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Scientific research trends for plant factory with artificial lighting: scoping review

Tendências de pesquisas científicas para *plant factory with artificial lighting*: revisão de escopo

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ABSTRACT

Plant Factory With Artificial Lighting consists of a protected horticulture system in controlled environment facilities, in combination with various levels of growing surface and factors such as lighting, cultivation system, crop nutrition, and energy efficiency. The objective of this study was to identify in published scientific articles the current topics addressed, the potentialities and challenges identified, and their future position on the this system. This is a scoping review of 49 articles published in scientific journals that answered the research question "What are the topics addressed in the Journal Article on Plant Factory With Artificial Lighting?" from 2015 to 2022. The reviewed articles demonstrated that the development of alternatives for cultivation methods, lighting systems with variation of light spectrum, irrigation systems, and new technologies for the production chain, aimed at increasing production capacity, is a trend. They also indicated that, although the Plant Factory With Artificial Lightning has shown potential for the production of several crops, technical and economic optimization requires greater attention, pointing out that technological development and production methods are fundamental factors to establish the system as an alternative of agricultural production in sustainable urban centers.

Keywords: technology; challenges; possibilities; economy; production.

RESUMO

A *Plant Factory With Artificial Lighting* (PFAL) consiste em um sistema de horticultura protegido em instalações de ambiente controlado, em combinação com vários níveis de superfície de crescimento e associação de fatores como iluminação, sistema de cultivo, nutrição das culturas e eficiência energética. O objetivo deste estudo foi identificar nos artigos científicos publicados os atuais temas abordados, as potencialidades e desafios identificados e seu posicionamento futuro sobre as PFAL. Trata-se de uma revisão de escopo de 49 artigos publicados em periódicos científicos que davam a resposta à pergunta de investigação, "Quais são os temas abordados em artigos científicos sobre PFAL?", no período de 2015 a 2022. Os artigos revisados demonstraram como tendência o desenvolvimento de alternativas para os métodos de cultivo, sistemas de iluminação com variação do espectro de luz, sistemas de irrigação e novas tecnologias de cadeia produtiva, visando ao aumento da capacidade produtiva. Também mostraram que, embora a PFAL tenha demonstrado potencial para a produção de diversas culturas, a otimização técnica e econômica requer maior atenção, apontando-se que o desenvolvimento tecnológico e os métodos produtivos são fatores fundamentais para ela se estabelecer como alternativa de produção agrícola em centros urbanos sustentáveis.

Palavras-chave: tecnologia; desafios; possibilidades; economia; produção.

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Introduction

"The Food Waste Index Report", published by the United Nations Environment Programme in 2021, highlights the need to develop new concepts to minimize food waste and improve the yield, quality, and sustainability of agricultural production. This approach is critical to achieving target 3 of Sustainable Development Goal 12 (SDG 12).

The Plant Factory With Artificial Lighting (PFAL) emerges as a system that corresponds to the demands inherent in the transformations in the agricultural sector, food production chain, and application of sustainable technologies. They are able to meet needs such as feeding the global population, preserving the environment, promoting health, and stimulating economic growth while reducing the consumption of natural resources and environmental degradation. In this way, this system fits the concept of sustainable development.

The term PFAL refers to a plant production facility with a structure similar to a thermally insulated and nearly airtight warehouse, with multiple cultivation shelves, and vertically stacked electric lamps. Stacking shelves optimize land use, and fluorescent or light-emitting diode (LED) lamps optimize plant growth. Other equipment present includes air conditioners, air circulation fans, nutrient solution supply units, and an environmental control unit (Kozai, 2013).

Interest in PFALs has experienced a significant increase in recent years, as evidenced through research released by the MarketandMarkets consultancy. According to this research, it is estimated that the vertical farm market will more than triple, from US$ 3.1 billion in 2021 to US$ 9.7 billion in 2026. On the other hand, PFAL has raised a series of issues regarding production and cultivation methods, financial return, energy use, and the need for innovative technologies, which must be analyzed, studied, and solved (Kozai et al., 2019).

Given the aforementioned considerations, this study is justified by the need to identify current scientific research proposals carried out in the area since these researches underlie the future development of PFALs. The objective was to analyze the topics addressed, the potentialities and challenges identified, as well as the future positioning regarding these technologies."

Material and Methods

This is a scoping review, developed according to the method proposed by the Joanna Briggs Institute (JBI) (Nyanchoka et al., 2019; Peters et al., 2020). Scoping reviews serve to synthesize evidence and assess the scope of knowledge produced on a given subject (Tricco et al., 2018). This type of study comprises five phases, namely:

- identification of the research question;
- identification of relevant studies;
- study selection;
- data mapping;
- grouping, summarizing, and reporting the results (Nyanchoka et al., 2019; Peters et al., 2020).

In order to prepare the review summary, the recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) checklist (Page et al., 2021) were followed.

The research question, "What are the topics addressed in the Journal Article on Plant Factory With Artificial Lighting?", was guided by the PCC mnemonic (P: population, C: concept, and C: context), as guided by the JBI Manual (Peters et al., 2020), with "P" being the population of the Journal Article, "C", the concept of interest (research results), and "C", the context of PFAL.

In order to define the eligibility criteria, the following were considered:

- primary articles, case studies, and reports with quantitative and/or qualitative approach, published in any language, which addressed studies focused on Vertical Farm with emphasis on PFALs;
- published in scientific journals.

The time limit established for publication was from 2015 to 2022; as it is a new technology, this would be the period with the most publications on the subject. We excluded from the sample articles that did not meet the research question and review articles that referred to the PFALs but did not contemplate them as the main theme of the study, as well as abstracts and annals of congresses, editorials and books.

The search strategy was designed to locate studies that answered the research question. The research platforms that presented the selected studies in the area were: MDPI – Publisher of Open Access Journals; ScienceDirect; ResearchGate; Google Scholar; Springer Science+Business Media, and Frontiers Media. After the search, all selected studies were grouped in the Mendeley® Reference Manager. Duplicates were identified and removed. For the selection of studies, reading was performed independently, analyzing titles and abstracts and, subsequently, reading the articles in total.

The keywords used were: vertical farming; plant factory; urban agriculture; plant factory with artificial lighting; hydroponics; productivity; light quality; daily light integral; sustainability; greenhouse; microenvironment; controlled environment; controlled environment agriculture; artificial lighting; production cost; light energy use efficiency; management; indoor farming; smart agriculture; energy demand; horticulture; food security; urban farming; plant factories; automation; led; and supplemental lighting.

The results obtained from these expressions entered in the databases were checked up to the tenth page of results for each search. A data extraction form was constructed using Excel® software, adapting the JBI model (Peters et al., 2020), and developed specifically for the scoping review. This allowed the extraction of relevant data from each document, according to publication, author, title, year, country, journal, platform, research area, type of research, objective, conclusion, keywords, and citation.

Revision

Characteristics of PFALs

The PFALs are a closed plant production system (CPPS), where all inputs applied are implemented in projects with minimal emissions to the external environment. The advantages of PFALs over conventional systems are:

- It can be built anywhere since it does not use sunlight or soil (Song et al., 2018);
- The cultivation environment is not affected by the external environment (Fang and Chung, 2018);
- Production is constant throughout the year and about 100 times more productive than in the field (Touliatos et al., 2016);
- Product quality can be improved by manipulating the environment (Bantis, 2021; Chen et al., 2021b);
- The products are pesticide-free, so no washing is required before consumption (Roberts et al., 2020);
- The generated product has a longer shelf life (Hayashi et al., 2020; Hayashi et al., 2022);
- The system lowers expenses with transportation (end product to consumer) (Ohyama, 2015);
- The use of resources is highly efficient, with minimal pollutant emissions (Kozai et al., 2016).

However, there are a number of challenges and disadvantages of PFALs that must be faced such as:

- High initial and production cost (Tricco et al., 2018);
- High cost of electricity, labor and materials (seeds, fertilizers, packaging, delivery, among others) (Yan et al., 2019);
- Lack of information on culture and environmental control (Liu et al., 2020);
- High cost of operating equipment (Shomefun et al., 2018);
- Low financial return (Hang et al., 2019);
- Competition with conventional products (Jürkenbeck et al., 2019).

Approach of the articles

The revised articles presented alternatives to PFAL challenges and disadvantages, aiming at reducing costs and resources and maximizing results. These points are evidenced in the review articles through studies on resource use reduction, application of Internet of Things (IoT) in the production control system, methodology for rational use of electric energy, cultivation methods for different types of vegetables, and light spectrum analysis.

Reduction of resources

An et al. (2020) applied a drip system as an alternative to the conventional irrigation system based on aquaponics, which worked in a closed system, aiming to reduce water use in irrigation. The drip system provided an expressive growth of vegetables.

Urairi et al. (2017) used a flashing lighting system. This study evaluated the growth of vegetables under interval light, that is, a system with controlled interruptions in light supply, aimed at reducing energy consumption. The study demonstrated that the vegetables reached the same level as those cultivated under continuous lighting.

Park et al. (2018;, 2020) reinforced the claim that the use of adequate pulses of LEDs can save energy while inducing plant growth similar to that of continuous LEDs.

All studies demonstrated systems with results similar to traditional systems regarding plant growth and development, however, at lower cost and use of resources.

IoT application

Ismail and Norashikin (2017), Chuah et al. (2019), and Haris et al. (2019) demonstrated that the integrated use of production systems, with real-time monitoring and control (temperature, nutrient, monitoring of plant growth from germination to flowering), can optimize production, irrigation, and temperature control of a PFAL.

Light spectrum analysis

PFAL light spectrum analysis studies followed the same applicability pattern, using leaf spectrum analysis to assess pigment composition and plant health status. It is known that light spectrum and intensity can affect leaf pigment composition and spectral absorbance differently in cultures (Bae et al., 2019). The main light spectra analyzed (Dou et al., 2018) were red (R), blue (B), white (W), and green (G). The experiments consisted of submitting various types of plants (tomato, mustard, radish, green basil, red amaranth, garlic chives, pea sprouts, and orchids) under different light spectra, using LED lamps at different times, observing the tendency of plant growth, and evaluating photosynthetic and nutritional characteristics (Joshi et al., 2017; Bantis et al., 2018; Fang et al., 2020; Lee et al., 2020).

Chen et al. (2021a) and Modarelli et al. (2022) evaluated light spectra for lettuce leaves. Studies indicated that the proportions of Red and Blue wavelengths (R and B) affected the energy efficiency and quality of lettuce; however, plant responses to these proportions varied according to different light intensities. These results are in line with the studies by Saito et al. (2020) and Sankhuan et al. (2022), who highlighted the importance of adequate light intensity to promote plant growth and qualitative traits to achieve high production targets. Therefore, preliminary screening of plant performance under different light treatments is essential to improve plant response to artificial lighting.

Economic viability

Avgoustaki et al. (2020) indicated that the current PFALs have an increasing production/yield rate, competing with values of products close to those grown in an open environment. Since 2016, monetary values (sales/costs), working hours (kg of product/h), electricity (kg of product/kW·h), area and time of cultivation (kg of product per unit of area of cultivation and time unit) improved considerably in many PFALs.

These productivity improvements resulted from the introduction of LEDs, robotic/automated units, improved farm units with production management software, and increased public acceptance (Kozai et al., 2019).

Jürkenbeck et al. (2019) highlighted that the true value-adding potential of a PFAL lies in clarifying to the consumer that the product is cleaner and more sustainable, without pesticides, and that its culture impacts less on the environment; this would bring a niche of consumers willing to pay a slightly higher price for a more sustainable product.

Shao et al. (2016) emphasized that the PFALs in operation have not yet entered the phase of generating profit, and that, analyzing the current technology and cultivation methodologies, the PFALs will only be successful in places where agriculture encounters difficulties due to the lack of land for cultivation, aggressive weather, pests or other impediments. However, it should be taken into account that, since the publication of the article, several technological and technical changes (use of IoT, better use of light spectra, mechanization of the system, changes in production practices) occurred in the PFALs that can give a perspective different from the author's conclusion.

Results

The database search identified 173 potentially eligible articles. With the application of inclusion and exclusion criteria, 49 articles were selected to compose the final sample of this scoping review, as shown in Figure 1.

The Graphs 1, 2, 3 and 4 highlight the results of the analyses of the control parameters "year of publication", "country of origin", "type of research" and "objective of research".

Graph 1 reveals that the years 2018, 2019, and 2020 had the highest number of publications and Graph 2 shows the countries that lead in publications related to the topic. These two investigations are justified since in the period from 2016 to 2020, China and Japan showed a growing opening of PFAL model companies. Japan had a total of 186 PFALs in 2017, rising to more than 200 in 2019; more than half of them used LED lamps in their production and their market value was approximately 70 million dollars in 2015, forecast to reach 350 million dollars in 2026 (Kozai et al., 2019). According to projections, the Chinese market would have opened, by 2017, more than 80 PFALs (Shao et al., 2016).

The fields of analysis of Graphs 3 and 4, "Types of Research" and "Main Research Themes", demonstrate that 75% of the researches are quantitative and 25% are qualitative, and of the total of themes 43% are directed to the lighting area, 20%, to the development and application of new technologies, and 19% to the development/improvement of cultivation techniques.

Discussion

Although PFAL demonstrates the potential for the production of a wide range of crops, it still requires more attention to maximize productivity and reduce system costs. Furthermore, PFAL is currently led by industry start-ups and independent researchers, which demands knowledge on the feasibility of useful food production scales. Therefore, both situations call for further research.

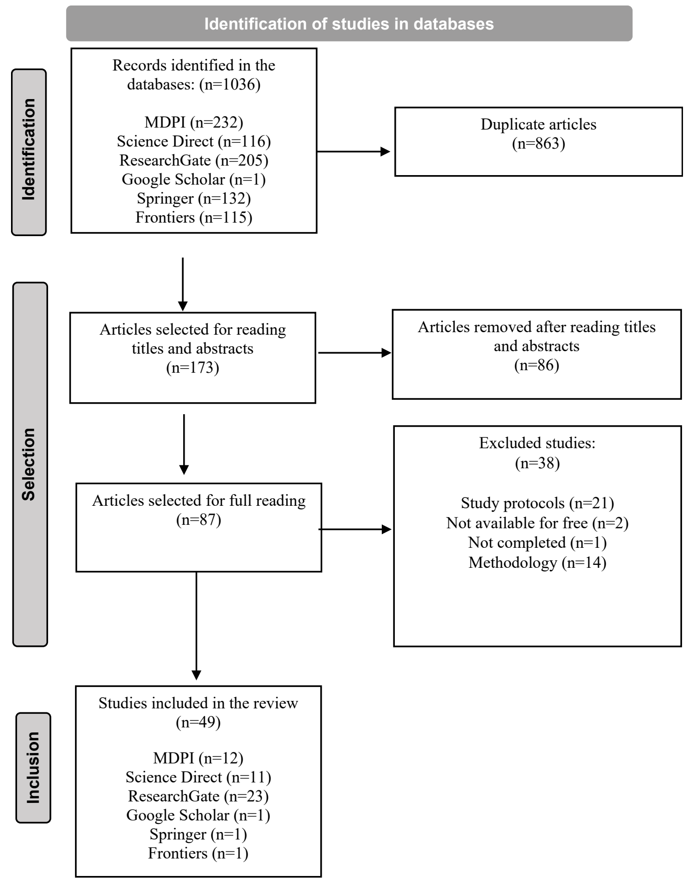
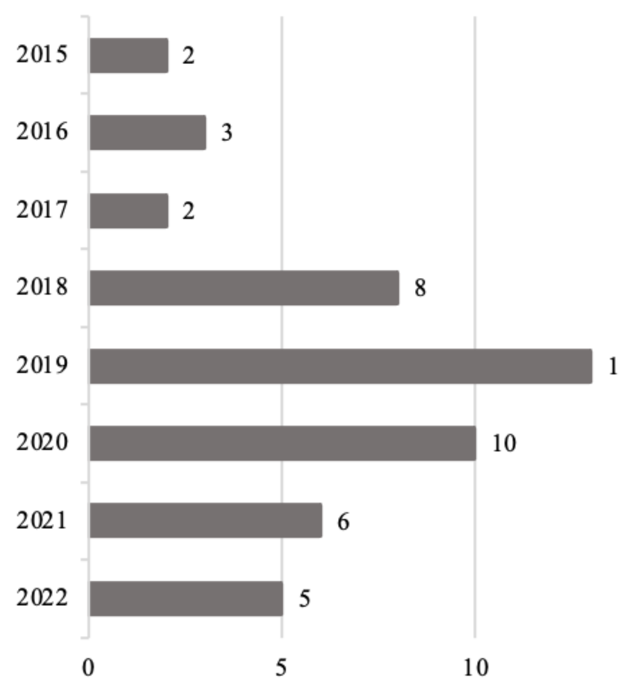
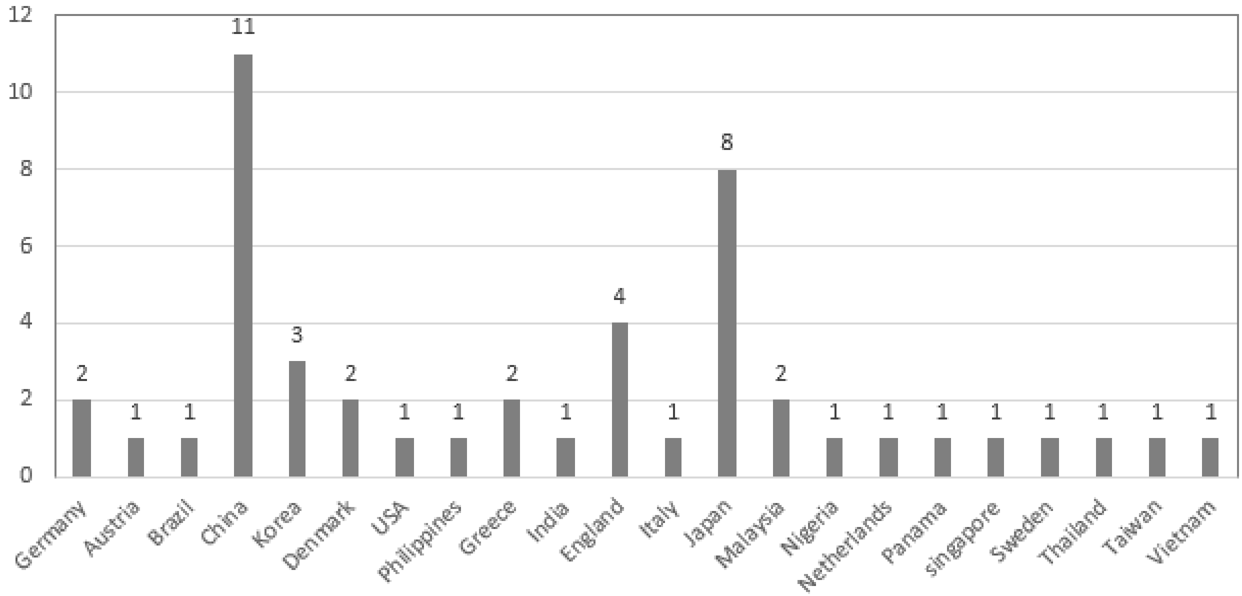


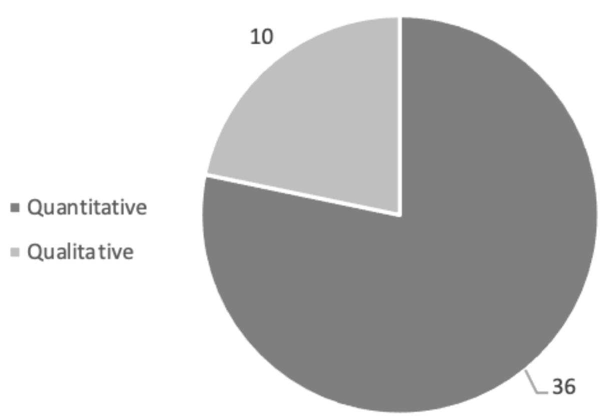
Figure 1 – Flowchart of the study selection process.
Source: Adapted from Page et al. (2021).



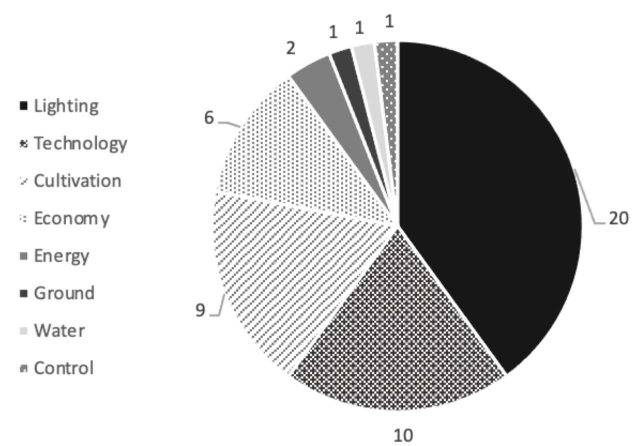
Graph 1 – Number of articles per year.



Graph 2 – Production by country.



Graph 3 – Types of research.



Graph 4 – Main research themes.

A next-generation PFAL is expected to be deployed that integrates advanced technologies (LEDs, robotic/automated units, and enhanced farm units with production management software) and increased public acceptance, by presenting the system as more environmentally friendly than conventional systems, which will considerably improve productivity, and solve economic, environmental, and social problems. However, before introducing these advanced technologies, it is necessary to create a concept and a methodology relevant to PFAL design and management.

Improvement points

Based on the challenges and issues contextualized in the review articles, it was possible to identify the following points for improvement in PFAL systems:

- Cost of production: The main components of PFAL production costs are depreciation (or initial investment), labor (hours of work), and electricity. The average annual cost percentages are 26% of depreciation, 21% of labor, 18% of electricity, and 11% of profit for sales, with the remainder consisting of consumables (6%), logistics

(5%), seeds (2%) and others (11%) (Bhowmick et al., 2019; Peters et al., 2020). Thus, reductions in the three main cost components are critical to lowering the total cost of production.

- Practices to improve production:
  - Electricity: Electricity consumption for lighting accounts for 75–80% of the total consumption in the grow room (Avgoustaki, 2019). There are approximately three ways to improve electricity productivity in terms of lighting: Using LEDs with high efficiency of photosynthetic photon number (or electrical energy-photon conversion coefficient) (Dieleman et al., 2019); Improving the percentage of photosynthetic photons received by leaves relative to those emitted by LEDs, using light reflectors within the growing space (Fang et al., 2020); and Improving photosynthetic photon yield (ratio of photosynthetic photons fixed as chemical energy in leaves to those absorbed by leaves) by controlling aerial and root zone environments, cultivar selection, and/or cultivation methods (Liu et al., 2020);
  - Automation systems: Deploying automation systems improves hourly productivity by 30–40%, but significantly increases initial investment (Lauguico et al., 2019). It is expected that, soon, no person will enter the cultivation room of a large-scale PFAL, except for periodic maintenance and emergency measures, with more than 90% of the handling operations being automated (Monteiro et al., 2018). In consequence, the productivity of the working hour will be improved substantially;
  - Monetary productivity: The productivity capacity of a PFAL must be more than tripled in order to make a profit from growing vegetables such as tomatoes and berries such as strawberries, raspberries and blueberries (Meng and Runkle, 2019).
- Environmental control: The environmental control rate of a PFAL is high, depending largely on the reliability of sensors, control software, and actuators. The success of the PFAL operation is highly dependent on the control system and its reproducibility (Ren et al., 2022).

Critical points

Despite significant advances in recent technologies such as IoT, artificial intelligence (AI), continuous measurement of plant traits (phenotyping), solar cells with batteries, and breeding using DNA markers, they are still rarely implemented in conventional PFALs, where people still plant, collect and control plants, using resources from non-renewable sources (Kozai et al., 2019).

Therefore, the current technologies applied to PFAL and to planting methodologies of the existing chains are a barrier, when analyzed economically. Although several studies demonstrate methods of accelerated plant growth or a decrease in production cost, the value of the product is still higher than those produced conventionally, around 27% (Kozai et al., 2019). It is tangible the fact that the future viability of PFALs depends largely on the development of cultivation techniques and the improvement of technologies used. Other characteristics can also influence the success of PFALs, such as the substitution of electricity from fossil fuels for energy from renewable sources, but this issue is more linked to making the system more ecologically correct than economically viable since the change to more renewable sources does not influence the drop in the price of energy consumed.

In view of the above, PFAL presents some challenges recognized in the reviewed articles:

- Because it is a recent technology, vegetable cultivation and growth methods are less widespread and publicized. There is a lack of technical information disclosed from real projects in execution with much of the material shared coming from marketing materials;
- The academic field of study has few publications and research funding. Nabout et al. (2021) demonstrate that research disciplines with a high number of financial contributions have a favorable impact on the indication and collaboration between authors, culminating in a substantial increase in knowledge sharing and the progressive advancement of the area in question. Barra and Rojas-Hernandez (2022) cite that the dilemma also rests on the administration, magnitude, direction and prioritization of resources allocated to research. Furthermore, it depends on the criteria and indicators established to measure and evaluate both scientific productivity and academic trajectories;
- One of the strengths of PFALs is the number of products that can be grown; however, this same strength becomes a weakness considering that, for each new product, a different technique of lighting, irrigation, cultivation, energy use and waste treatment needs to be developed. There are about 50 vegetables that can be grown in a PFAL, in addition to medicinal plants. Each of these products requires unique and particular cultivation conditions to achieve its highest productive capacity, which requires studies and tests for each subject, in different aspects, leading to increased costs (Beacham et al., 2019);
- The published economic viability analyses of the projects are rare and susceptible to abrupt changes depending on technology progress or changes in the location implemented;
- There is a great urgency to develop more efficient cultivation methods, but the literature is scarce, and the analysis of how these enterprises will affect the community they serve and the small farmers who belong to the so-called green belts is non-existent.

Future trends in environmental and growth control

The fundamental characteristics desired for the improvement of PFALs are those linked to productivity maximization, that are, greater yield and quality, minimizing resources input and the emission of environmental pollutants. Current studies already follow this research trend and indicate that future PFALs will have the following characteristics:

- The light energy emitted by the lamps is fully received by the leaves and distributed equally in all leaf regions;
- All aerial and root zone environmental factors, including air current velocity and nutrient solution flow velocity, are spatially uniform in the plant canopy, aiming at uniform growth of all seeds and plants;
- The environmental factors of the aerial and root zone are controlled so that light energy is converted at maximum efficiency into chemical energy from carbohydrates in the leaves;
- Plant spatial density and growth rate are uniform and high at any stage of growth.

High efficiency in the use of resources

- Water and carbon dioxide (CO2): 100% efficiency in use and recycling.
- Nutrient element: 100% efficiency in use, without nutrient solution recycling.
- Substrates and other supplies: minimized or recycled to minimize waste production.

Environmental light control and plant physiological factors

- The quality of light, the flux density, the cycle, and the lighting direction optimized per hour/day are important factors to be controlled in order to maximize the cost and production ratio;
- Photosynthesis and photomorphogenesis, phototropism (heliotropism), biological clock, gravitropism, thermoperiodism, and some physiological disorders of the plant, such as tipburn and tumescence, are other important factors to be administered.

Key ideas for designing and managing ideal PFALs

In addition to the trends presented in the studies, some ideas are shown to be necessary to achieve ideal production conditions in a PFAL:

- Light supplied dynamically downwards, sideways, and upwards, inside and/or outside the canopy;
- Air supplied up, sideways, and/or down, into and/or out of the canopy;
- High-quality seeds carefully selected and grown in spatially uniform environments;
- All transpired water vapor condensed by air conditioners for reuse. All CO2 supplied and respired by plants is absorbed by plants under light;
- Time course of the supply rate of ions of each nutrient element in the controlled cultivation beds, considering the schedule of growth/production of the plant;
- Control of the total concentration of ions or electrical conductivity in the nutrient solution;
- Use of minimal amounts of supports (substrate) and other consumables. All consumables are biodegradable or chemically/biologically inert;
- Expansion of the grow room with minimal changes;
- Automatic handling units (seeding, spacing, transport etc.) installed;
- Units for intelligent lighting, phenotyping, and data storage installed.

Conclusion

The reviewed articles showed a tendency to develop alternatives for cultivation methods (9 articles), applying new concepts and methodologies in the use of technology with IoT (10 articles) in the production control system (1 article), methodology of electricity rational use (2 articles), cultivation methods (9 articles) for different types of vegetables, and analysis of the light spectrum (21 articles), aiming at increasing production capacity and reducing the use of resources.

The studies demonstrated the potential for the production of different crops, technical and economic optimization requiring greater attention, and that the technological development and production methods are fundamental for the PFAL system to establish itself as a viable alternative for agricultural production in sustainable urban centers.

The next-generation PFAL, to be deployed integrating the advanced technologies (LEDs, robotic/automated units, and enhanced grow units with production management software) and greater public acceptance, is expected to improve productivity considerably, solving economic, environmental and social problems.

Contribution of authors:

DA LUZ, C. D.: conceptualization; formal analysis; data curation; methodology; writing — first draft; writing — edition & review. DIÓGENES, A. N.: supervision; validation; visualization — first draft; writing — edition & review.

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