Light environment and plant growth in plant factories

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Abstract. A plant factory with artificial light is an effective system producing food to satisfy specific demands on yield, morphology, taste and nutrient accumulation in plants. All environmental factors inside a plant factory can be controlled without climate and location limitation. Light is one of the most important factors affecting plant growth and quality. By regulating light aspects, such as light intensity, light period, light quality, lighting position, and daily light integral, the growth and quality of the plants grown in a plant factory can be largely enhanced. As known, the initial and operating cost for a plant factory with artificial light is high, particularly the cost of electrical energy related to lighting. Identifying the optimal light environment that promotes plant growth and quality is critical for commercialization of plant factories. Recent researches have paid great attentions to the effects of light environment on the growth and morphology of leafy vegetables. On the other hand, the demand on functional plants that contain high concentration of bioactive compounds is increasing rapidly. Bioactive compounds in plants have been intensively studied to evaluate their effects on human health and many of them are proved to be clinically active against various types of diseases (e.g. anti-cancer effects). More and more people prefer to take health product derived from natural plants for disease prevention. Solutions to realize sustainable production of high quality functional/medicinal plants can be provided by developing environmental control technologies, such as light recipe, in plant factories. Aromatic herbs such as coriander; medicinal plants such as perilla and water spinach are subjected to different light conditions and root zone environments. Some bioactive compounds e.g. perillaldehyde and rosmarinic acid in perilla leaves; phenolic compounds and flavonoids, especially rutin and chlorogenic acid in coriander can be enhanced. The effects of each light aspect on plant growth vary with plant species and other environmental conditions, however, there are also some general trends that can be used to guide commercial application. This presentation introduces the basic of light and its effects on plant growth in plant factories, demonstrates research results that have been published in scientific journals, reports the current study on herbs and medicinal plants, and summarizes the general application of light in plant production.

Light is one of the most important factors that affect plant production and its quality. Understanding of the interactions between light and plant's growth is critical for successful production in plant factories. What is light? The definition of light is the visible part of the spectrum in electromagnetic radiation. Therefore, the light is placed in the very narrow part. We called it the visible part of the electromagnetic radiation. Its wavelength started from 380 nm to 780 nm. These ranges of wavelengths are also being used in plant factories.
When we discuss the light for plants, we need to know the unit for describing light intensity for plants i.e. the \( \text{mol m}^{-2}\text{s}^{-1} \) and for human eyes we used lux as the unit for light. When humans have more lux levels, it means brighter light for humans, but it will mean high intensity for plants. Light influences the plant over its lifetime. Mainly in two ways, first, in photosynthesis and another is in plant development. Through the whole lifetime of the plant, starting from germination and ending at the seed production, all these processes are affected by light. Sometimes, the light often regulates plant roots and also the growth of shoots, the direction of the leaves and sometimes affected the branches. As we observed in Sycamore, light also regulates the stomata opening which is essential for photosynthesis to accumulate sugar. In some plants, especially for plants that are sensitive to the light period (photo period), it affects the flowering. Not to mention that in the growth process, light receptors or photo-receptors also play an important role in a plant's lifetime.

Chlorophyll a is the most abundant pigment in plants, it absorbs light in wavelength about 400 nm and 662 nm and chlorophyll b absorbs light in the 453 nm and 642 nm [2]. The carotenoid, a class of extraordinary pigment, occurs in all photosynthetic organisms, and they absorb light maximum between 460 nm to 550 nm. Based on Figure 1., the most blue and red light can be absorbed at once, but the isolated chlorophyll and carotenoid transmit greenlight, so the greenlight can be absorbed only 20-30% one time. However, the intact chloroplast and whole leaf absorbs most of the visible light spectrum including the greenlight [3]. The red light and blue light are mostly absorbed in the illuminated side of the leaf. The greenlight is penetrated deeper into the leaf, increasing the chance to be absorbed at the greenlight photonic tables. The red light is more effective for photosynthesis but most light will be seen at a deeper region of the spectrum, including the greenlight is also efficiently utilized for photosynthesis [4].

Light affects plant growth in many aspects. The light quality, light intensity, and light photoperiod are common terms in the importance of light aspects that affect plants growth and development. Besides these three, the Daily Light Integral (DLI) overtime and sometimes the direction of light are important. And the light fluctuation, the light direction can be changed along with the weather condition and it will affect plant growth. Also, sometimes we need to consider the distribution of light over the plants. Therefore, when we discuss the light environment control of plant factories, we need to consider the light aspects to keep optimum balance of light for plant growth.

![Figure 1. Absorptance spectra of isolated photosynthetic pigments [1]](image-url)
Figure 2 shows that light intensity affects plant growth, in case of lettuce. In this experiment, the lettuce was grown at different light intensities: high, middle, and low level. We can clearly see after one month that the lettuce sizes are different. The shoot fresh and root fresh weight increased in the higher intensity, and decreased in the low light intensity compared to middle light intensity.

| Level   | Light Intensity (mol m⁻²s⁻¹) |
|---------|------------------------------|
| High (H)| 187                          |
| Middle (M)| 125                       |
| Low (L) | 85                           |

**Figure 2.** Effect of light intensity in terms of shoot and root weight

Figure 3 shows the effects of light intensity on lettuce:

(a) Leaves number difference
(b) Lettuce tipburn occurrence
(c) Tipburn in the shoot of lettuce

**Figure 3.** (a) Leaves number difference; (b) Lettuce tipburn occurrence; (c) Tipburn in the shoot of lettuce
Figure 3a showed that at the different light intensities, the leaf numbers are also different. At the high light intensity, although the growth rate is increasing rapidly, sometimes the tipburn issue is also more severe (Figure 3b). For instance, in this case when the light intensity is high, the tipburn on the top of the leaves also formed fast and more than other treatments (Figure 3c).

After the application of LED light, effects of light quality can be explored by changing the source of light. We found that the light quality can play an important role in plant growth. For example, when a plant is given only red color (R) or only blue color (B) or the combinations (blue and red/ B and R), the plant's response is also different. In the single red color light, the plant is cone-like-shape while under blue light influence the plant response is flat-like. And as for the mix (B and R), the plant is U-shape-like, in between R and B responses. Different R and B combinations showed that the color, shape and size of lettuce can be changed by different combinations of light quality, red and blue [5]. Therefore, we can try to adjust the product and suit the needs of the market or the needs of customer, by regulating the light quality

Single greenlight also could affect the plant growth. In this experiment, three light intensities with three different wavelengths in greenlight range are used for the treatment, with the control was fluorescent light. For the result, we can see that light intensity is 300 μmol m⁻² s⁻¹, even using single green light only, lettuce could grow normally [6].

Here is another example of different light-sources toward several plants. Based on Figure 5, there were four different light spectra, one is the traditional typical fluorescent light, and another three were LED with the mix of red and blue (RB), red and white (RW), and red and blue with far red light.
We can observe that the response of different crops to far red light was different. For example, the lettuce showed higher yield from the mix light with far red light. However, in spinach, the far-red light did not increase the yield. While the light spectrum did not significantly affect the growth of the mizuna plant.

Another factor that we can consider is the photoreceptor. Photoreceptor regulates genes related to secondary metabolites substances. Secondary metabolites (SMs) are natural compounds produced by biological organisms such as plants, fungi, or bacteria [7] and observed to have biological or pharmaceutical activities [8]. Secondary metabolite compounds from plants can be classified in four categories i.e. terpenoids, phenolic compounds, alkaloids and sulphur-containing compounds [9]. Based on Figure 6., when the red lettuce is exposed to different sources of radiation such as photosynthetically active radiation (PAR), UVA and UVB, and combinations of the radiations, different responses were observed. The UV and PAR radiations were applied for 7 days. After the red lettuce radiated, we could conclude that the coloration of lettuce leaves was enhanced by UV radiation treatment compared to controlled radiation. The constitution of several bioactive compounds considered both the PAR and PAR+UVA treatment. This means that the higher bioactive compounds which are considered beneficial for human health could be produced in short period.

UV light radiation also had variety response on lettuce growth. For the UV treatment, the shoot was significantly higher compared to the control group. In particular, there were significant differences at 5 to 7 days of the treatment. However, the growth rate decreased between the day 6th and the day 7th. In case there is contradictory result, it may depend on the type of the crop and the amount of the UV radiation exposed to the plants.
Secondary metabolites such as phenolic compounds as antioxidants components are also being observed. The antioxidant between day 1 and 4 after the treatment, particularly three days after the treatment, the total phenolic concentration and the antioxidant capacity and the UV-A were significantly higher around 30 or 40% higher than in the control group. And the highest anthocyanin concentration of lettuce leaves treated with UVA was absorbed after three days treatment.

In plant factories, the lettuce is the main crop for mass production. But recently, in different countries there are needs for the herb and medicinal plants which also can be produced in plant factories. And by regulating the light condition, the light environment, the plant growth and the nutrient level can also be controlled.

![Figure 7. Lettuce development after 7 days radiation](image)

![Figure 8. Green and red perilla production in response towards light environment](image)
Perilla is a kind of herb and also used as a medicinal plant in Indonesia. And we investigated effects of different light intensities and different levels of electrical conductivity (EC) towards green and red perilla. Our results showed that the growth of perilla plants affected by the light intensity (Figure 8) [12]. When we increased the light intensity the production also increased. The net photosynthetic rate also had the same trend.

Secondary metabolites also investigated, one of the most important components i.e the perillaldehyde concentration was not significantly affected by the light or EC condition. However, since the shoot growth of the plant is affected by the treatment, therefore, eventually the perillaldehyde content per plant accumulated the most in the middle level of light intensity, not at the higher level of light intensity for the green perilla. As for the rosmarinic acid concentration in green color perilla was significantly affected by EC level as well as the light intensity. Especially when the EC level is low, the concentration of the rosmarinic acid was the highest. In the red color perilla, the lower EC with the higher light intensity increases the concentration of rosmarinic acid.

Water spinach is a popular vegetable consumed in Indonesia, sometimes also considered as kind of a medicinal herb. And in plant factories, close hydroponic system was being used for its production since hydroponic system was suitable for growing water spinach. The light quality and light spectrum affected the growth of water spinach plant [13]. Based on Figure 10, the shape and the leaf numbers of the plants significantly affected by the light quality. Especially under single-color blue light and single-color red light. The morphology of the plants had different shape. Under blue light exposure, the plant has more leaves, but in the red light it developed a long stand. Therefore, we can choose different light qualities to produce different types of plant and shape to meet the needs of customer.

Figure 9. Perillaldehyde and rosmarinic acid content in green and red perilla

Figure 10. Response of water spinach towards different light intensities and spectrum
In recent years, the coriander plants became popular. And this plant also considered as suitable plant to be produced inside plant factories because it is similar to water spinach. Coriander requires higher environment temperature than lettuce. Another advantage of coriander is the whole plant including the leaves, the root, also if it has flowers or seed, all parts of the plant can be consumed, which means there is no waste. We found that the growth of coriander (the leaves, stand, and the root biomass) were highest when the root zone temperature (RZT) is 25 degrees with intensity of 300 \text{ mol m}^{-2}\text{s}^{-1} \text{[14].}

![Figure 11. (a) Effect of different light intensities and root temperature in coriander (b) Phenolic content and antioxidant capacity of coriander](image)

Total phenolic content of coriander was strongly enhanced when the light intensity was increased from 200 to 300 \text{ mol m}^{-2}\text{s}^{-1}. The highest amount of total phenolic concentration was achieved when the highest root zone temperature at 30 degree also at the highest light intensity at 300 \text{ mol m}^{-2}\text{s}^{-1}. Therefore, we can also consider that higher root zone temperature may increase the secondary metabolites in the coriander plant. Now, we can consider that the plant growth and secondary metabolites largely affected by the environment factors, not only by light. But also affected by other factors such as air temperature, water supply, EC level, also the root zone temperature.

Management of relevant factors are substantially important, we need to consider the plant whole system, not only consider the light environment. We also need to consider what crop we would grow, and how to balance it with other factors, for instance temperature, CO\textsubscript{2}, the root environment, and also the combinations of light with these factors. Because sometimes, we also have the optimum light environment for the crop but other factors may become limitation factors (boundary conditions). And the most important is the cost of performance. We need to estimate the input and output of each conditions and give a good balance for economic favorable but still with good results. By considering the whole system that affected by the factors, we can maximize the production and increase the plant quality to meet the needs of the market.
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