Energy Savings for Plant Factory: Review in China

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Abstract: The development history of Chinese plant factories is briefly reviewed. The properties and advantages of plant factories in modern agricultural farming are summarized. As a key to solve the high-cost barrier, the energy savings and some possible solutions are stressed for the development of plant factories. Especially for lighting system efficiency, four aspects are discussed for practical applications of electric power savings, including LEDs, optical components, heatsinks and LED drivers.

Key Words: plant factory, energy saving, lighting system efficiency

1. Introduction

In the past twenty years Plant Factories (PFs) have been developed in China with very fast growth rates. The first PF appeared in China in 1998[7] and now China has the second largest number of PFs next to Japan[12]. By the end of 2020, there were over 220 PFs built of various scales in China[16]. China has also boasted the world's largest PFs since 2015 (each with the cultivation area of over 20,000m^2) and has continuously broken its own records[10,11,15].

Researchers and governors in China all realize the strategic significance of PFs in modern agriculture. As the Chinese leading scientist Q. Yang mentioned[13], PFs with LED lighting are internationally recognized as the highest level in the development of facility agriculture. In recent years, PFs have also become an important component of urban agriculture in China.

Ten years ago, only a few developed countries like Japan, USA and Netherland mastered the PF technology and China mainly imported such equipment and technology from abroad. Professor Yang has witnessed China's role change from a quick learner to a confident developer and exporter of the advanced PF technology. He is currently the Deputy Director of the Institute of Urban Agriculture of the Chinese Academy of Agricultural Sciences, and Chairman of the National Smart Plant Factory Innovation Alliance.

As Professor Yang recalled[13], the systematic research of PFs started 15 years ago. Later, it was the national project "Intelligent Plant Factory Production Technology Research" that has accomplished a series of innovation breakthroughs including the intelligent control system based on internet and the proposed intelligent control methods for light and energy efficiency, and for nutritional quality improvement.

Luna-Maldonado AI, et al. (2016) defined the PF as a closed growing system using artificially controlled environmental agriculture (CEA) technologies, including light, temperature, humidity, carbon dioxide concentration, and nutrient solutions[5]. As a combination of high-tech and sustainable growing system of year-round production for indoor farming, PF applies hydroponic/aeroponic or other soilless systems, with the advantages of less natural environmental impact, greater predictability and higher productivity. Compared with conventional one-layer farming on the ground, a PF can apply multiple-story nursery frame for vertical farming, maximizing the utilization of the space's square footage. Therefore, the overall unit area nursery efficiency of a PF can be enhanced by more than 40 times, and the nursery cycle can be shortened by over 40% [13].

Especially for hydroponics, the most popular soilless cultivation method with nutrient solution, the high usage of chemicals still incurs potential health and environment issues. With this concern, H.F.L. Upendri and B. Karunarathna (2021) summarized several efforts for an organic nutrient solution using agricultural residues and industrial wastes, with the target of a more environmentally friendly hydroponic system[9]. The challenges of such methods include how to control the rapid pH fluctuation to obtain the somewhat controversial organic certification, and to remove the unwanted components from the nutrient sources. Such high requirements on investment, techniques and experience hinder their practical application among "smallholders", i.e., smaller owners of PF, and call for further research to justify their efficacy.

As to the concern of plant quality, Y. Rouphael, et al. (2021) pointed out that soilless culture systems can provide the opportunity for quality improvement, in which specific nutrient solution management acts as the major factor[6]. Such improvement includes not only the external quality attributes of size and freshness, but also the internal ones such as the increase of health-promoting compounds and better flavor.

2. Energy saving strategies

For a classical PF in Japan, Japanese professor T. Kozai (2013) indicated that it contains six principal components: a thermally insulated and nearly airtight indoor structure, 4-20 tiers equipped with hydroponic culture beds and artificial light such as fluorescent and/or LED lamps, air conditioners, a CO_2 supply unit, a nutrient solution supply unit with water pumps, and an environment control unit[2]. These facilities enable the PF to have less limits for location and natural environmental impact, and to produce steadily all year round.

According to Q. Yang (2019), the controlled environmental elements of a plant factory can be classified into three groups: light (intensity, spectrum, photoperiod, distribution, etc.), air (temperature, humidity, CO_2, airflow, etc.) and root (rhizosphere including nutrient solution, pH, liquid temperature, etc.)[8]. These three groups of factors interact with each other for plant growth. Especially, the photoperiod, defined as the recurring cycle of light and dark periods for plants, is affected by temperature, CO_2 and other environmental factors. Therefore, an efficient lighting system should incorporate the consideration of other related environmental conditions.

Compared with traditional farming, a PF has a rather high-cost barrier including the initial investment cost and operational cost. For a typical Chinese PF of 1,000m^2, the initial investment cost excluding building construction is about 7,000-8,000 yuan (over $1,000)/m^2, mainly for equipment and facilities[16]. The key factors for a PF's operational cost include energy consumption, material loss, packaging/transportation and management, each occupies a quarter of the total amount[8]. Electric power saving is regarded as a key technical challenge to control the total operational cost of PFs[14].

Saya Murakami, et al. (2018) stressed the high-power consumption of PFs due to lighting, air conditioning and cultivation system[3]. For large-scale PFs, they proposed an operation planning model to minimize energy cost by scheduling the operation cycle of cultivation systems individually with consideration of weather factors. They also suggested that future research for further energy cost reduction could focus on the cooperation between the global air-conditioning control scheme and the local individual control scheme.

Q. Yang (2019) provided the evaluation formula for electric energy use efficiency (EUE) and light energy use efficiency (LUE)[8]. As he suggested, several ways to improve EUE and LUE include: (1) plant selection: choose plants that require relatively lower intensity of grow light and shorter cultivation period; (2) optimization of the light source production technology: choose light source with high quantum and radiation efficiency and low power loss; (3) optimization of light source distribution: set light source with closer distance and use focusing lenses to concentrate light energy; (4) optimization of lighting operational strategy: adjust the light intensity, space and time distribution based on plant needs at different growth stage.

3. Energy savings in practice: lighting system efficiency

The lighting system is a key factor in PFs since light is critical for the productions of metabolites in plants[1]. The heat radiation of the light source also affects the temperature control of the whole system. As the case study of various Chinese PFs by Q. Yang (2019) shows[8], lighting occupies 1/4 to 3/5 of the total energy consumption, and air conditioning occupies another 1/4. Obviously, an efficient lighting system is crucial for energy saving of the whole system.

To improve the artificial lighting system and lighting quality, light-emitting diodes (LEDs) demonstrate great advantages such as low radiant heat output, durable longevity, flexible control of spectral composition and the adaptive light intensity to match the plant photoreceptors for better growth[4]. For the evaluation of lighting system efficiency, LEDs outperform typical high-pressure sodium and fluorescent lamps, despite the higher initial investment cost[2].

The lighting engineers from Powerland Technology (Nanjing, China) introduced the general evaluation of lighting system efficiency (le) as the product of four factors: photoelectric coefficient of LED (li), optical efficiency (lo), thermal efficiency (lt) and LED driver efficiency (ld).

le=li*lo*lt*ld

Accordingly, four aspects can be considered in practice for the enhancement of lighting system efficiency: LED, optical components, heatsink and LED driver.

To improve li, the LEDs with high photosynthetic photon efficacy (PPE) are preferrable. To improve lo, it is recommended to choose material with high light transmission ratio, such as polycarbonate (PC), glass, poly (methyl methacrylate) (PMMA) and other coated materials. To improve lt, heatsinks with better cooling effects are an ideal choice. But all these recommendations should consider the trade-off between electricity saving and relative high investment cost.

To improve ld, non-isolated LED drivers that power the actual LEDs with low cost and high efficiency should be considered. But it requires more special insulation design for safety concern than does an isolated driver. It also causes the limited choices of optical material and heatsink.

In brief, an optimized plan for lighting system requires the synthetic selection of the above four elements, combined with the calculation of product cost, duration and electricity cost. It is required that such an efficient lighting system should provide the adjustable control system for the various lighting recipes of different plants, including light intensity, light spectrum, lighting period and distribution (continuous, alternative, or intermittent).

4. Conclusion

PF is a soilless indoor farming system with the property of technology-intensive, resource-efficient and controlled environment. It is regarded as the most promising farming in modern agriculture. But PF's high productivity has a high-cost barrier and high-power consumption that have to be considered – particularly for the requirement of artificial lighting and environmental control, as electricity costs amount to over 50% of the total operational cost. Therefore, energy saving becomes a key issue for the development of PFs.

Researchers have identified possible ways to improve the electric energy use efficiency and light energy use efficiency. Especially for an efficient lighting system, it requires a comprehensive solution with multiple choices of LED, optical components, heatsink and LED driver. Such decision making is based on the comparison between the investment cost and the relevant electric energy saving and productivity enhancement.

Further study could be focused on the incorporation of lighting systems with temperature and other controlled environmental factors for more potential energy savings and higher operational efficiency of the whole cultivation system of PFs.

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