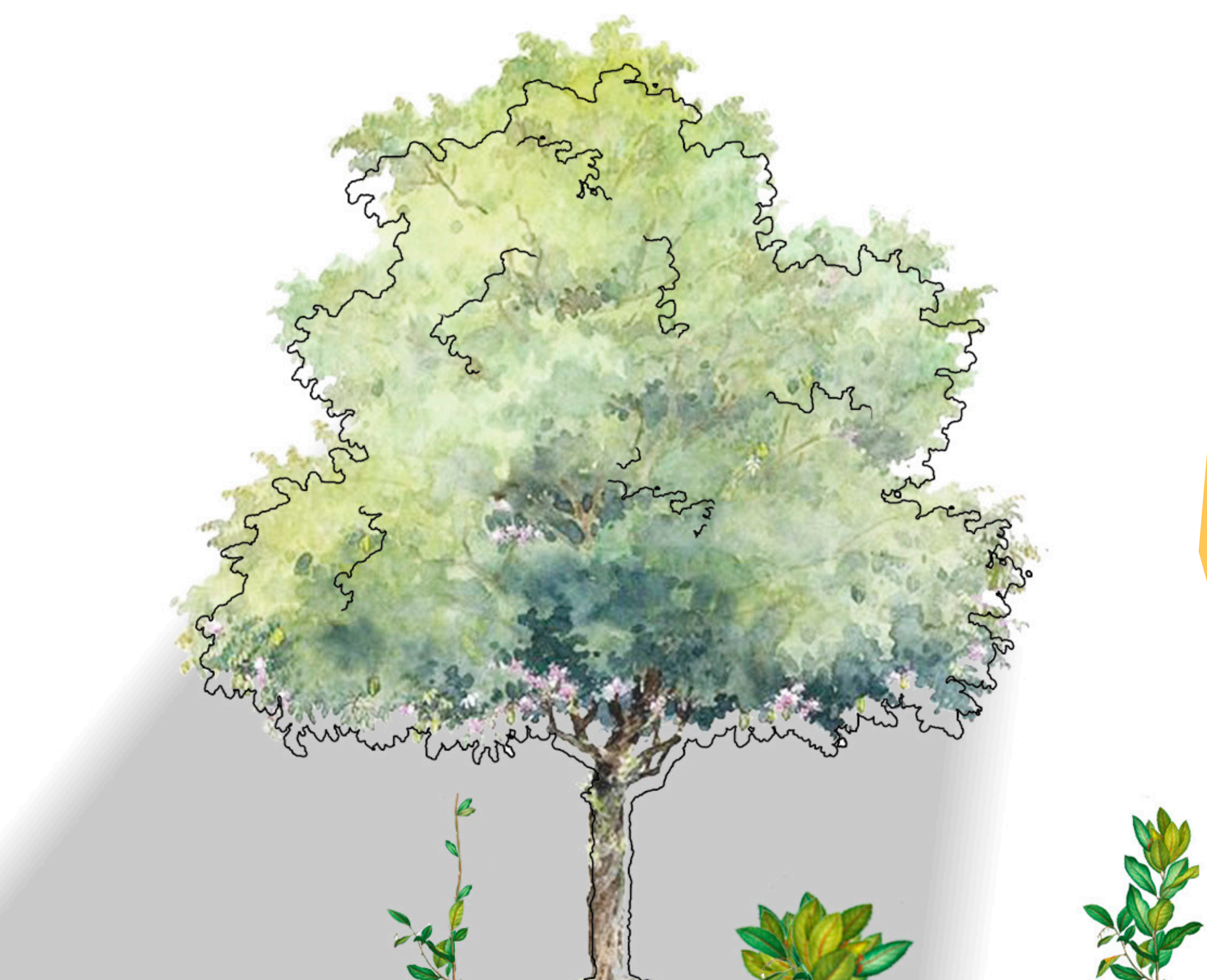
TUNING SPECTRUM: FAR-RED LIGHT

AN OVERVIEW

BY HERVÉ MAUMUS-HUE



TUNING SPECTRUM : FAR-RED LIGHT

AN OVERVIEW

CERES
GREENHOUSE SOLUTIONS®

TABLE OF CONTENTS:

ABSTRACT

Light Emitting Diodes (LED) is an emerging and increasingly popular technology. This is primarily a result of their efficiency compared to previous technologies such as High Pressure Sodium (HPS) for the same intensity of light.

In the world of artificial lighting, getting a uniform level of light intensity at the canopy is important. HPS lamps can cover a wider area of production than LEDs (Nelson and Bugbee, 2014). However for the same Photosynthetic Photon Flux (PPF) output , LEDs use approximately 40 to 60% less energy compared to HPS.

While LEDs are often promoted for reasons of efficiency, what is often underexplored is how they can be manipulated to mimic different parts of the color spectrum. Photosynthesis is associated with growth from direct light energy while photomorphogenesis is defined as the effect of light on plant development.

This is an emerging topic of research and it has led to ongoing commercial applications.

In this article we will see how changes in the spectrum can impact plant growth. It can manifest in different ways such as taste, flavour, pigmentation (anthocyanin concentration), chlorophyll content, shape, and flowering time.

A special focus will be given to Red and Far-Red radiations and how they can be applied to specific crops.

LIGHT SPECTRUM

The range of light that plants use for photosynthesis is known as PAR : Photosynthetic Active Radiation. The range of PAR wavelength is between 400 and 700 nm.

This definition is also used for the term PPFD : Photosynthetic Photon Flux density. This defines the number of photons active for photosynthesis, therefore between 400 and 700nm, reaching a surface of one square meter in one second.

This definition is evolving and now you can encounter PFD : Photon Flux Density. The unit of PPFD and PFD is expressed in µmol.m-2.s-1.

PFD has an extended wavelength range. This allows it to count for wavelengths lower than 400 (called UV), and higher than 700 nm called Far-Red.

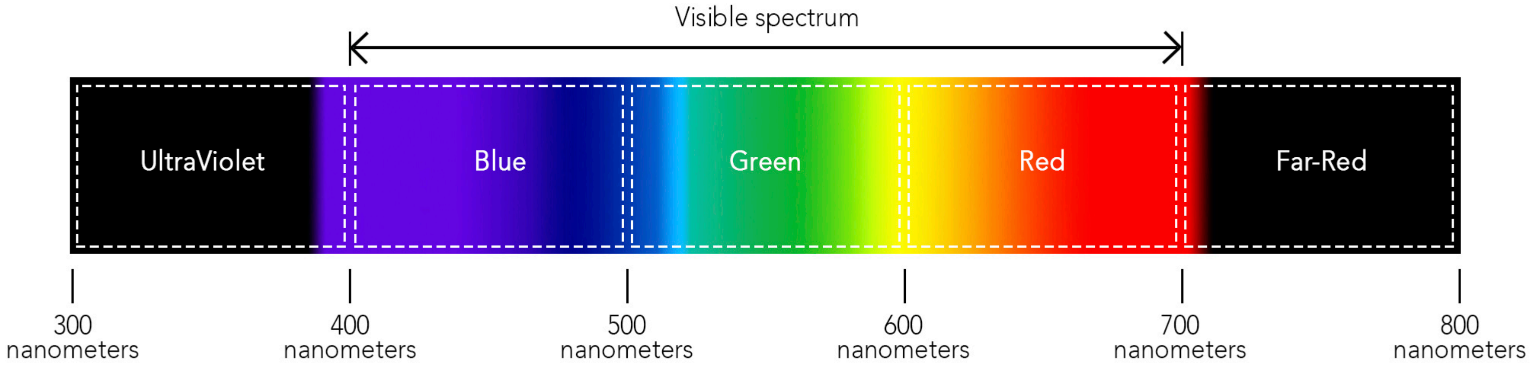


Figure 1. Light spectrum from 300 to 800nm.

Why is consideration of these wavelengths important? It has been “recently” discovered that photosynthesis doesn’t depend strictly on photons with a wavelength between 400 and 700nm, but also higher. Those photons are called “Far-Red photons”.

PHOTO ACTIVE PIGMENTS AND THEIR EVOLUTION

Early stages of understanding photosynthesis were based solely on how humans see. Humans are very good at detecting green variations. We can easily differentiate between dark and light green, therefore we can detect stress in plants when stress manifests in shades of green: water, nutrients deficiencies.

Interestingly, the color we detect the best is yellow, adjacent to green, with shorter wavelengths (cf. Figure 4. black dashed line "Luminous efficiency" around 500nm). As shown below, Chlorophyll is divided in two types called "Chlorophyll a" and "Chlorophyll b". Both have a peak of absorbance in the blue region and a peak in the red region.

Because of this, research and product development first focused on the Chlorophyll pigments. Chlorophyll is not very good at absorbing green light. This is also why plants appear green to us: the green is being reflected off the plant surface into our eyes.

Is it then logical that we started developing LEDs with blue and red spectrum to boost chlorophyll absorption.

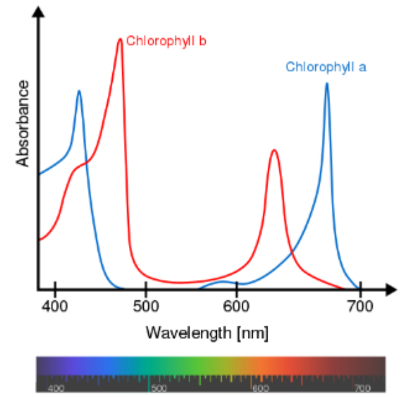


Figure 2. Taiz and Zeiger, Plant Physiology and development, 3rd Edition, 2002

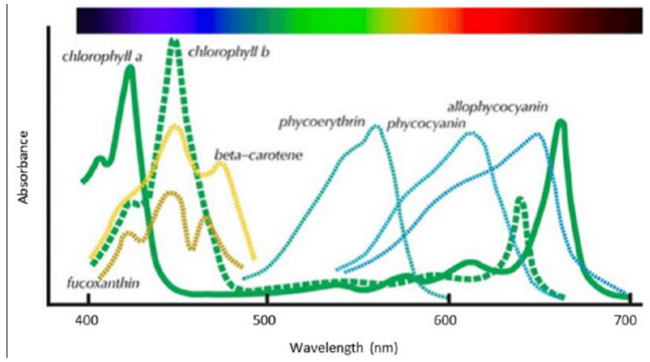


Figure 3. Taiz & Zeiger, 6th Edition, 2015

Chlorophyll was once the only pigment that was considered in the process of photosynthesis. Sunlight is loaded with green light. Does that mean that these photons are wasted? The answer is no. The same book of plant physiology written by L. Taiz and E. Zeiger, 13 years later, shows a totally different picture of photosynthesis and absorption from other pigments (cf. Figure. 3). Note that phycoerythrin is only found in algae.

The conclusion of this is that even a low absorption of chlorophyll with green light is enough to penetrate the canopy and have an effect on photosynthesis. Green light has an impact on photomorphogenesis as well as Blue, Red, and Far-Red radiations. Indeed, as shown by Folta & Al. green light can stimulate early stem elongation [3].

Green light matters. Fortunately the Sun gives us a lot.

RED & FAR-RED : WHY SO IMPORTANT?

Phytochromes

There are two forms of phytochromes when talking about Red and Far-Red radiation. One form absorbs the Red part of radiation (600 to 700nm) and its abbreviation is PR , the other form absorbs Far-Red radiation (700 to 800nm), it's abbreviation is PFR.

The graph below shows that plants are very efficient at absorbing Red. The green line "relative quantum efficiency" is how efficient the light is at different wavelengths for plants. The black dashed line "Luminous efficiency" is how the human eye sees light.

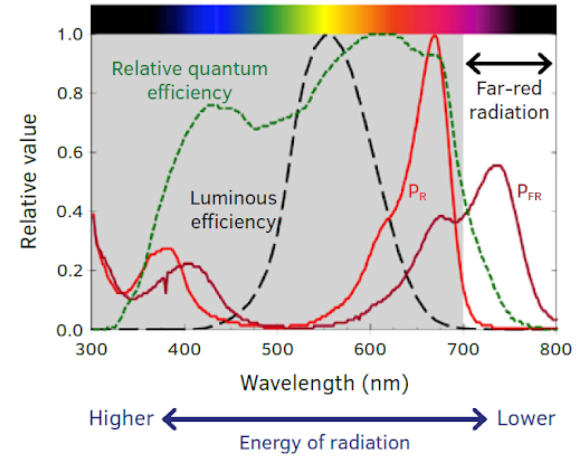


Figure 4. A closer look at Far-Red radiation, Erik Runkle.

It is important to note that both forms of Phytochromes share a common band of absorption. That means that every time that a plant receives light, both forms will be present.

The relative intensity of Red and Far-Red establishes an equivalence in terms of phytochrome and gives a relative proportion of PFR and PR. From these two values we define the Phytochrome PhotoEquilibrium PPE as:

• ***PPE = PFR / (PFR + PR)***

Another way of quantifying Far-Red radiation is more simple and is the amount of photons in Far-Red range. Total photons is measured in Total photons measured in TPFD (µmol.m-2.s-1).

• ***Percent Far-Red = FarRed Photons / Total Photons***
= Photons (700-800 nm) / Photons (400-800 nm)

However, there are some conditions where a certain form will be predominant compared to another. For example, because the Red is highly absorbed by a leaf, a leaf in the bottom of the canopy, i.e. in the shade, does not receive much of the Red light. On the other hand, Far-Red light is not absorbed well by leaves and so more easily reaches the bottom part of the canopy (cf. Figure5 below).

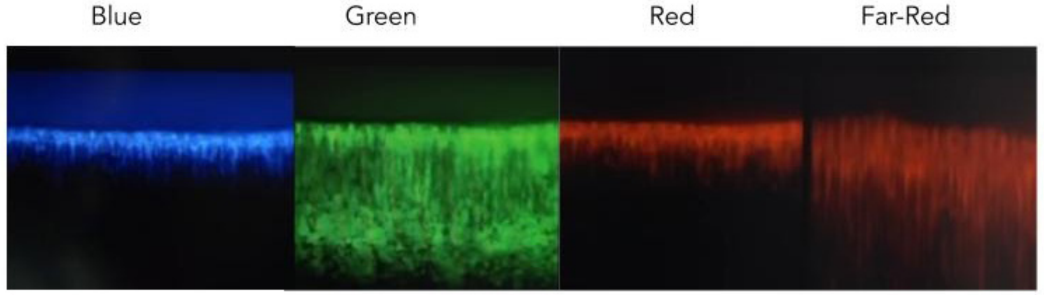


Figure 5. Brodersen & Vogelmann. 2010. Functional Plant Biology. 37:403-412

Emerson Enhancement Effect - Photosystem I & Photosystem II

Robert Emerson & al. (1958) looked at the rate of photosynthesis for isolated wave-lengths ranging from 380 nm to 760 nm. They were measuring the number of O2 molecules produced per quantum of light absorbed. As shown in figure 4 (green dashed line "Relative quantum efficiency"), there is a sudden drop in photosynthetic efficiency at 680nm. This is called the "Emerson red drop".

Emerson and his team also observed that combining red (680nm) with far-red (700+ nm) increases this efficiency. This research demonstrated the presence of two photo-systems : PS I and PS II. There is a counter-intuitive part of this process: photosystem II is the first one to take light as energy. PS II mainly uses the "classical" PAR spectrum (400-700nm) with a peak absorption in the red region. It produces adenosine triphosphate (ATP).

PS I is a subsequent photosystem that cannot exist alone. It needs PS II to bring the electrons to a certain level. Once they reach this level of energy, Far-Red photons (700nm to 752 nm [4]) will help build Nicotinamide adenine dinucleotide phosphate (NADPH).

ATP and NADPH are essential in photosynthesis: they are the molecules that store the energy coming from the light.

Einstein Stark's Law

Einstein-Stark's law postulates that "every photon excites an electron". This principle is not only important for us to understand the importance of Far-Red but it is applied to many other fields like solar cells acting through photovoltaic effects (converting light energy into electricity). .

FAR-RED MANIFESTATION ON PLANT GROWTH

Cell Expansion

Some plants react to a so-called "Shade avoidance" phenomenon. Plants compete for sunlight. They want to survive. Cell expansion means both stem elongation and leaf expansion. Most of the time both effects take place. They can manifest in two categories depending on the species:

- *Shade avoider*
- *Shade tolerator*

Most scientific attention is focused on shade avoiders.

In the shade, plants don't receive enough energy and so they start building processes in order to survive. They instinctively move toward light either by growing larger leaves (leaf expansion) to maximize the surface area and their chance to harvest photons, or by increasing their size (stem elongation) to reach the top of the canopy. In both cases what is happening is cell expansion.

It has been shown by Shuyang Zhen & al. at Utah State University that these processes are true for a wide variety of plants: spinach, tomato, basil, kale, red leaf lettuce, bean, soybean, Apogee wheat, tybalt wheat, corn, and sunflower.

This domain of research is so promising that both NASA and the USDA sponsored Utah State University to further research.

Their research showed that for the same artificial light intensity, under Red/Blue LEDs and warm-white LEDs, adding far-red light increased the quantum yield of photosystem II (PS II) by an average of 6.5% and 3.5% respectively [5].

This can potentially lead to an increase in yields (cf. figure below) . For Example, yields were increased 27% to 35% in lettuce cops in the experimental setup shown below (1). This is very promising as a method to increase yields (cf. figure 6 below).

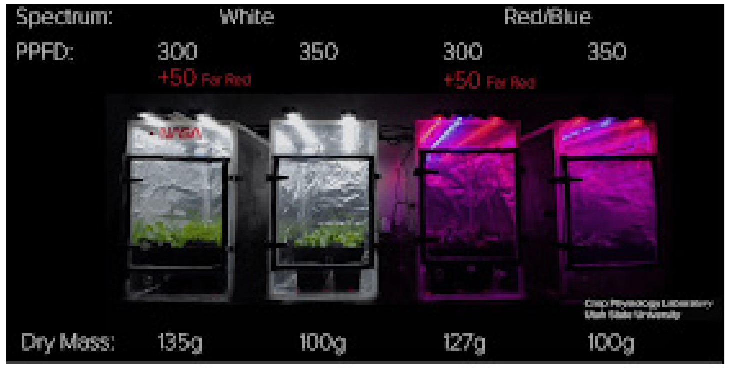


Figure 6. Growth chambers with lettuce under different LEDs spectrum.The overall photon flux density is the same for all chambers. Utah State [1]

For a normalized weight of 100g of dry product of lettuce in 4 different growth chambers, Bruce Bugbee et al. demonstrated an increase in yield of about 27%, and 35% for the two chambers having only 50 µmol.m-2.s-1 of far-red radiation mixed with respectively 300 µmol.m-2.s-1 of warm white and 300 µmol.m-2.s-1 of blue/red. The two other chambers where the normalized weight was taken from have 350 µmol. m-2.s-1 of both LEDs spectrum (white and blue/red).

Ceres Greenhouse Solutions installed Far-Red lights (Far-Red SS 100, California Lightworks) in a greenhouse in Canada. This facility is a commercial lettuce growing greenhouse and doesn't have enough data to get a scientific and significant statistical analysis. However, we hope to find that providing a low intensity Far-Red radiation (50 to 100 µmol.m-2.s-1) will send the "shade avoidance" signal to the lettuce. Therefore it will increase their leaf expansion, improving the customer's yield.

In general it appears that leafy greens (lettuce, spinach, basil) can benefit from that shade avoidance response [6]. However, it is important to note that cell expansion can have bad consequences for your crops as well.

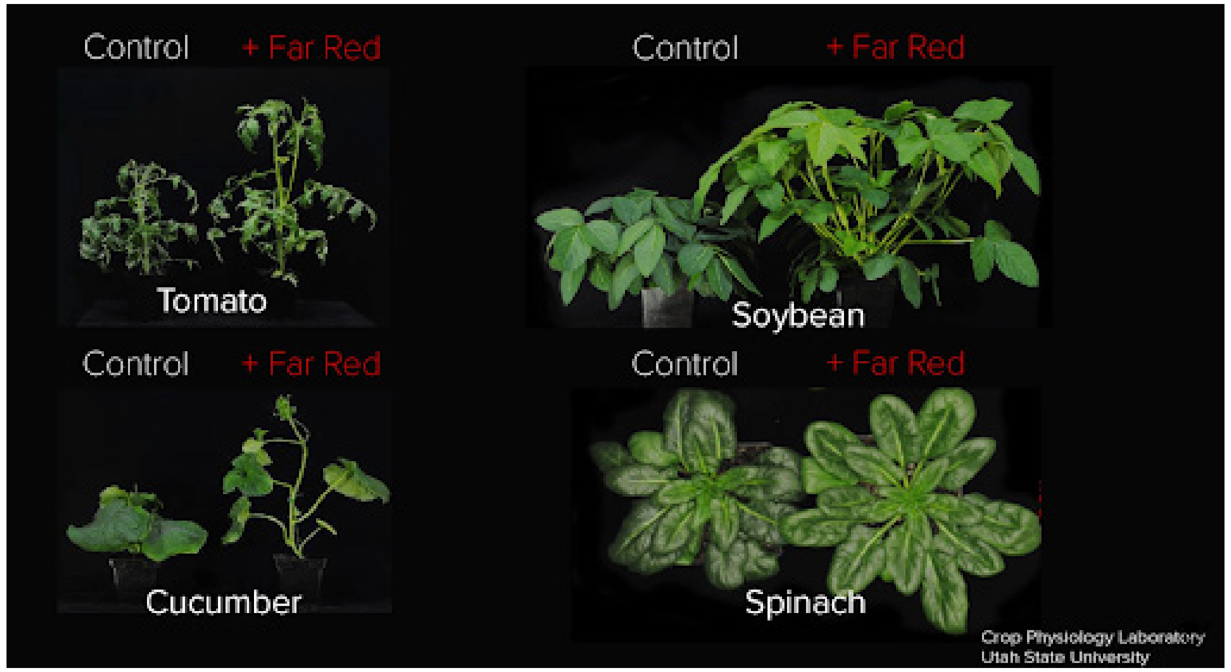


Figure 7. Far-red treatment on 4 different species. Utah State University.

For certain species such as tomato, soybean, cucumber, cannabis sativa, stem elongation is not desirable, especially for indoor grow rooms and greenhouses where the canopy space is relatively limited and needs to be optimized.

How to Predict Stem Elongation?

As mentioned in section 4.1, there are two terms to define the ratio of Phytochrome Red (PR) with respect to Phytochrome Far-Red (PFR) : PPE and Percent Far-Red. Richard Child and Harry Smith (1987) demonstrated a linear relationship between internode-elongation and Phytochrome Photoequilibrium (PPE) in light-grown mustard seedlings. This relationship has been used for decades to predict stem elongation and it works very well for a white broad spectrum such as sunlight.

Paul Kusuma (Utah State University) recently showed that using the percent Far-Red becomes more accurate when considering LED lighting with specific spectrum less broad than full spectrum sunlight.

Flowering Period

Evidence has shown that manipulating the flowering period by adding Far-Red can be effective. In a long-day plant such as petunia, the addition of FR (Phytochrome photoequilibrium PPE ≤ 0.70) accelerated subsequent flowering by 7 to 11 days, whether Blue radiation was already present in the spectrum or not [7].

Addition of FR on top of a 32 µmol.m-2.s-1 Blue radiation during seedling growth for long day plant snapdragon promoted flowering in a significant manner [2].

However, the impact on flowering time has not been demonstrated for short-day (cannabis, cotton, rice) or neutral-day plants (tomatoes, cucumber).

Furthermore, reducing flowering time can eventually lead to smaller yields, simply because of reducing the overall plant development. Pros and cons are evaluated in many articles, and are still subject to debate.

Blue Light - Interaction with Red/ Far-Red

Blue light has implications for photomorphogenesis and plant shape in general. It is known that seedlings, clones and young plants in the vegetative stage are grown under blue light to keep them compact and small while building a strong roots structure

Interaction of Blue with Red and Far-Red is a huge topic of research as well. We do not go into details here but it's interesting to note the variety of results that could be implemented in commercial grow operations.

The figure to the right shows how three different species of seedlings are under 6 light treatments with variations of Blue, Red and Far-Red. The number in the underscript indicates the Photon flux density in µmol.m-2.s-1 .

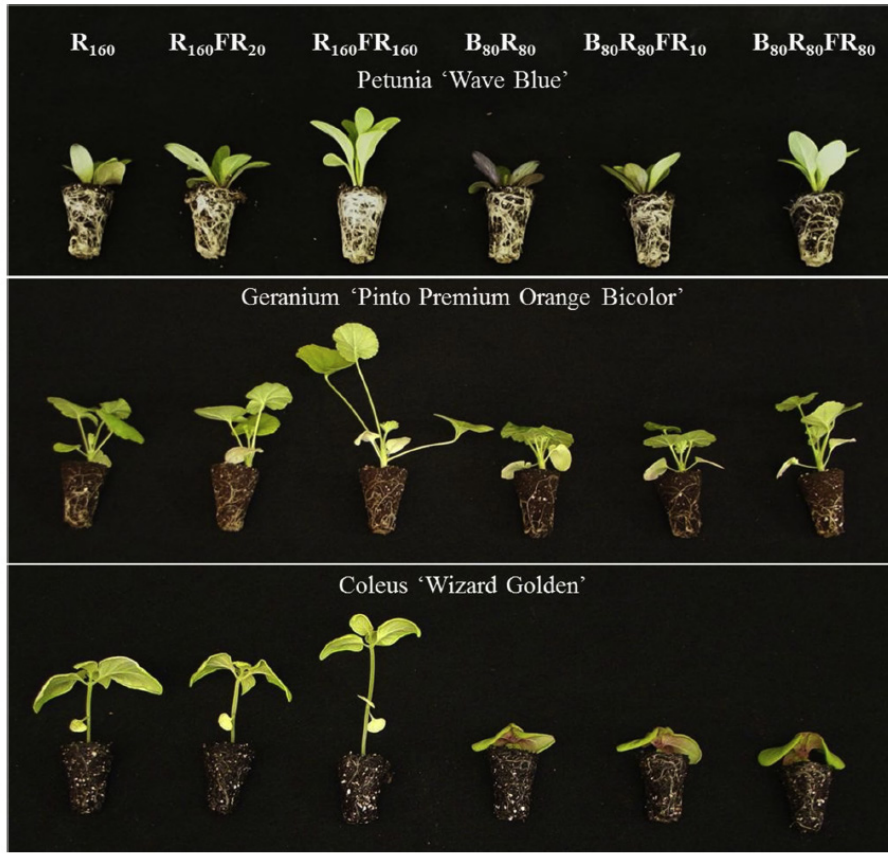


Figure 8. Seedlings of petunia, geranium, and coleus grown at 20 °C under six sole-source lighting treatments. [7]

The figure above shows that Blue seems to attenuate stem elongation caused by the R:FR radiation.

In their article, Park and Runkle [7] also discuss an interesting behavior in tomatoes (Solanum lycopersicum), cucumber (Cucumis sativus) and pepper (Capsicum annuum). Increasing blue radiation led to a significant reduction of stem length, leaf area, and an increased chlorophyll concentration.

This plant growth reaction to blue has been confirmed for a lower intensity in a study done by Hernandez and Kubuto in 2016 on cucumber. They observed a linear reduction of plant height, leaf area while a linear increase in chlorophyll concentration.

During another study, the number of flower buds increased with an increase in Blue radiation from 0 to 100%.

Blue radiation has definitely a big impact on plant growth: stem elongation response, leaf expansion, chlorophyll concentration and numbers of flowers.

These traits are species dependent and ratios of different parts of the spectrum dependent (how much of each spectrum B, R, FR there is compared to each other).

DISCUSSION

Implementing Far-Red Radiation to your LEDs : Improving Photosynthetic Photon Flux Efficiency (PPE)

Nowadays, most LED fixtures have a maximum efficiency between 2.2 and 3 µmol.J-1. Far-Red photons are efficiently generated by LEDs. Hence, if the scientific and horticultural community changes the definitions of lighting terms regarding the photo active spectrum (PAR), the efficiency of the fixture could potentially increase and reach 3 to 4 µmol.J-1. This is another reason why NASA is interested in that domain. Building more efficient artificial fixtures could be the key to produce food with less energy. (https://cubes.space/tags/news).

CONCLUSION

This article provides a wide preliminary background of plant physiology, light and photochemistry. Some information is missing and could be found on the Internet and/or many different textbooks. The purpose of this given background is to understand the processes involved in photosynthesis, photomorphogenesis and their link with the recent development of LEDs. A specific focus on Red and Far-Red radiation's ratio has been given: why and how it can be applied to your crop, and whether it is indoor or in a greenhouse environment. Leafy greens such as spinach, lettuce, basil and kale are the main crops that we see used in commercial applications and we at Ceres are currently implementing an experiment in one of our lettuce greenhouses.

A short introduction on the impact of Far-Red radiation on the flowering time is also given and benefits have been shown mostly for Day-long plants (14 to 18h/24 flowering photoperiod).

Furthermore, changing the definition of "efficiency" in the lighting terms to include wavelengths higher than 700nm as photosynthetic active photons could improve a better understanding of these "forgotten photons".

Finally a wider focus on the Blue light and how it can work with Red/Far-Red is discussed.

There are a lot of processes that remain not well understood and the plant physiology research's results will dictate new technologies and at the end how can people grow more efficiently.

REFERENCES

1. Far-Red : "The forgotten Photons", Bruce Bugbee, Apogee Instruments Youtube videos.

2. Park Y, Runkle ES. Far-red radiation promotes growth of seedlings by increasing leaf expansion and whole-plant net assimilation. Environ. Exp. Bot. 2017; 136: 41±49.

3. Folta, K. M. (2004). Green light stimulates early stem elongation, antagonizing light-mediated growth inhibition. Plant Physiol. 135, 1407-1416. Doi: 10.1104/pp.104.038893

4. Zhen, S., Haidekker, M., & van Iersel, M. W. (2018). Far-red light enhances photochemical efficiency in a wavelength-dependent manner. Physiologia Plantarum. doi:10.1111/ppl.12834

5. Zhen, S., & van Iersel, M. W. (2017). Far-red light is needed for efficient photochemistry and photosynthesis. Journal of Plant Physiology, 209, 115–122. doi:10.1016/j.jplph.2016.12.004

6. Far-red radiation interacts with relative and absolute blue and red photon flux densities to regulate growth, morphology, and pigmentation of lettuce and basil seedlings Qingwu Meng, Erik S. Runkle. Department of Horticulture, Michigan State University, 1066 Bogue Street, East Lansing, MI 48824-1325, USA

7. Blue radiation attenuates the effects of the red to far-red ratio on extension growth but not on flowering. Yujin Park, Erik S. Runkle. 2019

8. Far-red radiation interacts with relative and absolute blue and red photon flux densities to regulate growth, morphology, and pigmentation of lettuce and basil seedlings Qingwu Meng, Erik S. Runkle. Department of Horticulture, Michigan State University, 1066 Bogue Street, East Lansing, MI 48824-1325, USA