assembly adopted the 2030 Agenda for Sustainable Development, with the second goal being zero hunger [6]. This goal focuses on establishing and developing climate-resilient, sustainable agricultural production systems to enhance productivity and efficiency while protecting ecosystems and combating climate change [7].

This paper presents a comprehensive review on the optimization of growth parameters for leafy greens, vegetables, and herbs cultivated in hydroponic systems. The focus is on identifying the key growth parameters, understanding their relative importance, and examining their effects on plant growth. Optimizing these parameters in smart hydroponic systems is crucial for achieving optimal plant growth, maximizing yields, and ensuring efficient use of resources.

2. Sustainable and Climate-Resilient Smart Agriculture and Food Production Systems

For an agricultural production system to be sustainable, it should be resource efficient, socially acceptable, and environment friendly [8]. Traditional soil-based agriculture is increasingly under threat due to unpredictable weather patterns driven by rising temperatures, reduced soil productivity, degradation, soil-borne diseases, and poor water management practices, which contribute to significant water wastage [9]. As the urban population continues to expand, meeting food needs with minimal environmental and energy impact can be achieved through sustainable food production systems [7]. In regions scarce in water and land, there has been a shift towards high-yield agricultural production technologies like hydroponics [10] to meet the growing demands for nutritious, locally grown food. Compared to traditional farming techniques, hydroponics produces higher yields through effective space management and efficient use of essential nutrients [5]. Moreover, hydroponics enables year-round harvesting of multiple crops and employs various technologies to regulate essential plant conditions. Hydroponics maximizes water and chemical usage efficiency, reducing the risk of hazardous waste and residues [5].

Since 1965, the global per-person availability of arable land has decreased from 0.39 hectares to 0.20 hectares [11] and rising urban populations are contributing to an increase in food miles. Landlocked or highly populated areas are particularly vulnerable. Countries like Singapore, Hong Kong, the UAE, Egypt, and Norway have less than 5% arable land. Vertical farming systems can substantially enhance yield per unit area, even with spatial variations in environmental growth conditions [12]. These urban farms could be located nearer to the point of consumption and can integrate seamlessly into the city's infrastructure rather than requiring dedicated structures [12]. For instance, a recent study demonstrated that a hydroponic rooftop greenhouse in Lisbon could reduce energy consumption by half compared to the current supply chain for tomatoes. Carbon dioxide enrichment in greenhouses has increased yields by 30% with CO_2 levels maintained at 700–1000 ppm [13].

2.1. Smart Hydroponic Systems: An Efficient and Sustainable Alternative

The initial approach to meet the food requirements of the 2050 population is to prioritize sustainability in key human activities, especially agriculture [7]. Feeding the human population by 2050 is not our only concern today; present-day global warming and widespread pollution are pressing urgent environmental and socioeconomic issues. Hydroponics could offer partial solutions to the drawbacks of traditional agriculture, including its significant contributions to CO_2 emissions and the loss of cultivable land due to outdated and unsustainable practices. By eliminating soil, hydroponics addresses issues like soil degradation, enables more efficient nutrient and pesticide management, and helps prevent soil-borne diseases [5,9]. Recirculation and the avoidance of evapotranspiration in certain agricultural practices can lead to a 95% reduction in water usage and an almost 100% reduction in the need for pesticides. A study in Japan suggested that utilizing waste heat from coal-fired power plants in nearby plant factories could result in a reduction of 1024 tons of CO_2 per year [14].

Hydroponics, derived from the Greek words 'hydro' (water) and 'ponos' (labor), is a form of horticulture that employs mineral nutrient solutions to grow plants instead of traditional soil cultivation methods [15]. This soilless growing technique provides plants with a nutrient-rich water solution for essential nutrients and minerals uptake, supported by a substrate (growing media) throughout their growth life [15].

Four thousand years ago, the Egyptians grew plants in big pots, as depicted in the wall painting of the Deir el Bahari temple. The earliest documented experiments on hydroponics started in 1699, and after 1929, commercial aspects of hydroponically grown crops started developing [15,16]. Advantages of hydroponics include efficient space utilization, climate-resilient sustainable agricultural and food production, quality assurance, and easy-to-manage technologies [15,17].

However, there are also disadvantages, such as the high initial capital investment that is required, the need for skilled labor to operate the system, and the potential environmental hazards posed by nutrient solution dumping if not handled properly [5,18,19]. Various types of hydroponic systems exist based on crop application, design, and water circulation systems; most of these systems consist of a nutrient solution reservoir and an aerator. These system types include:

1. Nutrient film technique (NFT) [5,19,20]
2. Aeroponics [5,19,21]
3. Deep water culture (DWC) [5,18,19,22]
4. Drip system [5,22]
5. Ebb and flow [5]
6. Aquaponics [5,7,23]

In the nutrient film technique (NFT), the roots of the plants are submerged in a flowing liquid nutrient film stream (Figure 1a). In aeroponics, roots are suspended in the air and receive nutrients through a periodic mist from a system of sprinklers (Figure 1b). In deep water culture (DWC), the plant's roots are submerged in the nutrient solution, with the rest of the plant supported by growing media or substrate above the water level (Figure 1c). The drip system directly pumps the nutrient solution to the roots of the plants with a regulated flow (Figure 1d). The ebb and flow system involves placing plants in a tray that is periodically flooded and drained with nutrient-rich water pumped from a reservoir below (Figure 1e).

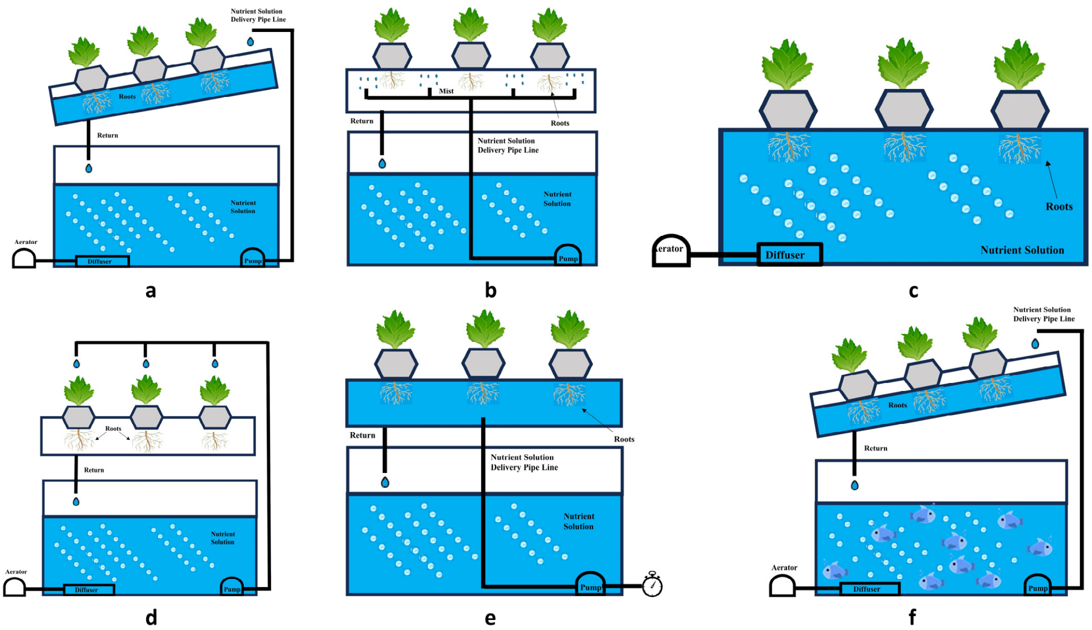

Figure 1. Different types of hydroponic systems. (**a**) NFT, (**b**) aeroponics, (**c**) deep water culture, (**d**) drip system, (**e**) ebb and flow, (**f**) aquaponics.

Aquaponics combines aquaculture (fish farming) and hydroponics. This technique utilizes the symbiotic relationship between plants and fish, where plants derive their nutritional requirements from fish waste. The plants absorb nutrients, and the microbial processes of nitrification and denitrification enable water recycling from the fish tank, establishing a balanced micro-ecosystem (Figure 1f).

Hydroponic systems are often referred to as plant factories because plants are cultivated under controlled conditions, such as pH, EC, TDS, etc. This approach not only improves productivity and efficiency but also enhances the nutritional value of the crops [24]. In a hydroponic system, plants receive necessary nutrients from mineral-rich solutions tailored to the specific needs of each plant species. Compared to traditional soil-based methods, this efficient nutrient delivery reduces losses from leaching, volatilization, and erosion. Industry 4.0 and the application of technologies like IoT, cloud computing, AI, and smart decision-making can make hydroponics even more efficient [22].

2.2. Challenges in Implementing Large-Scale Hydroponic Systems

When implementing hydroponic systems on a large scale, it is crucial to balance various key growth parameters due to the interdependence among different components of the systems [25]. Essential growth parameters, such as pH, EC, TDS, humidity, temperature (both nutrient solution and ambient), dissolved oxygen levels, and light intensity, must be closely monitored and managed [26]. When developed and adopted correctly, hydroponic systems can significantly enhance urban agriculture and contribute substantially to achieving Sustainable Development Goal 11 [12].

Hydroponic and fish production (aquaponics) are land-efficient food production systems that offer high yields and production benefits in urban areas with high population densities and limited, expensive farming land systems [7]. In these regions, where food demand is consistently high, aquaponics facilities can lower transportation costs and streamline supply chain management [27]. Adopting a decentralized production approach with small or medium-scale hydroponic systems in densely populated urban areas can minimize the ecological impact of agriculture, encourage self-employment and profitable business ventures, and foster community cooperation [5].

Recent studies in the hydroponic domain have focused on various aspects of the systems [23,24,28,29], management practices [30–33], types/species [22,34], energy use [7,35,36], sustainability, economy, and environment [37,38]. A complex system like hydroponics requires a deep understanding of multidisciplinary knowledge, encompassing agriculture, horticulture, mechanics, plant sciences, microbiology, chemistry, and more. Conducting a comprehensive review of hydroponics is a challenging task. Although the literature provides scattered data on important growth parameters for leafy greens and herbs, it lacks a single consolidated document consistent with all the available information [38–41].

2.3. Research Motivation and Paper Organization

Indoor farming requires a complete set of data for different species to be grown; this review, focusing on this aspect, provides a comprehensive data sheet to provide all the necessary data for important growth parameters for various leafy greens, herbs, and spices grown in a controlled environment.

This paper begins with an introduction and a comprehensive literature review. Section 3 describes the methodology and search criteria used to select papers for review. Section 4 discusses the key parameters that need to be monitored and controlled for optimal growth of leafy green vegetables and herbs in a hydroponic system. Section 5 outlines the application of AI and ML to smart hydroponic systems and future perspectives on existing research gaps and opportunities in the field and identifies key research areas for future work.

3. Research Methodology

The systematic literature review methodology can be divided into two main steps: (1) establishing the review protocol and (2) conducting the evaluation process.

3.1. Review Protocol

A review protocol outlines a clear strategy for conducting a literature review. This paper adheres to a systematic paper review process, which is a structured and methodical approach to analyzing and synthesizing existing literature on a particular topic. It involves defining specific criteria for selecting relevant papers, conducting a thorough search of academic databases, assessing the quality of the identified papers, and synthesizing the findings to draw conclusions or identify gaps in the existing research. This process aims to provide a comprehensive and unbiased overview of the current state of knowledge on the given subject.

The systematic review follows a well-defined protocol and aims to address a series of research questions. These questions cover various aspects and are designed to gain an understanding of the optimal growth parameters for different leafy greens, vegetables, and herbs in hydroponics. A preliminary search equation was formulated for the records search using Scopus, an online database for research articles. Based on this equation, a total of 1242 records were obtained. A year-wise comparison of the number of documents is presented in Figure 2, and the distribution of research article types is shown in Figure 3.

The majority of the records belonged to peer-reviewed journals and review papers. These records were further scrutinized based on the research questions and exclusion/inclusion criteria provided in Table 1.

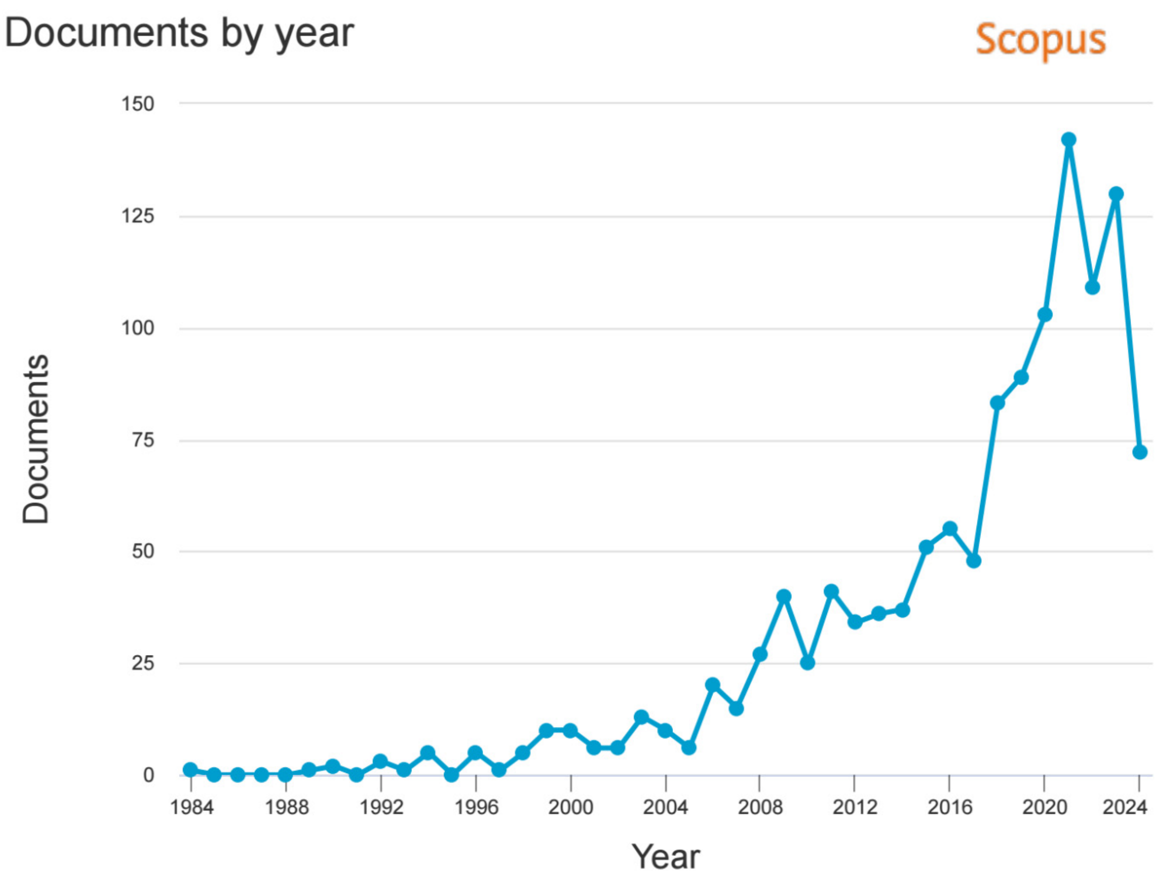

Figure 2. Year-wise data of records obtained from Scopus.

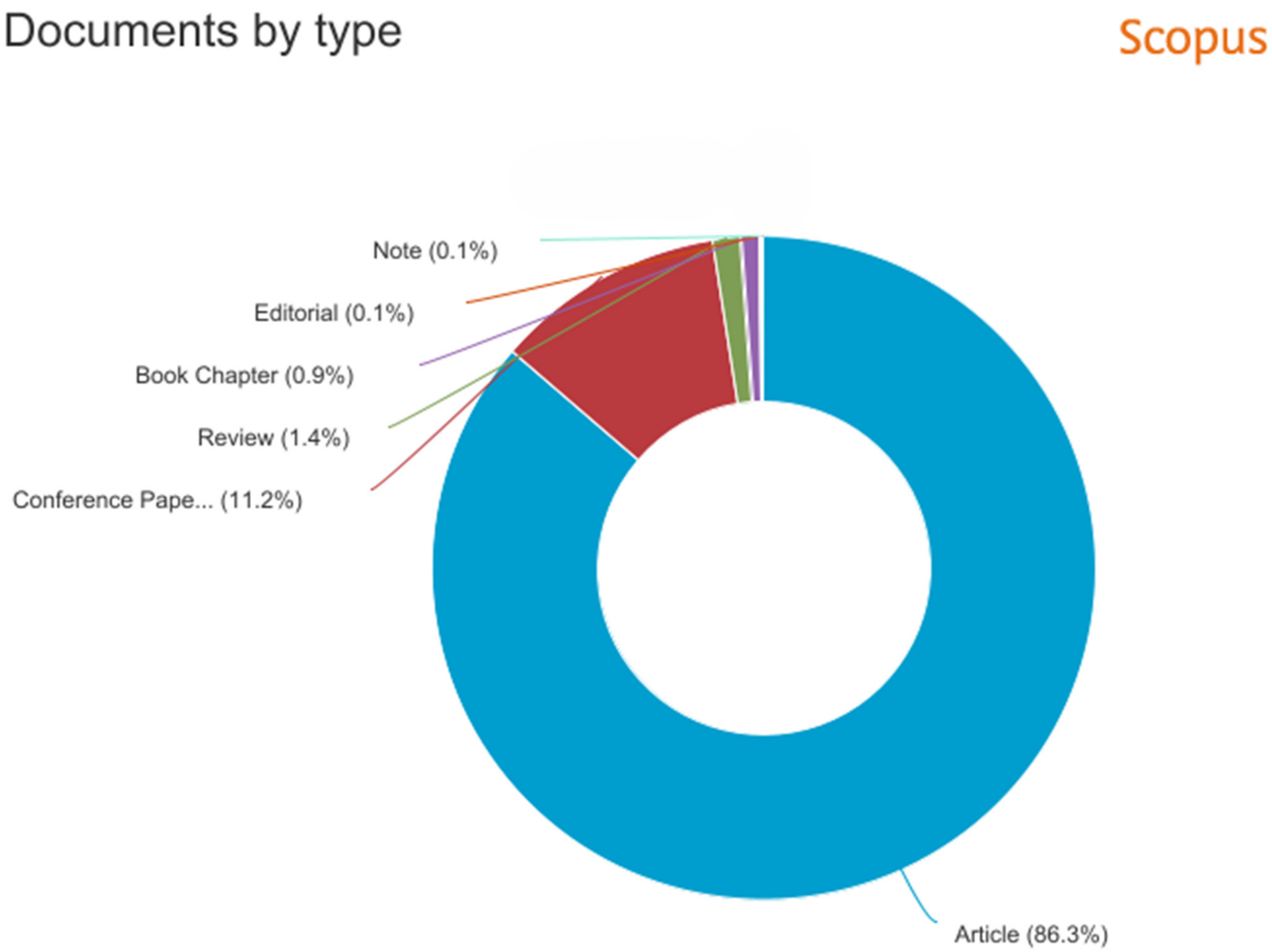

Figure 3. Research articles by their respective category.

Table 1. Review protocols, search questions, and inclusion/exclusion criteria.

Research Questions	• Classification of leafy green vegetables and herbs • What are growth parameters, and which growth parameters are most important (separately for leafy greens and herbs) for indoor/vertical/hydroponic farming? • What are the optimal ranges of the most important growth parameters for indoor farming, especially hydroponics (NFT and DWC in particular)? • How is growth affected by deviations from these optimal ranges? • How can IoT and automation be implemented to monitor, regulate, and correct these ranges? • Future directions considering sustainability and the Sustainable Development Goals (SDGs)
Search Equations	**Preliminary** • hydroponic AND growth AND parameters **Final Research Equation** • ALL (hydroponic, AND indoor AND farming, AND controlled AND environment, AND growth AND parameters, AND optimal AND growth) AND PUBYEAR > 2011 AND PUBYEAR < 2024 AND (LIMIT-TO (SUBJAREA, “AGRI”) OR LIMIT-TO (SUBJAREA, “ENGI”) OR LIMIT-TO (SUBJAREA, “ENVI”) OR LIMIT-TO (SUBJAREA, “ENER”)) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “re”) OR LIMIT-TO (DOCTYPE, “bk”) OR LIMIT-TO (DOCTYPE, “cp”)) AND (LIMIT-TO (LANGUAGE, “English”)).

Table 1. *Cont.*

Analysis Criteria	**Inclusion Criteria** • Conference papers and peer-reviewed journal articles • Studies published from 2011 to 2024 • Studies providing answers to research questions The article must include the title, abstract, source, DOI, and year of publication **Exclusion Criteria** • Summaries of editorials, seminars, events, and book reviews • Papers referring to optimal growth parameters or growth parameters but not applicable to aquaponics, hydroponic, or vertical farming • Papers published before 2011 • Non-English publications

Based on the above criteria and modified search equation to obtain more relevant and up-to-date literature, the final search equation yielded a total of 123 records, which were carried forward to the evaluation process.

3.2. Evaluation Method: PRISMA Approach

Once the review protocol is defined, the next step in the systematic analysis is to initiate the evaluation process. We utilized an evidence-based approach, PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) [42], which mapped out the number of records identified, screened, checked for eligibility, and eventually included in the systematic review. The modified search query yielded a total of 123 results. These were further evaluated by carefully examining the abstract of each paper. Papers that clearly addressed state-of-the-art hydroponic systems, optimization techniques, key parameters, optimal ranges, and the utilization of IoT and AI were retained for full-text eligibility checks, resulting in a total count of 65 (Figure 4).

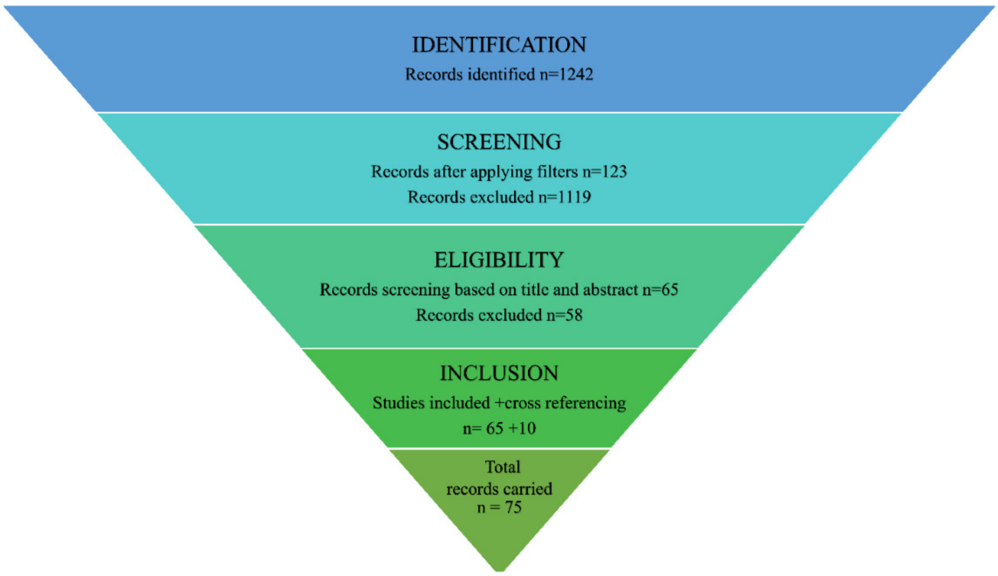

Figure 4. Evaluation of research articles based on PRISMA approach (adopted from [7]).

Subsequently, after a full-text review, 65 papers were selected for inclusion in this article. Among these, 25 papers primarily focused on growth parameters, optimization, and technology. The remaining papers discussed the fundamentals of hydroponic systems, key monitoring parameters, and optimal maintenance ranges. The systematic review yielded multidisciplinary articles. The majority of the articles were related to technology description (38.5%), artificial illumination (26.2%), and nutrient solution composition/parameters

(13.8%). Additionally, 10.8% of the articles pertained to the application of AI, digitization, and IoT, while remaining 10.7% articles focused on the application of sensors, slope, environment and economy (Figure 5).

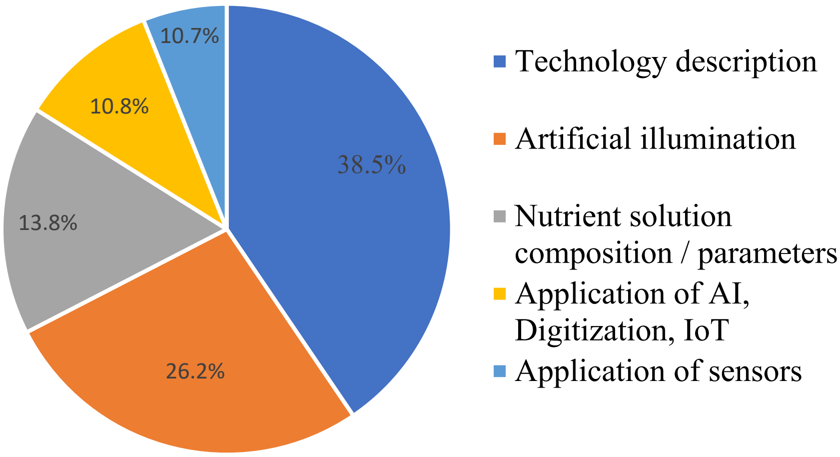

Figure 5. Percentage distribution of journal articles by field-related category.

This systematic review includes multidisciplinary articles from various subject areas, providing insights from different fields and contributing to a comprehensive summary of recent trends related to growth parameters in hydroponic systems. Major trends revealed through the systematic literature review included the effects of different growth parameters such as pH, EC, TDS, temperature (nutrient solution and ambient), substrate (growing/support media), dissolved oxygen, aeration, lighting conditions, and humidity on the growth of hydroponically grown plants. Other key areas included technology descriptions, growth parameters used for different types of hydroponic systems or indoor farming, and nutrient solution composition, delivery, and optimization. Additionally, artificial illumination and the application of emerging technologies in hydroponics were significant. These important parameters will be elaborated on in detail in the following sections.

4. Growth Parameters in Hydroponic Systems

The most important growth parameters to consider when monitoring and designing any controlled environment agriculture (CEA) system include water quality (nutrient solution), light intensity, nutrient availability, selected crop species, substrate/growing media, moisture availability, crop spacing, ambient temperature, air circulation and freshness, and relative humidity [43,44].

A systematic, careful, and balanced approach is necessary when dealing with the composition and management of the nutrient solution in any hydroponic system [45]. There are optimal ranges for these parameters for different plant species, which should be critically monitored and maintained to avoid resource wastage. The important growth parameters for any hydroponic system, and their ranges, measuring units, and relative importance and relevance, are presented in Table 2.

Table 2. Important growth parameters and ranges in hydroponic systems.

Sr No.	Parameter Description	Units	Linked to	Relative Importance/Significance	Optimal Range	References
1	pH	None	Nutrient solution	Highly significant	5–7.5	[4,5,15,21,22,34,44–84]
2	Electrical conductivity (EC)	Millisiemens per centimeter (mScm^{-1})		Highly significant	0.8–3.5	[4,5,7,15,21–23,38,41,50, 53,54,56,58,63–67,69–71,74–80,85]

Table 2. *Cont.*

Sr No.	Parameter Description	Units	Linked to	Relative Importance/Significance	Optimal Range	References
3	Temperature (nutrient solution)	Degrees centigrade °C		Highly significant	18–27	[21,23,26,29,37,41,43,54,57,58,60,62,72,78,85]
4	TDS	Parts per million (PPM)		Moderately significant	500–1800	[33,53,56]
5	Aeration/dissolved oxygen (DO)	Milligram per liter (mg L^{-1})		significant	3–10	[22,33,47,52,54,60,61,67,73,81,83,86]
6	Growing media/substrate		Plant growth/nutrient solution	Highly significant	Peat, mineral wool, rock wool, coconut coir etc.	[4,5,22,43,44,51–53,57,58,67,69–72,76,78–80,87–90]
7	Lighting/artificial illumination	PPFD (μmol $m^{-2}s^{-1}$)	Plant growth/overall system	Highly significant	80–600	[4,5,22,43,44,51–53,57,58,67,69–72,76,78–80,87–90]
8	Ambient temperature	Degrees centigrade °C	Overall system	Moderately significant	18–30	[13,21–23,33,38–41,43,47,51,54–57,60,61,63–65,67,71,75,78–80,82,83,91]
9	Relative humidity	None (percentage)	Overall system	Moderately significant	40–80	[4,13,22,33,38–41,43,47,51,54,55,57,60,63,65,67,70,71,75,78–80,85,91,92]
10	CO_2 dosing	Parts per million (PPM)	Plant growth	Optional supplementation	450–1200	[4,13,22,33,38–40,54,55,57,62–64,78,80,82,91,92]

4.1. Parameter Ranges in Hydroponic Systems

Crops can achieve higher quality through effective management of nutrient solutions [81]. Various physio-chemical phenomena can influence plant nutrient uptake [22,85]. The temperature of the nutrient solution can impact precipitation, co-precipitation, and complexation processes [85]. Maintaining an optimal temperature range of 18–27 °C [29,33,59,63,64,79] is crucial to prevent nutrient insolubility and ensure availability for plants.

The precipitation equilibrium is significantly influenced by pH variation. Continuous monitoring and control of pH are essential as it directly affects the nutrient uptake of the plants [4,23,33,74]. A pH above 7 can render zinc (Zn), iron (Fe), copper (Cu), manganese (Mg), and nickel (Ni) insoluble, while an acidic pH reduces the solubility of sulfur, phosphorus, and nitrogen. Even a minor change in pH has an apparent physiological response [81]. A pH range of 5–7.5 is generally recommended for most plant species in hydroponics [15,33,34,51,64].

Selective nutrient uptake in plant growth can deplete the solution of some of the nutrients, lowering the electrical conductivity (EC) of the nutrient solution. EC is an estimation of the ions present in the nutrient solution [35,85]; low EC indicates scarcity of nutrients in ionic form, and higher ranges indicate salt stress in plants. An EC range of 0.8–3.5 is suggested for smart hydroponic systems [15,33,76]. EC must be maintained at an optimal level for the healthy growth of the plants [4,5,22,76].

The choice of substrate or growing media depends on factors such as grower preference, nutrient solution pH, recyclability, and product shelf life [37,48]. An ideal substrate must have a balanced combination of these characteristics [76]: good aeration, durability, porosity, sterility, neutral pH, nutrient-holding capacity (cation exchange), lightweight, and ease of handling and reusability [5,16].

Light conditions significantly influence the nutritional and sensory qualities of plants [7,63,65]. For instance, lettuce shows optimal growth under artificial lighting with a photosynthetic photon flux density (PPFD) of 150–250 μmol$m^{-2}s^{-1}$ [7,62,64,93]. Hydroponics utilizes artificial illumination to supplement light requirements for the process of photosynthesis, a photochemical reaction that is crucial for converting CO_2 into carbohydrates [10,65]. Plant photoreceptors absorb this radiation and are responsible for the morphology and growth of the plant [7]. Light parameters, such as intensity, quality, wavelength, daily light integral (DLI), photosynthetically active radiation (PAR), and customized lighting recipes, play vital roles in plant chemical composition and sensory properties [86,88].

Maintaining an optimal humidity range is essential throughout the plant growth cycle, as humidity and temperature influence plant bio-metabolism [33,86,89]. A relative humidity range of 40–80% is considered to make a significant difference in plant growth in a hydroponic system [21,33,39,47,64]. Carbon dioxide (CO_2) concentration also affects plant growth significantly [23]. This is mainly because of related enhancements in photosynthesis and water use efficiency [13,90]. An ideal CO_2 concentration ranges from 450 to 1200 ppm, balancing higher yields without environmental harm [55,58,64,93]. Aerating the nutrient solution enhances plant growth, water uptake, and the leaf concentration of potassium, phosphorus, and magnesium [94]. There is a reasonable range within which plant growth is enhanced; higher aeration does not translate into a higher yield [95]. A range of 3–10 milligrams per liter (mg/L) is ideal for aeration to ensure the optimum growth of plants [34,49,61].

4.2. Plant Species-Based Growth Parameter Ranges for Hydroponic Systems

The previous section discussed the overall growth parameters for any hydroponic system, providing a wide range of parameters for optimal growth. This section focuses on the optimal growth parameters for specific plant species, as presented in Table 3.

Table 3. Plant specific (selected species) optimal growth parameters in hydroponic systems.

Plant Species	pH	EC (Milli Siemens cm^{-1})	Temperature (Nutrient Solution) (°C)	Growing Media/ Substrate	Lighting Intensity PPFD (µmol $m^{-2}s^{-1}$)	Photoperiod Hours (h) (Light/Dark)	Ambient Temperature (°C)	Relative Humidity (% Age)	References
Asparagus	6–6.8	1.4–1.8	20–28	Peat, mineral wool, perlite, rock wool, coconut coir etc.	150–200	8/16	18–30	45–80	[5,15,23,88]
Arugula	5.5–6.0	1.5–1.8	18–25		150–200	16/8	18–30	45–80	[1,7,23,67,91]
Basil	5.5–6.5	1.1–1.6	18–24		80–250	16/8	18–30	50–85	[1,4,5,7,15,21,50, 58,61,64,65,69,71, 89,96,97]
Celery	5.5–6.5	1.8–3	18–25		150	16/8	18–30	50–85	[5,15,23,90,93]
Kale	6–6.5	1.2–1.8	18–25		150–250	16/8	18–30	50–80	[7,60]
Leek	6.5–7	1.4–1.8	18–23		150–250	(12–14)/ (12–10)	18–30	60	[5,15,94,95]
Lettuce	5–7	1.5–2.5	18–25		150–250	14–17	18–27	45–80	[1,4,5,15,23,64,65, 70,80,91,93,96]
Parsley	6.0–6.5	1.8–2.2	18–25		150–200	16/8 or 14/8	18–30	45–80	[5,15,23]
Peppers	5.5–6	0.8–1.8	-		50–200	16/8	20–35	50–80	[1,5,15,23,65,77]
Strawberry	6.0	1.8–2.2	18–30		115–350	12–16	18–30	40–80	[1,5,7,15,23,64,84]
Spinach	6–6.5	1.8–2.2	20–30		100–150	13/11	20–35	20–30	[1,5,15,23,56,65, 72,96,98]
Tomato	5.5–6.5	2–4	-		50–200	15/9	-	-	[1,5,7,15,23,77,93]
Okra	5.5–6.5	2–2.4	-		-	-	20–35	50–80	[5,15,99]
Rhubarb	5.5–6.0	1.6–2.0	-		-	-	-	-	[5,15]
Rose	5.5–6.0	1.5–2.5	-		-	-	-	-	[5,15]
Sage	5.5–6.5	1.0–1.6	-		-	-	-	-	[5,15]

To achieve optimal growth in different plant species, different optimal levels of growth parameters are required, as presented in Table 3. Lettuce growth has been optimized [63] using 6.5, 2.3 mS/cm, 200 µmol $m^{-2}s^{-1}$, 16 h/day (light/dark), 24/21 °C day/night, 70/75% day/night, and 850 ppm ranges of pH, electrical conductivity, light intensity (PPFD), photoperiod, ambient temperature, relative humidity, and CO_2 level/supplementation, respectively. To obtain an optimal yield, strawberries and basil have been grown under pH 7, EC 2.3 mS cm^{-1}, ambient temperature 21 ± 2 °C, 55–70% relative humidity and 450 ppm CO_2, photoperiod 16/8 h/day (light/dark), and a light intensity of 200 µmol $m^{-2}s^{-1}$ [64]. A pH of 5.8, EC 1.85 mS/cm, ambient temperature 21 ± 2.5 °C, relative humidity 65 ± 5%, photoperiod hours/day (light/dark) and light intensity of 200 ± 5 µmol $m^{-2}s^{-1}$ have been used [65] to cultivate lettuce, spinach, kale, basil, and sweet Pepper in a controlled environment to check the growth effect of different light combinations on these species.

A recommended photoperiod of 16/8 h/day (light/dark) is generally used for most of the plant species grown hydroponically, and too much light is damaging to plants [96]. In one study, halophytes (salt-tolerant plants) were hydroponically grown using a photoperiod of 14/10 h/day (light/dark), PPFD 371.0 ±12.0 µmol $m^{-2}s^{-1}$, nutrient solution temperature of 22.9 ± 0.7 °C, pH of 7.8 ± 0.2, and a dissolved oxygen concentration of 6.7 ± 0.6 mg L^{-1} [60] to extract dissolved inorganic nutrients through an integrated multi-trophic aquaculture (IMTA). Additionally, Chinese kale was grown at five photo periods (12/12, 14/10, 16/8, 18/6, and 20/4 h/day (light/dark)) and five different light intensities (100, 130, 160, 190, and 220 µmol m^{-2} s^{-1}) [60] while other parameters were held at the same values (temperature, humidity, CO_2 concentration, photoperiod, light intensity, EC, and pH with values, 25 ± 3 °C, 65 ± 5%, 1000 ± 100 ppm, 16/8 h/day (light/dark), 150 µmol m^{-2} s^{-1}, 1.2 ± 0.1 (mS m^{-1}), and 6.5 ± 0.5, respectively). Better growth performance was observed under a light intensity of 160 and 190 µmol $m^{-2}s^{-1}$ with photoperiods of 16/8 and 18/6 h/day (light/dark), respectively [60].

In another study, arugula or rocket was grown at five different ECs (1.2, 1.5, 1.8, and 2.1 mS/cm) [67] while keeping other parameters like ambient temperature, humidity, light intensity, pH, and nutrient solution temperature at 18.5 °C, 50.85%, 200 µmol $m^{-2}s^{-1}$, 5.8, and 18.3 °C, respectively. An EC range of 15–1.8 mS/cm proved to be optimal for this experiment [67]. A group of researchers grew basil and lettuce under five different EC values, and it was concluded that 1.2 mS/cm is optimal for basil and 0.9 mS/cm is optimal for lettuce growth in an ebb and flow hydroponic system [4]. Three pH ranges (5.0–5.5, 5.5–6.0, 6.0–6.5) were shown to have significant effects on the physiological responses of lettuce in [80], with the lowest range causing a significant decrease in leaf area.

5. Discussion and Future Prospects

Further discussions and answers to the research questions regarding the application of smart technologies and tools, such as the Internet of Things (IoT), artificial intelligence (AI), machine learning (ML), and digital twinning in smart hydroponics, are detailed below.

5.1. Smart Hydroponic System

Smart agriculture relies on communication technologies and information for decision-making [75]. It utilizes smart monitoring devices and sensors to gather data from sources like IoT (Internet of Things) and ML (machine learning) to predict growth parameters for various plants, enabling precision farming [86,100]. In the smart agricultural domain, IoT devices collect data related to crop parameters and environmental conditions, such as pH, EC, humidity, temperature, leaf color, aeration, and lighting conditions. These data are then transmitted for further processing and action [20].

5.2. IoT-Assisted Parameters Control

In recent years, numerous efforts have been made to develop smart agricultural systems capable of monitoring and controlling various plant growth parameters such as light intensity, temperature, resource utilization, energy consumption, relative humidity, electrical conductivity, dissolved oxygen, and pH [7]. Utilizing IoT and automation techniques, a digital twin was developed for hydroponics that measures real-time parameters like pH, EC, humidity, and water temperature, and also predicts the growth and fresh weight of crops [23]. Furthermore, a model has been successfully developed to monitor growth parameters like pH, dissolved solids, fish feed rate, fish weight gain, nitrates, and plant growth. However, this model could not predict plant growth rate [101]. Through a manufacturing execution system (MES), Witzel et al. developed an aquaponics farm capable of capturing data from various sensors (relative humidity, light intensity, temperature, water level, energy consumption, and plant growth) to monitor and control real-time parameters of the system [102].

In another study, a digital twin based on a cyber-physical system (CPS) was developed, capable of gathering soil parameters data through probes and displaying the data on a dashboard, thus creating a fully functional digital twin [103]. Despite these advantages, IoT monitoring and parameter control face challenges such as a lack of standards, high initial costs, and security issues due to network encryption [7].

5.3. AI and ML for Parameters Optimization

Artificial intelligence (AI) and machine learning (ML) combined with big data and IoT are driving agricultural digitization. These technologies have the potential to improve real time monitoring, enhance production, and achieve greater control over the growth of crops [104]. ML algorithms and techniques are implemented in various aspects of agriculture, including crop management (yield prediction, species recognition, disease detection), livestock management, and water and soil management (type, pH, temperature, moisture content) [103].

One hydroponics system based on multi nodal data analysis demonstrated the ability to monitor and optimize six growth parameters (ambient temperature, air flow speed, relative humidity, CO_2 concentration, pH, EC, and nutrient solution temperature) related to plant growth in a hydroponic plant factory [79]. A group of researchers developed a control kit for application to any size hydroponic system in order to control some of the growth parameters (pH, EC, DO, temperature of nutrient solution) to an optimal level. This kit was able to increase lettuce yield by 21% as compared to uncontrolled growth [51]. Some novel KNN-algorithms have been shown to predict plant growth with 93% accuracy [52] in an NFT-hydroponic system by optimally controlling growth parameters. An Android-based app using cyber-physical system (CPS) was developed for real-time monitoring of vertical farms, with optimized control of parameters such as light, CO_2 volume, temperature, pH, and humidity, and live feedback through the app. This app also manages algae growth, which can pose a risk to plant growth [51]. A test bed was developed based on an open IoT platform for monitoring hydroponic systems. It optimizes and monitors parameters, sends alerts if parameters are not within optimal ranges, and estimates power consumption [49]. This test bed provides key insights into the optimization and correlation of different growth parameters.

5.4. Parameters Control in Hydroponic 4.0/5.0

Although the digitization of agriculture (Hydroponics 4.0) through the application of AI, ML, IoT, and similar technologies can help reduce food scarcity and increase production, several barriers exist, including technical, social, and economic challenges [24]. Agriculture 5.0 often lacks social fairness and a sustainable approach, focusing more on digitization and AI technologies for flexibility and enhanced productivity [32]. In 2021, the European Commission formally adopted Industry 5.0, which emphasizes sustainable, resilient, and human-centric production and technology systems [105,106]. Industry 5.0 aims to refine the interaction between humans and machines, creating robust systems and reducing environmental impacts through a circular economy. Key technologies of Industry 5.0 include collaborative robots (cobots), digital twins, smart materials, energy-efficient and secure data management, AI, and renewable energy resources [24,105].

Applying the principles of Industry 5.0 to hydroponics, termed Hydroponics 5.0, can significantly enhance agricultural production and quality. A cyber-physical cognitive system (CPCS) can be developed for hydroponic systems, capable of perceiving situations and taking remedial actions accordingly. This involves assigning repetitive tasks such as parameter monitoring, control, and optimization of subsequent actions to cobots, while humans handle critical thinking. Digital twins can help detect diseases and predict yield/growth, leading to better control over the growth period. This approach paves the way for sustainable, resilient, and climate-smart hydroponic systems [24,105,106].

6. Conclusions

Global food demand and food insecurity have paved the way for intensive agricultural production methods and techniques. Scientists and researchers are tirelessly working to integrate Industry 4.0 concepts into modern agriculture and farming to increase yields, reduce waste, minimize cost, and ensure sustainable production. Hydroponics offers a solution to food insecurity, enhances sustainability, and allows for the integration of modern technologies. However, it requires meticulous monitoring and control of various plant growth parameters to be economically and socially viable.

This paper provides insights into crucial growth parameters and their optimized ranges for hydroponic systems. Numerous research papers were analyzed to determine the optimal ranges for pH, electrical conductivity (EC), temperature (nutrient solution and ambient), aeration/dissolved oxygen (DO), growing media/substrate, lighting/artificial illumination, relative humidity, and CO_2 dosing, as well as plant-specific parameters. The concluded optimal ranges for these parameters are: pH, 5–7.5; EC, 0.8–3.5 mS/cm; temperature, 18–27 °C; aeration, 3–10 mg/L DO; growing media, peat, mineral wool, rock wool, or coconut coir; light intensity, 80–600 μmol $m^{-2}s^{-1}$; relative humidity, 40–80%; and CO_2 concentration, 450–1200 ppm. This paper also discusses the application and beneficial effects of smart monitoring, digital twins, machine learning (ML), artificial intelligence (AI), the Internet of Things (IoT), and Industry 4.0/5.0 in hydroponic systems. Additionally, potential roadblocks to adopting these technologies are highlighted.

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References

1. Nájera, C.; Gallegos-Cedillo, V.M.; Ros, M.; Pascual, J.A. Role of Spectrum-Light on Productivity, and Plant Quality over Vertical Farming Systems: Bibliometric Analysis. *Horticulturae* **2023**, *9*, 63. [CrossRef]
2. United Nations Department of Economic and Social Affairs, Population Division. *World Population Prospects 2022 Summary of Results*; UN DESA/POP/2022/TR/NO. 3; United Nations Department of Economic and Social Affairs, Population Division: New York, NY, USA, 2022.
3. World Population Clock: 8.1 Billion People (LIVE, 2024)—Worldometer. Available online: https://www.worldometers.info/world-population/ (accessed on 19 February 2024).
4. Hosseini, H.; Mozafari, V.; Roosta, H.R.; Shirani, H.; van de Vlasakker, P.C.H.; Farhangi, M. Nutrient Use in Vertical Farming: Optimal Electrical Conductivity of Nutrient Solution for Growth of Lettuce and Basil in Hydroponic Cultivation. *Horticulturae* **2021**, *7*, 283. [CrossRef]
5. Velazquez-Gonzalez, R.S.; Garcia-Garcia, A.L.; Ventura-Zapata, E.; Barceinas-Sanchez, J.D.O.; Sosa-Savedra, J.C. A Review on Hydroponics and the Technologies Associated for Medium- and Small-Scale Operations. *Agriculture* **2022**, *12*, 646. [CrossRef]

6. The Sustainable Development Agenda—United Nations Sustainable Development. Available online: https://www.un.org/sustainabledevelopment/development-agenda/ (accessed on 19 February 2024).
7. Gillani, S.A.; Abbasi, R.; Martinez, P.; Ahmad, R. Review on Energy Efficient Artificial Illumination in Aquaponics. *Clean. Circ. Bioeconomy* **2022**, *2*, 100015. [CrossRef]
8. Food and Agriculture Organization of the United Nations. *Sustainable Food Systems Concept and Framework: What Is a Sustainable Food System? Why Take a Food Systems Approach? Changing Food Systems*; FAO: Rome, Italy, 2018.
9. St. Clair, S.B.; Lynch, J.P. The Opening of Pandora's Box: Climate Change Impacts on Soil Fertility and Crop Nutrition in Developing Countries. *Plant Soil* **2010**, *335*, 101–115. [CrossRef]
10. Trivellini, A.; Toscano, S.; Romano, D.; Ferrante, A. The Role of Blue and Red Light in the Orchestration of Secondary Metabolites, Nutrient Transport and Plant Quality. *Plants* **2023**, *12*, 2026. [CrossRef] [PubMed]
11. World Bank Publications. *World Development Report 2016: Digital Dividends*; World Bank Publications: Chicago, IL, USA, 2016.
12. Buehler, D.; Junge, R. Global Trends and Current Status of Commercial Urban Rooftop Farming. *Sustainability* **2016**, *8*, 1108. [CrossRef]
13. Ward, R.; Jans-Singh, M.; Choudhary, R. Quantifying the Environmental and Energy Benefits of Food Growth in the Urban Environment. In *Smart Plant Factory: The Next Generation Indoor Vertical Farms*; Springer: Singapore, 2018; pp. 245–287; ISBN 9789811310652.
14. Togawa, T.; Fujita, T.; Dong, L.; Fujii, M.; Ooba, M. Feasibility Assessment of the Use of Power Plant-Sourced Waste Heat for Plant Factory Heating Considering Spatial Configuration. *J. Clean. Prod.* **2014**, *81*, 60–69. [CrossRef]
15. Electrical Conductivity and PH Guide for Hydroponics. Available online: https://www.researchgate.net/publication/309293679_Electrical_Conductivity_and_pH_Guide_for_Hydroponics?channel=doi&linkId=5808bddc08ae5ed04c012573&showFulltext=true (accessed on 21 August 2024). [CrossRef]
16. Torabi, M.; Mokhtarzadeh, A.; Mahlooji, M. The Role of Hydroponics Technique as a Standard Methodology in Various Aspects of Plant Biology Researches. In *Hydroponics—A Standard Methodology for Plant Biological Researches*; Asao, T., Ed.; InTech: Rijeka, Croatia, 2012.
17. Hydroponics | Oklahoma State University. Available online: https://extension.okstate.edu/fact-sheets/hydroponics.html (accessed on 21 August 2024).
18. Sharma, A.; Manpoong, C.; Devadas, V.S.; Kartha, B.D.; Pandey, H.; Wangsu, M. Crop Hydroponics, Phyto-Hydroponics, Crop Production, and Factors Affecting Soilless Culture. *ACS Agric. Sci. Technol.* **2022**, *2*, 1134–1150. [CrossRef]
19. Niu, G.; Masabni, J. Hydroponics. In *Plant Factory Basics, Applications and Advances*; Academic Press: Cambridge, MA, USA, 2022; pp. 153–166. [CrossRef]
20. Spehia, R.S.; Devi, M.; Singh, J.; Sharma, S.; Negi, A.; Singh, S.; Chauhan, N.; Sharma, D.; Sharma, J.C. Lettuce Growth and Yield in Hoagland Solution with an Organic Concoction. *Int. J. Veg. Sci.* **2018**, *24*, 557–566. [CrossRef]
21. Lakhiar, I.A.; Gao, J.; Syed, T.N.; Chandio, F.A.; Buttar, N.A. Modern Plant Cultivation Technologies in Agriculture under Controlled Environment: A Review on Aeroponics. *J. Plant Interact.* **2018**, *13*, 338–352. [CrossRef]
22. Ragaveena, S.; Shirly Edward, A.; Surendran, U. Smart Controlled Environment Agriculture Methods: A Holistic Review. *Rev. Environ. Sci. Biotechnol.* **2021**, *20*, 887–913. [CrossRef]
23. Reyes Yanes, A.; Abbasi, R.; Martinez, P.; Ahmad, R. Digital Twinning of Hydroponic Grow Beds in Intelligent Aquaponic Systems. *Sensors* **2022**, *22*, 7393. [CrossRef]
24. Abbasi, R.; Martinez, P.; Ahmad, R. The Digitization of Agricultural Industry—A Systematic Literature Review on Agriculture 4.0. *Smart Agric. Technol.* **2022**, *2*, 100042. [CrossRef]
25. Ahmed, N.; Turchini, G.M. Recirculating Aquaculture Systems (RAS): Environmental Solution and Climate Change Adaptation. *J. Clean. Prod.* **2021**, *297*, 126604. [CrossRef]
26. Reyes-Yanes, A.; Gelio, S.; Martinez, P.; Ahmad, R. Wireless Sensing Module for IoT Aquaponics Database Construction. *Int. J. Electron. Electr. Eng.* **2021**, *9*, 43–47. [CrossRef]
27. Oliver, L.P.; Coyle, S.D.; Bright, L.A.; Shultz, R.C.; Hager, J.V.; Tidwell, J.H. Comparison of Four Artificial Light Technologies for Indoor Aquaponic Production of Swiss Chard, Beta Vulgaris, and Kale, Brassica Oleracea. *J. World Aquac. Soc.* **2018**, *49*, 837–844. [CrossRef]
28. Abbasi, R.; Yanes, A.R.; Martinez Villanuera, E.; Ahmad, R. Real-Time Implementation of Digital Twin for Robot Based Production Line. In Proceedings of the Conference on Learning Factories (CLF) 2021, Edmonton, AB, Canada, 4 June 2021. [CrossRef]
29. Yang, T.; Kim, H.J. Comparisons of Nitrogen and Phosphorus Mass Balance for Tomato-, Basil-, and Lettuce-Based Aquaponic and Hydroponic Systems. *J. Clean. Prod.* **2020**, *274*, 122619. [CrossRef]
30. Pringle, A.M.; Handler, R.M.; Pearce, J.M. Aquavoltaics: Synergies for Dual Use of Water Area for Solar Photovoltaic Electricity Generation and Aquaculture. *Renew. Sustain. Energy Rev.* **2017**, *80*, 572–584. [CrossRef]
31. Ghamkhar, R.; Hartleb, C.; Wu, F.; Hicks, A. Life Cycle Assessment of a Cold Weather Aquaponic Food Production System. *J. Clean. Prod.* **2020**, *244*, 118767. [CrossRef]
32. Saiz-Rubio, V.; Rovira-Más, F. From Smart Farming towards Agriculture 5.0: A Review on Crop Data Management. *Agronomy* **2020**, *10*, 207. [CrossRef]
33. Yanes, A.R.; Martinez, P.; Ahmad, R. Towards Automated Aquaponics: A Review on Monitoring, IoT, and Smart Systems. *J. Clean. Prod.* **2020**, *263*, 121571. [CrossRef]

34. Maucieri, C.; Nicoletto, C.; Junge, R.; Schmautz, Z.; Sambo, P.; Borin, M. Hydroponic Systems and Water Management in Aquaponics: A Review. *Ital. J. Agron.* **2018**, *13*, 1–11. [CrossRef]
35. Silva, L.; Valdés-Lozano, D.; Escalante, E.; Gasca-Leyva, E. Dynamic Root Floating Technique: An Option to Reduce Electric Power Consumption in Aquaponic Systems. *J. Clean. Prod.* **2018**, *183*, 132–142. [CrossRef]
36. Kikuchi, Y.; Kanematsu, Y.; Yoshikawa, N.; Okubo, T.; Takagaki, M. Environmental and Resource Use Analysis of Plant Factories with Energy Technology Options: A Case Study in Japan. *J. Clean. Prod.* **2018**, *186*, 703–717. [CrossRef]
37. Arakkal Thaiparambil, N.; Radhakrishnan, V. Challenges in Achieving an Economically Sustainable Aquaponic System: A Review. *Aquac. Int.* **2022**, *30*, 3035–3066. [CrossRef]
38. Kelly, N.; Choe, D.; Meng, Q.; Runkle, E.S. Promotion of Lettuce Growth under an Increasing Daily Light Integral Depends on the Combination of the Photosynthetic Photon Flux Density and Photoperiod. *Sci. Hortic.* **2020**, *272*, 109565. [CrossRef]
39. Sapkota, S.; Sapkota, S.; Liu, Z. Effects of Nutrient Composition and Lettuce Cultivar on Crop Production in Hydroponic Culture. *Horticulturae* **2019**, *5*, 72. [CrossRef]
40. Johkan, M.; Shoji, K.; Goto, F.; Hahida, S.; Yoshihara, T. Effect of Green Light Wavelength and Intensity on Photomorphogenesis and Photosynthesis in Lactuca Sativa. *Environ. Exp. Bot.* **2012**, *75*, 128–133. [CrossRef]
41. Thakulla, D.; Dunn, B.; Hu, B.; Goad, C.; Maness, N. Nutrient Solution Temperature Affects Growth And○ Brix Parameters of Seventeen Lettuce Cultivars Grown in an NFT Hydroponic System. *Horticulturae* **2021**, *7*, 321. [CrossRef]
42. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G. Guidelines and Guidance Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *Ann. Intern. Med.* **2009**, *151*, 264–269. [CrossRef] [PubMed]
43. Sarkar, A.; Majumder, M. Fuzzy Logic Approach in Prioritization of Crop Growing Parameters in Protected Farms: A Case in North East India. *CIGR J.* **2017**, *19*, 211–217.
44. Abbasi, R.; Martinez, P.; Ahmad, R. Data Acquisition and Monitoring Dashboard for IoT Enabled Aquaponics Facility. In Proceedings of the 2022 10th International Conference on Control, Mechatronics and Automation (ICCMA), Belval, Luxembourg, 9–12 November 2022; pp. 168–172. [CrossRef]
45. Sambo, P.; Nicoletto, C.; Giro, A.; Pii, Y.; Valentinuzzi, F.; Mimmo, T.; Lugli, P.; Orzes, G.; Mazzetto, F.; Astolfi, S.; et al. Hydroponic Solutions for Soilless Production Systems: Issues and Opportunities in a Smart Agriculture Perspective. *Front. Plant Sci.* **2019**, *10*, 923. [CrossRef] [PubMed]
46. Trejo-Téllez, L.I.; Gómez-Merino, F.C. Nutrient Solutions for Hydroponic Systems. In *Hydroponics—A Standard Methodology for Plant Biological Researches*; Asao, T., Ed.; InTech: Rijeka, Croatia, 2012.
47. Nguyen, T.P.D.; Jang, D.C.; Tran, T.T.H.; Nguyen, Q.T.; Kim, I.S.; Hoang, T.L.H.; Vu, N.T. Influence of Green Light Added with Red and Blue Leds on the Growth, Leaf Microstructure and Quality of Spinach (*Spinacia oleracea* L.). *Agronomy* **2021**, *11*, 1724. [CrossRef]
48. Baiyin, B.; Tagawa, K.; Yamada, M.; Wang, X.; Yamada, S.; Yamamoto, S.; Ibaraki, Y. Study on Plant Growth and Nutrient Uptake under Different Aeration Intensity in Hydroponics with the Application of Particle Image Velocimetry. *Agriculture* **2021**, *11*, 1140. [CrossRef]
49. Chowdhury, M.E.H.; Khandakar, A.; Ahmed, S.; Al-Khuzaei, F.; Hamdalla, J.; Haque, F.; Reaz, M.B.I.; Al Shafei, A.; Al-Emadi, N. Design, Construction and Testing of Iot Based Automated Indoor Vertical Hydroponics Farming Test-Bed in Qatar. *Sensors* **2020**, *20*, 5637. [CrossRef]
50. Yegül, U. Development of an Embedded Software and Control Kit to Be Used in Soilless Agriculture Production Systems. *Sensors* **2023**, *23*, 3706. [CrossRef]
51. Chuah, Y.D.; Lee, J.V.; Tan, S.S.; Ng, C.K. Implementation of Smart Monitoring System in Vertical Farming. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *268*, 012083. [CrossRef]
52. Mamatha, V.; Kavitha, J.C. Machine Learning Based Crop Growth Management in Greenhouse Environment Using Hydroponics Farming Techniques. *Meas. Sens.* **2023**, *25*, 100665. [CrossRef]
53. Fimbres-Acedo, Y.E.; Servín-Villegas, R.; Garza-Torres, R.; Endo, M.; Fitzsimmons, K.M.; Emerenciano, M.G.C.; Magallón-Servín, P.; López-Vela, M.; Magallón-Barajas, F.J. Hydroponic Horticulture Using Residual Waters from Oreochromis Niloticus Aquaculture with Biofloc Technology in Photoautotrophic Conditions with Chlorella Microalgae. *Aquac. Res.* **2020**, *51*, 4340–4360. [CrossRef]
54. Ibrahim, L.A.; Shaghaleh, H.; El-Kassar, G.M.; Abu-Hashim, M.; Elsadek, E.A.; Alhaj Hamoud, Y. Aquaponics: A Sustainable Path to Food Sovereignty and Enhanced Water Use Efficiency. *Water* **2023**, *15*, 4310. [CrossRef]
55. Noh, K.; Jeong, B.R. Increased Carbon Dioxide by Occupants Promotes Growth of Leafy Vegetables Grown in Indoor Cultivation System. *Sustainability* **2021**, *13*, 13288. [CrossRef]
56. Yessenamanova, M.; Yessenamanova, Z.; Tlepbergenova, A.; Moldir, M.; Nurgul, B. Optimization of Acidity and Electrical Conductivity in Hydroponic Vegetable Production: A STEM Educational Perspective. *Int. J. Des. Nat. Ecodynamics* **2023**, *18*, 1517–1524. [CrossRef]
57. Wang, L.; Ning, S.; Zheng, W.; Guo, J.; Li, Y.; Li, Y.; Chen, X.; Ben-Gal, A.; Wei, X. Performance Analysis of Two Typical Greenhouse Lettuce Production Systems: Commercial Hydroponic Production and Traditional Soil Cultivation. *Front. Plant Sci.* **2023**, 14. [CrossRef]
58. Priya, G.L.; Baskar, C.; Deshmane, S.S.; Adithya, C.; Das, S. Revolutionizing Holy-Basil Cultivation with AI-Enabled Hydroponics System. *IEEE Access* **2023**, *11*, 82624–82639. [CrossRef]

59. Atmaja, P.; Surantha, N. Smart Hydroponic Based on Nutrient Film Technique and Multistep Fuzzy Logic. *Int. J. Electr. Comput. Eng.* **2022**, *12*, 3146–3157. [CrossRef]
60. Custódio, M.; Villasante, S.; Calado, R.; Lillebø, A.I. Testing the Hydroponic Performance of the Edible Halophyte Halimione Portulacoides, a Potential Extractive Species for Coastal Integrated Multi-Trophic Aquaculture. *Sci. Total Environ.* **2021**, *766*, 144378. [CrossRef] [PubMed]
61. Sutulienė, R.; Laužikė, K.; Pukas, T.; Samuolienė, G. Effect of Light Intensity on the Growth and Antioxidant Activity of Sweet Basil and Lettuce. *Plants* **2022**, *11*, 1709. [CrossRef]
62. Boros, I.F.; Székely, G.; Balázs, L.; Csambalik, L.; Sipos, L. Effects of LED Lighting Environments on Lettuce (*Lactuca sativa* L.) in PFAL Systems—A Review. *Sci. Hortic.* **2023**, *321*, 112351. [CrossRef]
63. Carotti, L.; Pistillo, A.; Zauli, I.; Meneghello, D.; Martin, M.; Pennisi, G.; Gianquinto, G.; Orsini, F. Improving Water Use Efficiency in Vertical Farming: Effects of Growing Systems, Far-Red Radiation and Planting Density on Lettuce Cultivation. *Agric. Water Manag.* **2023**, *285*, 108365. [CrossRef]
64. Piovene, C.; Orsini, F.; Bosi, S.; Sanoubar, R.; Bregola, V.; Dinelli, G.; Gianquinto, G. Optimal Red:Blue Ratio in Led Lighting for Nutraceutical Indoor Horticulture. *Sci. Hortic.* **2015**, *193*, 202–208. [CrossRef]
65. Naznin, M.T.; Lefsrud, M.; Gravel, V.; Azad, M.O.K. Blue Light Added with Red LEDs Enhance Growth Characteristics, Pigments Content, and Antioxidant Capacity in Lettuce, Spinach, Kale, Basil, and Sweet Pepper in a Controlled Environment. *Plants* **2019**, *8*, 93. [CrossRef] [PubMed]
66. Custódio, M.; Cartaxana, P.; Villasante, S.; Calado, R.; Lillebø, A.I. Led Lighting and High-Density Planting Enhance the Cost-Efficiency of Halimione Portulacoides Extraction Units for Integrated Aquaculture. *Appl. Sci.* **2021**, *11*, 4995. [CrossRef]
67. Yang, T.; Samarakoon, U.; Altland, J.; Ling, P. Photosynthesis, Biomass Production, Nutritional Quality, and Flavor-Related Phytochemical Properties of Hydroponic-Grown Arugula (*Eruca sativa* Mill.) 'Standard' under Different Electrical Conductivities of Nutrient Solution. *Agronomy* **2021**, *11*, 1340. [CrossRef]
68. Carotti, L.; Potente, G.; Pennisi, G.; Ruiz, K.B.; Biondi, S.; Crepaldi, A.; Orsini, F.; Gianquinto, G.; Antognoni, F. Pulsed Led Light: Exploring the Balance between Energy Use and Nutraceutical Properties in Indoor-Grown Lettuce. *Agronomy* **2021**, *11*, 1106. [CrossRef]
69. Dou, H.; Niu, G.; Gu, M.; Masabni, J.G. Responses of Sweet Basil to Different Daily Light Integrals in Photosynthesis, Morphology, Yield, and Nutritional Quality. *HortScience* **2018**, *53*, 496–503. [CrossRef]
70. Kong, Y.; Nemali, A.; Mitchell, C.; Nemali, K. Spectral Quality of Light Can Affect Energy Consumption and Energy-Use Efficiency of Electrical Lighting in Indoor Lettuce Farming. *HortScience* **2019**, *54*, 865–872. [CrossRef]
71. Ercan Karaayak, P.; Inanoglu, S.; Karwe, M.V. Impact of Cold Plasma Treatment of Sweet Basil Seeds on the Growth and Quality of Basil Plants in a Lab-Scale Hydroponic System. *ACS Agric. Sci. Technol.* **2023**, *3*, 675–682. [CrossRef]
72. Farooq, A.; Verma, A.K.; Hittinahalli, C.M.; Varghese, T.; Pathak, M.S. Iron Supplementation in Aquaculture Wastewater and Its Impact on Osmoregulatory, Haematological, Blood Biochemical, and Stress Responses of Pangasius with Spinach in Nutrient Film Technique Based Aquaponics. *Aquaculture* **2023**, *567*, 739250. [CrossRef]
73. Nursyahid, A.; Agung Setyawan, T.; Sriyanto Nugroho, A.; Novitasari, M.; Pramono, S.; Dwi Wardihani, E. Performance of Acidity Nutrient Automation Using MQTT Protocol in Dutch Bucket System Hydroponic. *J. Eng. Sci. Technol.* **2023**, *18*, 214–228.
74. Langenfeld, N.J.; Pinto, D.F.; Faust, J.E.; Heins, R.; Bugbee, B. Principles of Nutrient and Water Management for Indoor Agriculture. *Sustainability* **2022**, *14*, 10204. [CrossRef]
75. Abd Ghani, R.; Omar, S.; Jolánkai, M.; Tarnawa, Á.; Khalid, N.; Kassai, M.K.; Kende, Z. Response of Shoot and Root Growth, Yield, and Chemical Composition to Nutrient Concentrations in Soybean Varieties Grown under Soilless and Controlled Environment Conditions. *Agriculture* **2023**, *13*, 1925. [CrossRef]
76. Stathopoulou, P.; Tsoumalakou, E.; Levizou, E.; Vanikiotis, T.; Zaoutsos, S.; Berillis, P. Iron and Potassium Fertilization Improve Rocket Growth without Affecting Tilapia Growth and Histomorphology Characteristics in Aquaponics. *Appl. Sci.* **2021**, *11*, 5681. [CrossRef]
77. Wei, Y.; Li, W.; An, D.; Li, D.; Jiao, Y.; Wei, Q. Equipment and Intelligent Control System in Aquaponics: A Review. *IEEE Access* **2019**, *7*, 169306–169326. [CrossRef]
78. Kim, H.; Oh, D.; Jang, H.; Koo, C.; Hong, T.; Kim, J. Development of a Multi-Node Monitoring System for Analyzing Plant Growth and Indoor Environment Interactions: An Empirical Study on a Plant Factory. *Comput. Electron. Agric.* **2023**, *214*, 108311. [CrossRef]
79. Lam, V.P.; Kim, S.J.; Park, J.S. Optimizing the Electrical Conductivity of a Nutrient Solution for Plant Growth and Bioactive Compounds of Agastache Rugosa in a Plant Factory. *Agronomy* **2020**, *10*, 76. [CrossRef]
80. Kudirka, G.; Viršilė, A.; Sutulienė, R.; Laužikė, K.; Samuolienė, G. Precise Management of Hydroponic Nutrient Solution PH: The Effects of Minor PH Changes and MES Buffer Molarity on Lettuce Physiological Properties. *Horticulturae* **2023**, *9*, 837. [CrossRef]
81. Fussy, A.; Papenbrock, J. An Overview of Soil and Soilless Cultivation Techniques—Chances, Challenges and the Neglected Question of Sustainability. *Plants* **2022**, *11*, 1153. [CrossRef]
82. Vatistas, C.; Avgoustaki, D.D.; Bartzanas, T. A Systematic Literature Review on Controlled-Environment Agriculture: How Vertical Farms and Greenhouses Can Influence the Sustainability and Footprint of Urban Microclimate with Local Food Production. *Atmosphere* **2022**, *13*, 1258. [CrossRef]

83. Sipos, L.; Balázs, L.; Székely, G.; Jung, A.; Sárosi, S.; Radácsi, P.; Csambalik, L. Optimization of Basil (*Ocimum basilicum* L.) Production in LED Light Environments—A Review. *Sci. Hortic.* **2021**, *289*, 110486. [CrossRef]
84. Warner, R.; Wu, B.S.; MacPherson, S.; Lefsrud, M. How the Distribution of Photon Delivery Impacts Crops in Indoor Plant Environments: A Review. *Sustainability* **2023**, *15*, 4645. [CrossRef]
85. Hendrickson, T.; Dunn, B.L.; Goad, C.; Hu, B.; Singh, H. Effects of Elevated Water Temperature on Growth of Basil Using Nutrient Film Technique. *HortScience* **2022**, *57*, 925–932. [CrossRef]
86. Naim Khalid, S.M. *FAO Crop Production Manual a Guide to Fruit and Vegetable Production in the Federated States of Micronesia*; FAO: Rome, Italy, 2020.
87. Lefsrud, M.G.; Kopsell, D.A.; Sams, C.E. Irradiance from Distinct Wavelength Light-Emitting Diodes Affect Secondary Metabolites in Kale. *HortScience* **2008**, *43*, 2243–2244. [CrossRef]
88. How to Grow Hydroponic Asparagus—Hydrobuilder Learning Center. Available online: https://hydrobuilder.com/learn/hydroponic-asparagus/ (accessed on 18 March 2024).
89. Pennisi, G.; Orsini, F.; Landolfo, M.; Pistillo, A.; Crepaldi, A.; Nicola, S.; Fernández, J.A.; Marcelis, L.F.M.; Gianquinto, G. Optimal Photoperiod for Indoor Cultivation of Leafy Vegetables and Herbs. *Eur. J. Hortic. Sci.* **2020**, *85*, 329–338. [CrossRef]
90. Yan, D.; Ding, K.; He, Y.; Fan, L.; Wang, S.; Jiang, X. Strontium Uptake and Effects in Hydroponically Cultivated Celery. *Water Air Soil Pollut.* **2020**, *231*, 279. [CrossRef]
91. Pennisi, G.; Pistillo, A.; Orsini, F.; Cellini, A.; Spinelli, F.; Nicola, S.; Fernandez, J.A.; Crepaldi, A.; Gianquinto, G.; Marcelis, L.F.M. Optimal Light Intensity for Sustainable Water and Energy Use in Indoor Cultivation of Lettuce and Basil under Red and Blue LEDs. *Sci. Hortic.* **2020**, *272*, 109508. [CrossRef]
92. Karimi, M.; Ahmadi, N.; Ebrahimi, M. Red LED Light Promotes Biomass, Flowering and Secondary Metabolites Accumulation in Hydroponically Grown *Hypericum perforatum* L. (Cv. Topas). *Ind. Crops Prod.* **2022**, *175*, 114239. [CrossRef]
93. Rahman, A.; Wahjuni, S.; Priandana, K. The Development of Hydroponic Nutrient Solutions Control Using Fuzzy and BPNN for Celery Plant. *Int. J. Adv. Sci. Eng. Inf. Technol.* **2022**, *12*, 431–436. [CrossRef]
94. Hydroponic Gardening—Leeks | Avocados Love Hydroponics. Available online: https://avocado99.wordpress.com/2008/07/02/hydroponic-gardening-leeks/ (accessed on 18 March 2024).
95. Growing Leeks Hydroponically—Nutrients, PH, and EC | Agri Farming. Available online: https://www.agrifarming.in/growing-leeks-hydroponically-nutrients-ph-and-ec (accessed on 18 March 2024).
96. Stamford, J.D.; Stevens, J.; Mullineaux, P.M.; Lawson, T. LED Lighting: A Grower's Guide to Light Spectra. *HortScience* **2023**, *58*, 180–196. [CrossRef]
97. IEEE Xplore Full-Text PDF. Available online: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=10198435 (accessed on 14 July 2024).
98. Rahman, M.M.; Field, D.L.; Ahmed, S.M.; Hasan, M.T.; Basher, M.K.; Alameh, K. LED Illumination for High-Quality High-Yield Crop Growth in Protected Cropping Environments. *Plants* **2021**, *10*, 2470. [CrossRef]
99. Rodrigues da Silva, A.A.; Francisco do Nascimento Sousa, P.; Soares de Lima, G.; Soares, L.A.d.A.; Gheyi, H.R.; de Andrade Silva, L.; Lopes Araújo Rocha, J.; Alberto Vieira de Azevedo, C. Salicylic Acid Alleviates the Effects of Salt Stress on the Physiology, Growth, and Production of Hydroponic Okra. *Arid. Land Res. Manag.* **2023**, *37*, 602–618. [CrossRef]
100. Mamledesai, H.; Soriano, M.A.; Ahmad, R. A Qualitative Tool Condition Monitoring Framework Using Convolution Neural Network and Transfer Learning. *Appl. Sci.* **2020**, *10*, 7298. [CrossRef]
101. Ahmed, A.; Zulfiqar, S.; Ghandar, A.; Chen, Y.; Hanai, M.; Theodoropoulos, G. Digital Twin Technology for Aquaponics: Towards Optimizing Food Production with Dynamic Data Driven Application Systems. *Commun. Comput. Inf. Sci.* **2019**, *1094*, 3–14. [CrossRef]
102. Witzel, O.; Wilm, S.; Karimanzira, D.; Baganz, D. Controlling and Regulation of Integrated Aquaponic Production Systems—An Approach for a Management Execution System (MES). *Inf. Process. Agric.* **2019**, *6*, 326–334. [CrossRef]
103. Liakos, K.G.; Busato, P.; Moshou, D.; Pearson, S.; Bochtis, D. Machine Learning in Agriculture: A Review. *Sensors* **2018**, *18*, 2674. [CrossRef]
104. Talaviya, T.; Shah, D.; Patel, N.; Yagnik, H.; Shah, M. Implementation of Artificial Intelligence in Agriculture for Optimisation of Irrigation and Application of Pesticides and Herbicides. *Artif. Intell. Agric.* **2020**, *4*, 58–73. [CrossRef]
105. Xu, X.; Lu, Y.; Vogel-Heuser, B.; Wang, L. Industry 4.0 and Industry 5.0—Inception, Conception and Perception. *J. Manuf. Syst.* **2021**, *61*, 530–535. [CrossRef]
106. Maddikunta, P.K.R.; Pham, Q.V.; Prabadevib, B.; Deepa, N.; Dev, K.; Gadekallu, T.R.; Ruby, R.; Liyanage, M. Industry 5.0: A Survey on Enabling Technologies and Potential Applications. *J. Ind. Inf. Integr.* **2022**, *26*, 100257. [CrossRef]