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# Research Progress on Energy-saving and Consumption-Reducing Technologies for Plant Factories

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## ABSTRACT

As the global food system is under multiple pressures from climate change, resource scarcity and population growth, countries are seeking new solutions. Plant factories, as an important form of controlled environment agriculture, are seen as a key technology to alleviate food supply problems. This article begins by introducing the basic concept of a plant factory. The content includes the definition, classification and core modules of plant factories, while emphasizing the importance of environmental control. Next, the article analyzes how environmental factors such as temperature, relative humidity, and carbon dioxide concentration affect plant growth. This paper further explores the methods of regulating these factors and systematically reviews the key technologies for energy conservation and consumption reduction in plant factories, covering lighting technology, HVAC systems, photovoltaic technology and intelligent control technology. The study shows that by optimizing the spectrum and light intensity, improving the energy form and envelope of the HVAC system, and integrating photovoltaic technology with intelligent control strategies, the energy consumption of plant factories can be significantly reduced and energy utilization efficiency can be improved. Overall, this paper provides a theoretical basis and technical reference for improving the energy efficiency of plant factories and for future related research.

## KEYWORDS

Plant Factory; Controlled Environment Agriculture; Energy Saving; Lighting; HVAC; Photovoltaic; Smart Control.

## 1. INTRODUCTION

In recent years, the world has faced multiple challenges such as climate change, resource shortages and population growth. These challenges have put unprecedented pressure on the global food system. Surveys show that by 2050, controlled environment agriculture (CEA) is expected to be the most promising model of technological innovation in food production and is seen as an effective countermeasure to ease the current tight food supply situation[1]. Among them, plant factories, as an important component of CEA, are considered to have great potential.

From the development history of plant factories, in the early stage, they relied on nutrient solution cultivation and mineral nutrition theory; in the middle stage, they focused on hydroponics and artificial light source technology; and in the later stage, they gradually introduced LED lighting and intelligent control. This process indicates that plant factories not only alleviate the tension in food supply caused by the reduction of arable land, ensure food safety and clean production, but also address the current situation of a decrease in young people entering agriculture due to population aging. Data shows that since 2010, global commercial plant factories have continued to grow, with

Japan being the first to establish commercial plant factories; the maturity of technology has also increased consumer support for their products [2]. However, currently, plant factories face challenges such as high construction costs, high energy consumption, and low economic benefits. Therefore, reducing energy consumption has become a research focus. For this reason, scholars have optimized the lighting layout, adjusted the LED spectrum, improved the light energy conversion efficiency, and regulated parameters such as nutrient solution temperature, CO2 concentration, vapor pressure difference, air flow speed, and electrical conductivity, while introducing solar energy storage technology to achieve energy conservation and consumption reduction.

Although many scholars have explored the energy consumption of plant factories, research on energy-saving and consumption-reducing technologies is still insufficient. This paper first presents the conceptual framework of plant factories, summarizes the research results in the field of environmental control, and sorts out effective ways to reduce energy consumption. Subsequently, the progress of energy-saving and consumption-reducing technologies in plant factories is systematically reviewed, and detailed analyses are conducted in key areas such as lighting, HVAC, photovoltaics, and intelligent control, providing a theoretical basis for improving energy utilization efficiency and subsequent research.

## 2. ENVIRONMENTAL CONTROL FACTORS IN PLANT FACTORIES

Plant factories, which use automated systems to precisely control plant growth elements and achieve efficient, large-scale, and undisturbed facility agriculture, are regarded as the highest stage of facility agriculture. According to the light source, plant factories are classified as solar-type, artificial light-type, and a combination of both, with the narrow definition of plant factories referring to the artificial light-type. With controlled environment agriculture (CEA) as the target, its core modules include LED, plant growth and environmental control, while also demanding computing, communication and intelligent manufacturing. In vertical stacking cultivation, environmental control, nutrient solution regulation, light and automation systems work together to determine productivity. The growth environment of the plant factory encompasses temperature, humidity, light, air flow rate and $CO_2$ concentration, where temperature directly affects crop growth and humidity regulates transpiration balance. Therefore, to achieve high efficiency and quality production, precise control of temperature, humidity and $CO_2$ concentration is required for plant growth.

### 2.1. Temperature

Indoor temperature significantly affects plant growth. A suitable temperature can accelerate growth, but above the threshold it slows down or even stops, and leads to a decline in growth quality. Therefore, plant factories should be precisely controlled in terms of temperature.

Indoor air flow has a significant effect on temperature changes. Studies have shown that the ideal temperature for the growth of seedlings is 20-25 ℃, which can be regulated by adjusting the air supply mode. Lee et al. installed perforated plates on the back of the cultivation rack and introduced air conditioning systems through heat exchangers to achieve precise control with an average temperature error of 1.65 ℃ and a humidity error of 14.1%[3]. In addition, regulating the temperature difference between day and night in an artificial lighting plant factory can effectively prevent plant overgrowth caused by insufficient light and dense planting.

In addition to indoor temperature, root zone temperature (RZT) is also crucial for plant growth. Levine et al. found that adjusting the RZT to 15 ℃, 25 ℃, and 35 ℃ under the overall temperature increase significantly promoted anthocyanin accumulation in lettuce[4]. Therefore, RZT should be adjusted in a timely manner at each growth stage to optimize growth effect and increase pigment content.

## 2.2. Relative Humidity

Humidity control is a major challenge in horticultural agriculture. Plant respiration and transpiration cause frequent fluctuations in local humidity: too low humidity limits growth, and too high humidity can cause pests and diseases, so appropriate humidity is crucial. Research shows that under conditions of 50 ℃ and 50% relative humidity, jujube fruit had the least weight loss, shortened ripening time and the best economic benefits; And compared with RH70 and RH90, the RH50 treatment significantly increased the water vapor pressure difference between the lettuce leaves and the air, promoting water vapor diffusion and increasing stomatal conductance, thereby enhancing transpiration and calcium ion absorption and reducing dry heartburn[5]. In conclusion, humidity control is not only related to plant growth, but also a key direction for the sustainable development and economic benefit improvement of horticultural agriculture.

The continuous transpiration during plant growth makes maintaining the optimal humidity a difficult problem in actual production. At present, humidity control mainly relies on two strategies: modeling prediction and local air supply. Jung et al. constructed a long short-term memory network model based on tomato greenhouse data to predict evapotranspiration and humidity, achieving errors of 5.76% and 6.45% in 20-day training and 3-day testing, respectively, verifying the accuracy of the model[6]. In addition, local distribution of air over the crop canopy to increase the vapor pressure difference (VPD) can effectively control humidity and prevent tip burning.

## 2.3. Carbon Dioxide Concentration

$CO_2$ concentration plays a significant role in plant growth: not only in photosynthesis, but also in regulating stomatal conductance and carboxylation capacity. The $CO_2$ enrichment effect changes the photosynthetic rate, local climate and photosynthetic product transport efficiency of greenhouse leaves, thereby promoting plant growth and photosynthetic product accumulation.

An adequate amount of $CO_2$ not only increases the photosynthetic rate but also promotes the accumulation of photosynthetic products. Lettuce needs 800-1200 ppm of $CO_2$ to grow normally, and $CO_2$ enrichment can effectively regulate this concentration. Chen et al. found in an artificial light-type plant factory that when the $CO_2$ concentration was set at 1600 μmol·mol-1, the growth rate of lettuce, the number of leaves, and the maximum leaf area all increased significantly, thereby enhancing the efficiency of light energy utilization[7]. However, the dry matter growth efficiency did not double that at 800 μmol·mol-1, indicating that although the $CO_2$ concentration increased the yield, the effect was not linearly enhanced, so the concentration needed to be reasonably controlled.

In addition, the leakage of $CO_2$ affects indoor concentrations. Zhang et al. used CFD models to simulate the spatial distribution of $CO_2$ in strawberry greenhouses and predicted short-term concentration changes more accurately, providing theoretical support for preventing leaks[8].

Overall, in controlled environment agricultural systems such as plant factories, increasing the concentration of $CO_2$ can significantly accelerate plant growth rates and increase yields. In addition, $CO_2$ enrichment also has corresponding effects on the nutrient content and biomass accumulation of plants.

# 3. ENERGY CONSERVATION AND CONSUMPTION REDUCTION TECHNOLOGIES

Plant factories have advantages such as controllable environment, high production efficiency and good product quality, but their high energy consumption and high cost have become urgent challenges to be addressed. Therefore, exploring and developing energy-saving technologies is crucial for reducing energy consumption.

### 3.1. Lighting Technology

In artificial light plant factories, the power consumption of light sources accounts for approximately 80% of the total energy consumption. Common light sources include high-pressure sodium lamps, metal halide lamps, fluorescent lamps, hybrid electrode fluorescent lamps and light-emitting diodes (LED), and studies have shown that LEDs have higher energy efficiency and lower heat output, which help maintain the appropriate growth temperature, and thus are gradually becoming the main light source. Based on this, the focus of this review is on optimizing lighting systems and reducing energy consumption.

#### 3.1.1. Spectra and Light Intensity

In the field of plant factory lighting, spectra and light intensity are crucial for plant growth. Vatistas et al. systematically analyzed the physiological responses of lettuce, cabbage, spinach and roquette seeds under different spectra and photoperiods and found that lettuce and spinach had higher germination rates under both light and dark conditions, but performed better under specific spectra[9]. Cabbage and arugula showed significantly higher germination rates under light, suggesting that light not only breaks dormancy but may also activate related genes to promote germination.

Spectrum significantly affects the germination and growth of plant seeds. Different seeds respond differently to the spectrum, and the synergistic effect of spectrum composition and nutritional status directly influences photosynthetic efficiency and yield. In plant factories, the spectrum and light intensity should be precisely adjusted according to the characteristics of different plants to achieve energy conservation and high efficiency. Precisely matching the spectrum requirements not only improves the utilization rate of light energy and reduces energy consumption but also avoids photooxidative damage caused by excessive light or restricted photosynthesis due to insufficient light, thereby ensuring the healthy growth and high yield of plants.

#### 3.1.2. Utilization of Light Energy

In the field of lighting technology for plant factories, improving the utilization rate of light energy is regarded as one of the key links to achieve energy conservation and consumption reduction. To further improve energy efficiency and reduce lighting costs, Zou et al. proposed an environmental control method using regenerated scattered energy, and experiments showed that the quality, leaf count and growth status of lettuce in high-reflection environments were superior to those in high-absorption environments[10]. In addition, unconventional methods such as alternating, intermittent and continuous lighting also achieved the dual benefits of high yield and energy conservation.

The technical approaches to improving the utilization rate of light energy in plant factories are diversifying. This technology not only significantly improves the conversion efficiency of electrical energy to effective light energy, but also regulates light parameters according to the needs of plants, providing a guarantee for achieving energy conservation and consumption reduction as well as high yield and quality. In the future, through the integration of technologies and intelligent integration, it is expected to break through the bottleneck of light energy utilization and drive plant factories towards greater efficiency and lower carbon.

#### 3.1.3. Lighting Strategies

In the field of lighting technology for plant factories, building lighting strategies based on scientific evidence is crucial for achieving energy conservation, consumption reduction and efficient production. Related research has proposed a series of practical solutions by exploring innovative control methods and optimizing lighting parameters.

Pereira et al. developed a low-cost, intelligent LED lighting system that ADAPTS the supply of artificial light based on real-time changes in natural light, breaking the limitation of fixed-time lighting and achieving precise matching of light energy to plant needs, thus avoiding energy waste when natural light is abundant[11]. Experiments showed that the system reduced energy consumption by at least 43% compared to the initial scheme, while significantly improving energy utilization efficiency, providing a practical low-cost, energy-saving lighting solution for plant factories, at the core of which lies intelligent perception and regulation. On the other hand, Zou et al. optimized the uniformity of photosynthetic luminous flux density (PPFD), increasing it from 71% to 85% and reducing the standard deviation from 75 to 15[12]. Under the 16-hour light regime, combined with 12 hours of auxiliary lighting, the height, leaf width and fruit weight of strawberry plants increased by 55%, 40% and 36% respectively, while energy was saved by approximately 43%, fully demonstrating the advantages of high-efficiency lighting in enhancing plant nutrient accumulation and reproductive performance.

The study reveals an important trend in lighting strategies for plant factories. The strategy is centered on meeting the needs of plant growth and relies on intelligent and precise control technologies in order to optimize the efficiency of light energy utilization.

## 3.2. HVAC Systems

As an essential component of environmental regulation in plant factories, the core function of the HVAC system is to precisely control the temperature and humidity within the growing space, while complementing with carbon dioxide and air filtration to ensure a stable and clean growing environment for the crops. In addition, the system's energy consumption exceeds 50% of the total energy consumption, making it a key target for energy conservation and consumption reduction renovations in plant factories.

### 3.2.1. Energy Form

Heat pumps cool in summer and heat in winter, and have the advantages of energy conservation, moisture regulation and stable air circulation. Among them, ground source heat pumps are particularly crucial in energy supply technology. The principle is as follows: In winter, the water in the hot water well of the plant factory is exchanged with the cold water in the cold water storage tank through the heat exchanger, and the cold water is then fed back into the cold water well after the heat exchange; In summer, it operates in the opposite direction. Gorjian et al. analyzed that heat exchangers using low-temperature water or geothermal fluids could provide 38.86 tons per hour of heat for strawberry cultivation rooms with a room temperature of 15 °C, with thermal coefficients of the vertical and horizontal heat exchangers being 3.1-3.6 and 3.2-3.8 respectively, thereby reducing the use of fossil fuels[13]. Overall, heat pump energy supply technology combines the advantages of energy conservation, environmental protection and high efficiency.

In terms of solar thermal energy technology research, Bazgaou et al. designed an active heating system based on the thermosiphon effect using planar solar collectors[14]. Experiments showed that the system could increase tomato production by 55% in winter, while improving thermal comfort and nutrient absorption in the crop root zone and reducing heating energy consumption. Vacuum plate collectors operate more efficiently at medium to high temperatures, effectively compensating for heat loss at low radiation.

### 3.2.2. Enclosure Design

Plant factories need to maintain an environment suitable for vegetable growth throughout the year to avoid external disturbances, thereby applying building insulation technology to significantly reduce energy consumption. In the renovation of building shells, Liu et al. used a thermochromic superhydrophobic coating prepared by the brushing method to increase the reflectance after decolorization in summer, which was verified by EnergyPlus energy consumption simulation to effectively reduce building energy consumption[15]. The total energy consumption composition of the plant factory was 50% for lighting, 2% for heating, 34% for dehumidification and 14% for explicit cooling. Graamans et al. demonstrated the potential of rational building design in energy conservation by reducing the internal heat load by decreasing the building surface area and facade, thereby reducing overall energy consumption, which can effectively stabilize the indoor temperature and further reduce energy consumption[16].

## 3.3. Photovoltaic Technology

Solar energy, as a clean and scalable renewable energy source, has great potential for integration with plant factories. The utilization technologies are mainly divided into solar thermal technology and photovoltaic technology. The use of solar energy can reduce plant factories' reliance on traditional electricity and generate and store electricity through photovoltaic module integration. The parabolic concentrating roof system developed by Wu et al. can convert excess light energy into electrical and thermal energy, with a maximum electrical energy conversion efficiency of 18% detected using Monte Carlo ray tracing[17]. Zhu et al. improved the efficiency and stability of perovskite solar cells (PSCs) by adding HPC and HEC to prepare high-quality perovskite films, with a power conversion efficiency of 21.25%[18]. In addition, energy storage using vanadium REDOX flow batteries (VRFBs) can significantly reduce greenhouse gas emissions. Therefore, the development of solar cell technology is crucial to ensuring the continuity and stability of photovoltaic power supply for plant factories.

## 3.4. Intelligent Control Technology

Intelligent control technology uses sensors to collect environmental data and automatically issues instructions to HVAC, lighting and other equipment based on the growth needs of crops, thereby achieving precise and automated environmental regulation and reducing reliance on manual intervention. The appropriate application of this technology can reduce energy consumption in plant factories to some extent.

### 3.4.1. Environmental Control System

In the study of the application of intelligent control technology to environmental control systems, CFD technology provides key support for the optimization of thermal environment and airflow in plant factories. The related research mainly laid the theoretical and practical foundation for improving energy utilization efficiency and precise environmental regulation through numerical simulation of thermal fluid behavior and optimization of design parameters. Kang et al. used CFD simulation to optimize the design parameters of vertical farms with side supply air function, involving supply air, exhaust air and corridor width[19]. The results show that reducing the size of the air outlet, placing it near the LED light, and combining it with the exhaust mechanism in the corridor ceiling can more effectively remove the residual heat generated by the LED; At the same time, bringing the air supply closer to the LED, using larger openings, and eliminating the corridor space can all improve the air distribution. These applications not only reduce energy waste caused by improper environmental regulation, but also stabilize the plant growth environment and enhance production efficiency, providing a solid technical guarantee for the development of plant factories towards intelligence and energy conservation.

### 3.4.2. Digital Management Techniques

In plant factories, to maximize yield per unit area, multiple layers of shelves are densely arranged, resulting in an uneven plant growth environment and increased energy consumption. With the continuous advancement of Internet of Things technology, the problem of environmental inequality in facility agriculture has been gradually alleviated. Digital management, with the help of Internet of Things and computer technology, enables real-time monitoring and regulation of environmental parameters and equipment status, allowing managers to make intelligent decisions, thereby improving production efficiency and product quality and reducing energy consumption. Wang et al. proposed an environmental feedback control method for plant factories based on wireless networks, control algorithms, and photosynthetic rate prediction models[20]. Experimental results show that the method achieves precise regulation of the growth environment of lettuce, not only maintaining the environment in the optimal state, but also increasing the yield by 38.7% and significantly reducing the system energy consumption. In addition, the overall performance and commercial production level of the plant can be further enhanced by regulating the plant microenvironment and germination time through management techniques.

## 4. CONCLUSION

As an advanced form of facility agriculture, plant factories enable large-scale plant production through automated regulation of growth factors. The core of it lies in the organic combination of environmental control technology and energy conservation and consumption reduction technology. In terms of environmental control, temperature regulation focuses on both air temperature and root zone temperature. Precise temperature control can be achieved by using technologies such as multi-hole exhaust systems and differential regulation. At the same time, managing the temperature difference between day and night can help suppress excessive plant growth. The regulation of relative humidity needs to be combined with the characteristics of the crops, using measures such as CFD modeling and local air supply to ensure that the humidity is maintained within the appropriate range. In addition, while increasing $CO_2$ concentration helps improve photosynthetic efficiency, it must be controlled within a reasonable threshold to prevent waste of resources. LED lighting is at the core in the field of energy-saving technologies. It significantly reduces energy consumption and improves light utilization through spectral customization, secondary optical design, light energy reuse, and smart lighting strategies including dynamic regulation and uniformity optimization. HVAC systems rely on heat pump technologies (such as ground source heat pumps), solar thermal technologies and envelope optimizations (such as the use of thermochromic coatings and phase change materials) to reduce energy consumption. Photovoltaic technology provides clean electricity for the system by integrating photovoltaic modules with plant factories, and new perovskite solar cells also show good application prospects. Meanwhile, smart control technology relies on CFD simulation, digital management and multi-objective optimization algorithms to achieve precise regulation of environmental parameters and coordinated management of energy, significantly improving production efficiency and reducing energy consumption.

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