Lighting Strategy in Plant Factory with Artificial Light

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A plant factory with artificial light (PFAL) is defined as an advanced agricultural production system with a precisely controlled environment, playing an important role in vertical farming and urban food supply. Artificial light is one of the core technologies in PFALs and accounts for a large part of energy consumption; elevating the light utilization efficiency of plants is vital for the sustainable development of PFALs. Meanwhile, the enclosed structure of the plant factory resulted in the independence of its light environment, indicating that the light environment in PFALs can be custom-made. Lighting strategy is an attempt to reprogram the light environmental parameters in unconventional ways, resulting in innovative lighting modes for energy-saving, high-yield, and high-quality production in PFALs.

plant factory | artificial light | lighting strategy | energy conversion efficiency

1. Introduction

Plant factories are a type of closed production system, which integrated modern industrial technologies for the annual efficient production of crops [1][2]. As an artificially controlled environment production system, environmental factors in plant factories, such as temperature, humidity, light, CO_2, nutrients, and water, are precisely controlled by artificial intelligence systems and electronic sensors, according to the requirement of crops, largely avoiding the restriction of a natural fluctuant environment and contributing to green manufacture [1][3][4]. Consequently, food production in plant factories is not limited by geographical factors, seasonal changes, and available spaces, producing green crops all year round and representing future agriculture [5]. With the continued expansion of the human population and the acceleration of urbanization, plant factories with artificial lighting (PFALs) possess extensive application prospects in the urban life of modern society [6].

2. Alternate Lighting

Distinct monochromatic spectrum exerts different specific effects on the photomorphogenesis, physiological performance, and developmental status of plants [7][8]. In the natural environment and conventional PFALs cultivation, plants were constantly irradiated by multichromatic sunlight or tailored spectral composition with a fixed ratio, so the potential of the light spectrum on crop production was still underestimated. Alternate lighting is an attempt that alternately irradiates plants with different light spectrums or spectral compositions for efficient crop production, including full-alternated lighting mode and overlay-alternated lighting mode [9][10][11]. Compared with full-alternated lighting, overlay-alternated lighting was relatively complicated and extendable, which shifted the irradiation time of blue/red light forward/backward based on concurrent lighting, ensuring crops were irradiated by the monochromatic spectrum for a certain time interval [10][12]. Some biological characteristics of crops were positively affected when exposed to alternate lighting; meanwhile, with the optimization of parameters, such as spectral composition, alternating intervals, and light intensity, the energy conversion efficiency in PFALs was elevated, and resulted in increased biomass and nutritional quality [9][13].

Blue light and red light were the most frequently used spectrums in alternate lighting, as they were photosynthetically active spectrums, being widely used in PFALs [14][15]. Besides, the physiological effects of both spectrums were extensively reported [16]. Although monochromatic blue and red light failed to meet the requirement of plants and led to dysfunctional photosynthetic responses [17], alternate lighting might be a good resolution. Chen et al. [9] alternately irradiated lettuce with monochromatic red and blue light under plant factory conditions, and the results revealed that phenotype and nutritive properties of lettuce were largely affected; specifically, significantly higher biomass was achieved compared with concurrent irradiation without extra energy consumption [9].

Surprisingly, alternate lighting might be a potential method of avoiding the negative effects of continuous lighting. A long photoperiod was negative for the normal growth of crops, as it usually caused interveinal chlorosis consequently [18]; nevertheless, continuous 24 h supplemental lighting with alternate blue and red light could alleviate the injury and led to increased net carbon exchange rates in tomato [19]. For lettuce cultivation in a plant factory, alternate lighting of blue and red light over a 24 h photoperiod resulted in significantly increased biomass, while ideal nutritive quality was simultaneously obtained [20].

3. Intermittent Lighting

The rotation of Earth on its axis leads to the alternation of day and night, serving as an important environmental signal for the metabolism and development of plants [21]. In PFALs, the light–dark cycle was independent of sunrise and sunset, providing huge space for innovative regulation of the light environment. Intermittent lighting was another attempt to artificially remold the light environment in PFALs based on photoperiods, which separate the standard 24 h day/night alteration into short light/dark cycles and irradiate plants temporarily [22]. Besides, the short flash created by pulsed LEDs was considered as another kind of intermittent lighting, providing light on the seconds scale, even on the milliseconds scale [23][24]. Up to now, many endeavors have demonstrated that intermittent lighting is beneficial for crop production and possesses large potential in reducing energy consumption in PFALs [23][25]. Moreover, frequency and duty ratio (duration ratio of light in a whole light/dark cycle) are important design parameters of intermittent lighting [26][27].

Cheng et al. [22] divided the light/dark cycle of 16 h/8 h into short combinations of 8 h/4 h, 6 h/3 h, 4 h/2 h, 3 h/1.5 h, and 2 h/1 h under identical energy consumption, with results revealing that lettuce exposed to intermittent lighting treatments almost all show increased biomass, except for 6 h/3 h. Besides, the sweetness and crispness of lettuce were also influenced [22].

The stimulating effect of intermittent lighting on growth is partially attributed to its positive regulation of photosynthesis efficiency [24]. Further study revealed that adequate frequencies could improve fluorescence emission parameters of chlorophyll as Fv′/Fm′(maximum efficiency of PSII), NPQ (nonphotochemical quenching), ΦPSII (quantum efficiency of photosystem II), ETR (electron transport rate), and ø CO_2 (quantum yield of CO_2 assimilation) [28]. Notably, intermittent lighting was an effective strategy for regulating the photosynthetic pathway of CAM plants [29]. A short light/dark cycle of 2 h/2 h was reported to switch the photosynthetic pathway of *Dendrobium officinale* from CAM to C3, resulting in increased net CO_2 exchange amounts and higher biomass [30]. However, this process is incompletely reversible, as *D. offcinale* maintained an increased net CO_2 exchange amount when transferred back to 12 h/12 h [29]. Besides, it was assumed that more photoreceptor cells were formed when exposed to intermittent radiation [24].

4. Continuous Lighting

As the sole irradiation source in PFALs, artificial light provides energy and acts as an important environmental signal for the growth and development of cultivated crops. Continuous lighting (CL) is an efficient cultivation strategy by extending the duration of light, theoretically driving crops to grow unceasingly in PFALs [31][32]. Crops exposed to a 24 h photoperiod displayed distinct statuses, as some of them experienced severe physiological damage, while some of them adapted well and obtained increased yield [33]. Particularly, for a life support system in space or basements in the polar regions, the food supply problems could be well resolved by this strategy. Besides, continuous lighting was also supposed to be used in breeding research, as the vegetative growth was stimulated and shortened the time for crop selection.

Continuous lighting has the potential to induce injury to photosynthetic organs, leading to various symptoms, such as photo-oxidative damage, early senescence, and/or decreased photosynthetic efficiency, which are usually mediated by hyperaccumulation of carbohydrates or negative effects on photoreceptors [32]. Velez-Ramirez et al. [32] reported that lettuce achieved increased biomass under CL, while tomato displayed CL injuries. This phenomenon is partly due to differences in CL tolerance. On the other hand, endogenous circadian rhythm may also play an important role. Besides, the phenotype of continuous lighting-induced injury was influenced not only by irradiation intensity, but the light spectrum also exerted a huge influence. Tomato seedlings exposed to continuous red or blue light displayed varied symptoms, while their combination could largely relieve it [34]. On the other hand, photoinhibition caused by continuous lighting is reversible when the duration time is short, while the accumulation of ROS and lipid peroxidation is inevitable in long-term treatment [35]. Integrating continuous lighting with alternate lighting of red and blue light might be a good resolution, as photosynthetic parameters under continuous lighting were similar to that of a 12 h photoperiod; moreover, diurnal metabolism of carbohydrate was also observed [20]. On the other hand, continuous lighting decreased the mineral contents of lettuce, as the growth was largely enhanced. However, it has been reported that an adequate combination of light quality and intensity was able to elevate biomass and mineral content simultaneously [31].

Considering the negative effects of continuous lighting in the long term and disproportionate input–output ratio, it was commonly used in the short term as a pre-harvest strategy for the enhanced nutritional quality of crops, and the harvested biomass was simultaneously enhanced [36][37].

Soluble sugars and Vc (Vitamin C) are also important quality traits of crops, which could be substantially improved by continuous lighting [35][37][38][39]. As the direct product of photosynthesis, soluble sugar biosynthesis is significantly elevated by extended lighting, leading to a more delicious taste in crops [40]. Vc, also named as ascorbic acid, exists widely in plants, as an antioxidant chemical, and is beneficial for human health [41][42]. Accumulation of Vitamin C in plants commonly acts as a defense mechanism, helping to wipe off the elevated excitation energy, and maintain the normal operation of photosynthetic apparatus from photooxidative damage under continuous lighting [35]. Besides, the content of Vc and the activities of enzymes involved in Vc biosynthesis were positively correlated with the light intensity [35]. As a result, stronger irradiation usually leads to a higher content of Vc in plants [39]. Besides, phytochemicals with antioxidant ability, such as glutathione [35] and phenolic substances [36], were induced to be increased, and antioxidant activity of the treated plants was also detected to be enhanced [43][44].

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