Agrochimica, Vol. 67 - Special Issue (2023)

Plant factory with artificial light: pros and cons

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Keywords: energy efficiency, leafy vegetables, LED light, urban agriculture, vertical farming

Summary: Plant factory with artificial lights (PFALs) could be useful to produce more food of high quality and reduce the use of agrochemical and transportation costs. PFALs is a complete controlled indoor farming system, mainly dedicated to the production of edible plants with small size and a short cultivation, that allows to provide a reliable production of high-quality vegetables. The development of PFALs was possible thanks to the steady price decline of Light Emitting Diode (LED) lights along with the rapid improvement of their photon efficacy. In typical PFALs with LED lights, electricity, labour, and depreciation are the three major components of the production costs. The energy-efficiency must be improved to an ecologically friendly development of PFALs.

The reduction of energy consumption and the increase in production and commercial value can be achieved by improving the digital control of the cultivation and by applying models to predict both crop growth and development.

Introduction

Current crop production has to tackle the reduction and the deterioration of water resources and fertile soils, respectively and the need to reduce the use of agrochemicals and the costs of transportation while providing more food to the growing population. In 2022, the global population reached 8 billion people and will be 9.3 billion people in 2050, with 6.7 billion of them estimated to reside in cities (United Nations, 2022). The amount of food needed by the urban population in 2050 will be approximately 70% higher than it was in 2009. In addition, customers are increasingly demanding fresh food that is safe, nutritious, tasty, and sustainably grown. Plant factory with artificial lights (PFALs) cultivation is an innovative, climate-smart option that could be able to meet these demands (Kozai, 2018a).

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DOI 10.12871/00021857202305

The first applications of the PFAL concept occurred in the second half of the last century in Denmark (Anpo et al., 2019). However, the lack of cost-effective lighting system advancements has prevented the commercial feasibility of PFALs (also known as vertical farms; Anpo et al., 2019).

Urban farming and PFALs

A steady and efficient production system, together with short, stable and balanced supply chains is important for the supply of high-quality horticultural products accessible to urban areas (Zhang et al., 2022). Plant factory is one of the solutions used for food production in urban areas. Urban farming includes non-professional community gardens and professional rooftop greenhouse horticulture. In urban horticulture, PFALs perform a range of tasks, such as provisioning (e.g., the delivery of horticultural products and medicinal plants), social action (e.g., sharing of knowledge in horticulture), and cultural activity (e.g., recreation). Horticultural plants grown in PFALs give urban residents' access to a large variety of vegetables useful in a healthy diet (Zhang et al., 2022). Additionally, PFALs can promote the cultivation of horticultural crops on and inside restored or unused buildings. The establishment of PFALs inside shopping malls is another possibility. These facilities would be outfitted with cutting-edge vertical farming technology and would combine the production of high-quality horticultural products with other services like catering and entertainment (Edmondson et al., 2020).

Agronomic and technological aspects of PFALs

Vegetables grown un PFALs provide many advantages. No matter the weather, in a PFALs there is always an ongoing supply of vegetables at a fixed price thanks to a steady production. Vegetables are grown in a clean environment under carefully supervised circumstances, and as a result, they contain far less germs and pathogens than vegetables grown on soil. The product tracking system also ensures the safety and quality of vegetables from seedling to growing and export (Anpo et al., 2019). In PFALs, the management of all environmental and growing conditions (as light, temperature, humidity, CO_2 content and mineral nutrients) is possible, this allows to produce plants characterized by a high concentrations of phytochemicals (SharathKumar et al., 2020; Zhang et al., 2022).

Plant factories are mainly dedicated to the production of edible plants with small size and short cultivation cycle, such as leafy vegetables (baby-leaves), some herbs, and microgreens. Microgreens are young seedlings harvested 7-10 days after seed germination, when they have just a few true leaves that are rich in phytochemicals much more than leaves of bigger/older plants (Galieni et al., 2020).

PFALs is an indoor farming system, where plants can be cultivated on multiple layers. Optimized lighting recipes, energy-saving technology, and intelligent control systems are used in PFALs in order to grow plants in a green and sustainable way regardless of climatic and geographic conditions (Kozai, 2019; Zhang et al., 2022). Different facilities can be used for these crops: growth cabinets or chambers, containers, and greenhouse-like structures integrated in new or recovered buildings.

The horticulture production has been greatly increased by the improvement of vertical cultivation technology, such as the development of lightweight materials for structural bracing frames, of high-rise modular assembly layers as well as the use of operational technologies (e.g., auxiliary robots, operating machinery, and automation equipment). Additionally, the optimized environmental parameters and improved light efficacy considerably support plant growth and photosynthesis in PFALs (SharathKumar et al., 2020).

In PFALS, plants are grown in hydroponics and it is crucial to optimize the system. The following cultivation systems can be used: drip system, deep water culture, wick system, aquaponics, nutrient film technique, flood and drain, aeroponics, and aero-hydroponics (van Delden et al., 2021). In order to avoid damage from continuous cropping as well as poor or abnormal growth due to pathogens or insects common in outdoor or soil-based farming, the vegetables are grown in clean rooms in nutrient solutions containing the ideal concentration of chemical fertilizers for plant growth. These solutions are supplied to the plants through the inert substrate (by drip irrigation or subirrigation) or directly to the plant roots in aeroponic system. Factors involved in crop development may be totally regulated by adjusting the proportion of chemical fertilizers present in the nutrient solution. Hydroponics makes sure that the roots have easy access to water and nutrients. Since, this system enables the plant to spend more in shoot biomass, a compact root system is ideal for plant factories (Sambo et al., 2019). Water and nutrient absorption is optimal in well-aerated and temperature-controlled nutrient solution and growing medium. Improved plant production and quality may result from a greater understanding of how temperature regulates the root structure and function (Fazlil Ilahi et al., 2017). Moreover, the composition of the nutrient solution can be rapidly modified to achieve specific effects on crop plants, for example, to limit the nitrate leaf content (Fageria, 2016) or for microelements biofortification (e.g., with selenium and/or iodine; Puccinelli et al., 2021).

Air conditioning is also crucial to obtain a clean and uniform environment while using less electricity. Sensors for airflow, temperature, humidity, CO_2 concentration, light intensity, as well as for pH, ion concentration and dissolved O_2 in nutrient solutions can used for the full control of growing environment (Anpo et al., 2019). Typical set-points for internal climate parameters are 22-26 °C, 60-70% relative humidity (RH), 150-200 µmol m^{-2} s^{-1} PAR and 800-1000 vpm CO_2.

Advantages of Light Emitting Diode (LED) light

The steady price decline of LED lights along with the rapid improvement of their photon efficacy have driven the development of PFALs. Photon efficacy is the amount of PAR photons emitted per unit of applied electric energy; µmol J^{-1} is the typical unit for LED efficacy. The photon efficacy of current LEDs is 3 µmol J^{-1} or more against less than 2 µmol J^{-1} for High Pressure Sodium (HPS) lamps. In addition, LEDs have many other advantages over HPS lamps: for instance, LEDs allow an easy control of light timing, intensity and quality, last much more than HPS lamps and are suitable for multi-layer cultivation because of their compact size, light weight and low emission of thermal radiation (Pattison et al., 2018).

Different composition of light spectrum can also affect leaf quality in terms of organoleptic, nutritional and nutraceutical attributes. Thanks to a variety of photoreceptors, plants are sensitive to UV-A, UV-B (UVR8), blue, and red:far red light ratio (Dou and Niu, 2019). For example, UV-A and blue light can specifically enhance the phenylpropanoid pathway and thus the synthesis of phenolic (Jin, 2000). which may boost nutritional value (JIN, 2000). Blue and red light increase the amount of β-carotenoids and lutein in leafy greens, respectively (Rouphael et al., 2018). The red:blue light ratio also influences the content of phenolic compounds and nitrates, the antioxidant activity, the hardness, and the crispness of leaves (Taulavuori et al., 2016). Frequently and incorrectly, green light has been ignored. Indeed, several effects, likely mediated by cryptochromes or by unknown receptors, were reviewed by Smith et al. (2017). Blue light, by the formation of a stable neutral flavin semiquinone intermediate, may activate cryptochromes enabling them to absorbs green light, in addition to blue light (Bouly et al., 2007).

Indeed, it was observed that green light boosts the level of phytonutrients such vitamin C, tocopherols, and phenolic compounds while decreasing the production of anthocyanins (Carvalho et al., 2016).

LED lighting is a unique tool for managing secondary metabolites, thus enhancing the nutraceutical, organoleptic, and/or nutritional value of horticultural products. Light-regulated transcriptional factors are in charge of controlling the formation and breakdown secondary metabolites (Llorente et al., 2017). Several studies have concentrated on creating "lighting recipes" to optimize illumination (consisting in light intensity, spectrum, and photoperiod) in order to obtain high crop yield and quality along with greater energy efficiency. The application of modern lighting systems to plants in order to increase plant light absorption and provide uniform illumination on all leaf surfaces and the co-optimization of the other environmental parameters have been the focus of several research (SharathKumar et al., 2020).

Dynamic lighting in PFALs can be a tool to modify the plant's circadian rhythms and to control crop yield and quality. It would be prudent to keep an eye out for any potential spectral shifts during the light period. Moreover, there are new chances to consider a different photoperiod when the diurnal cycle's duration changes (Sanchez and Kay, 2016).

Economy of PFALs

The economy of PFALs is matter of intense discussion and for sure it has been dramatically affected by the current international scenario that has determined a huge increase in the cost of energy. In 2018, using a simple crop model and assuming a price of electricity on the US market of 0.10 $/kWh, Pattison and colleagues demonstrated that only high-value crops can be grown in plant factories. Indeed, the cost of electricity, expressed as percentage of produce market price is small (1.0%) for microgreens, high for most vegetables (5% to more than 100%), and unacceptable for staple crops (10.000%) which also cannot be grown in PFALs (Pattison et al., 2018).

Using simulation models, Graamans et al. (2018) compared PFALs and greenhouses for lettuce production in Sweden, The Netherlands, and United Arab Emirates. In PFAL, lighting represented the greatest electricity use per kilogram of lettuce dry matter production. Considering the energy use for heating in greenhouses, in Sweden the energy consumption was similar in PFALs and greenhouses. The authors concluded that PFALs were more suitable in extremely dark and cold areas than in tropical or subtropical regions, where much energy is free of charge since it is provided by sun. In greenhouses there was a lower use of electricity, but in PFALs the use of CO_2 and water was much more efficient. Moreover, a high and steady all-year round production of lettuces was possible, while in greenhouses most of the production was obtained during spring-summer period, and for this reason the annual yield was much higher in PFALs than in greenhouses (Graamans et al., 2018).

For PFALs to be developed in a way that is ecologically friendly and maximizes economic gains, energy efficiency must be improved. Researchers could be able to comprehend the energy balance and improve the control approach for weather circumstances to reduce energy consumption, for example, by developing energetic flows and using a flexible energy-efficiency model (Weidner et al., 2021). To date, the revenue of plant factory companies is around 10% (Kozai and Niu, 2019).

In a typical PFALs with LED lights, the three major components of the production costs are electricity, labour, and depreciation (Ijichi, 2018). If the PFALs is located distant from any major cities, the cost of packing and shipping might make up 12% of the total production cost (Ohyama, 2015). On the contrary, the costs for packaging and delivery would be between 6% and 8% if the PFALs is situated in or close to a major city (Kozai, 2018b, 2016).

Electricity costs make around 18-20% of the overall production cost for LED-PFALs (Ijichi, 2018). Less than 1% and up to 2% of electrical energy is fixed as chemical energy in the sellable parts of most common PFALs; the remaining electric energy (98-99%) is transformed into heat (Kozai and Niu, 2019). Power usage per kilogram of product may be lowered by 20%-30% quite readily and theoretically by 50%-80% (Kozai and Niu, 2019). It is possible to reduce the electricity by using: (1) cutting-edge LEDs to increase the photon efficacy and light interception by plant leaves; (2) optimal control of both aerial environment and root zone. It is not a good idea to use partially the solar light since this makes all the PFALs' controlled variables unstable and unpredictable (Kozai and Niu, 2019). Moreover, electricity could be produced by photovoltaic cells; however, it would be necessary about 3 m^2 of photovoltaic cells per each square meter of cultivation area (van Delden et al., 2021).

Because most PFALs are small-scale and the majority of handling procedures are done manually, labour represents 25% to 30% of the overall production costs. If most handling procedures are carried out manually, a 15-tier PFALs with a floor size of 1 hectare requires more than 300 full-time staff. In this way, even small-scale PFALs can support regional businesses and generate a sizable number of job positions. The majority of manual operations is safe and light labour and can be done in a comfortable environment. However, in The Netherlands, the majority of handling tasks in a greenhouse complex used to produce leafy greens, bedding plants, and transplants with a floor area of at least 10 ha is automated and only few workers per ha are employed (Kozai and Niu, 2019). Unfortunately, to date, the mechanized handling devices are too big to be implemented in PFALs. Automation of handling operations is becoming important in modern PFALs with a production capacity of over 10,000 leafy green heads in order to save production costs, gather and evaluate various data automatically (such as environmental factors, plant development, transplanting, harvesting, resource consumption, as well as expenses, transportation, and sales) (Kozai and Niu, 2019). Nowadays, advanced robotic technologies, including remote sensing, image processing, cloud computing, big data analysis, and 3D modelling are being used to automate PFALs (Kozai and Niu, 2019). Using artificial intelligence to analyse data is a powerful decision-making and automation tool, and IoT-enabled peripheral equipment may enhance agricultural productivity while reducing the need for human resources (Elijah et al., 2018).

Pros and cons of PFALs

PFALs is a promising horticultural crop growing method in fast development and it has the potential to yield healthy fresh food.

Plant factories have positive aspects associated with the increased environmental, social and economic sustainability. The reduced use of water and fertilisers, and the cultivation without any pesticide are probably the main advantages of plant factories. Indeed, PFALs is relatively sustainable in terms of water, fertilizers, and land use, by implementing stringent hygienic measures and constant monitoring (SharathKumar et al., 2020).

On the other hand, PFALs has also several drawbacks, in particular the high investment and running costs, due to the high use of energy for environmental control and lighting.

Conclusions

Urban plant factories are a relatively recent evolution of greenhouses, from which they differ in location and full dependence on artificial lighting. The sustainability of PFALs essentially depends on the reduction of energy consumption and on the increase in production and commercial value (e.g., through biofortification, pesticide-free cultivation). The digital control of the entire cultivation is essential to achieve these objectives and involves the installation of an adequate number of sensors capable of detecting the environmental and cultural parameters and the application of models capable of predicting both crop growth and development. Some types of sensors may soon enter the ‘toolbox’ of indoor farmers, such as those for determining the ion content in hydroponic nutrient solutions, which could allow a more efficient application of fertigation. A greater diffusion of PFALs also requires specific professional training, which could take advantage of digital teaching technologies. Finally, the selection of dwarf varieties would allow to grow inside plant factories other types of vegetables, e.g., fruit vegetables such as tomato.

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