Focusing on light-use efficiency:
A key factor for profitable indoor crop production.

Optimising light-use efficiency (LUE) and energy-use efficiency (EUE) creates opportunities to enhance both productivity and sustainability in indoor crop production. By moving beyond just focusing on annual productivity to include these efficiency measures, farms can build more sustainable business models. This guide introduces the concept of LUE in particular and provides several strategies for improving LUE of production in an indoor farm.

Three Keys to Success: Productivity, Light-Use Efficiency, and Energy-Use Efficiency

Beyond maximizing annual productivity, sound unit economics is achieved by producing greater yields with less light and therefore less electricity for lighting.

LUE indicates how effectively plants capture and convert light energy into biomass and is positively influenced by both an optimal light recipe and good growing conditions and techniques. When combined with efficient LEDs, good LUE leads to improved EUE, significantly reducing overall cost of production (CoP)[1]. **Table 1** provides detailed information on these KPIs.

Table 1: Key Performance Indicators (KPIs) for successful farming production efficiency, adapted from Janssen et al. (2019)

Key Performance Indicators	Units	Basic Definition
Annual productivity	$kg/m^2/y$ (or tonnes/ha/y)	Weight of saleable biomass produced per unit area of growth space per year.
Light-use efficiency (**LUE**)	g/mol	Weight of saleable biomass divided by total sum of light received during growing cycle.
Energy-use efficiency (**EUE**) of lighting	g/kWh	Weight of saleable biomass divided by total electricity used for lighting during a growing cycle.
Cost of production (**CoP**) for lighting	$/kg	The cost of producing a unit of saleable biomass based on the total electricity used for lighting during a growing cycle.
Light utilisation/interception	%	Proportion of photon flux that is absorbed by plant (i.e., not wasted)

The relationships between the various KPIs are illustrated in **Figure 1**. To understand your farm's production efficiency, start with the yield from a harvest cycle (kg/m^2). Then:

- ❑ Calculate EUE by dividing with the total energy (in kWh/m^2) consumed by your LED lights.
- ❑ Calculate Cost of production ($/kg) by dividing the price of energy with the EUE.
- ❑ Calculate LUE by dividing the yield from a cycle with the total light (in mol/m^2) your crops received.

These measurements help you make better decisions to improve your farm's productivity and reduce costs.

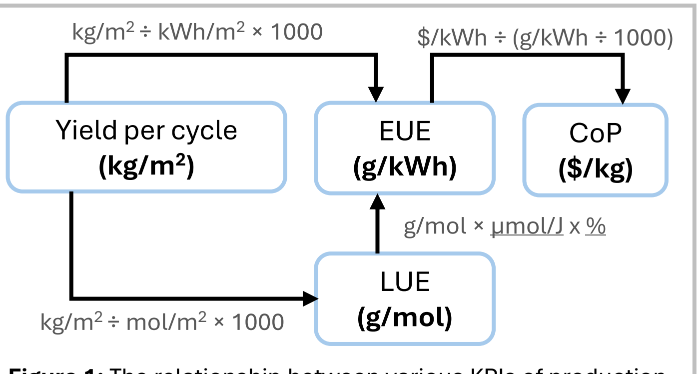


Figure 1: The relationship between various KPIs of production efficiency including productivity (yield per cycle), energy-use efficiency (EUE), light-use efficiency (LUE), and cost of production (CoP) for lighting. Underlined are LED efficacy (μmol/J) and light utilisation (%).

A higher LUE means a higher EUE and a lower cost of production.

LUE can be improved through both **light recipe optimisation** and **crop management practices** (plant density, climate, CO_2 concentration, air movement, and water and nutrient availability) and hence might offer more opportunities for short-term and piecemeal improvements. The following sections will explore how light recipes and crop management practices influence LUE.

Improving light-use efficiency (LUE) through light recipes

For background reading, refer to previous publications: "Guide to light-emitting diode (LED) grow lights for farms" & "Guide on effects of light spectrum in light-emitting diode (LED) grow lights for farms."

Recent studies show that adjusting LED lighting systems can improve LUE. You can enhance crop yield by modifying light intensity, spectrum and photoperiod. Since the effect of light recipe is cultivar specific and dependent on cultivation conditions, having multi-colour dynamic lighting control to fine-tune overall light recipe might be an attractive option.

Increase DLI with longer hours, not brighter lights

Increasing total amount of light your plants receive through the day (Daily Light Integral, DLI) leads to higher yields. However, simply making lights brighter to increase DLI is not efficient (**Figure 2**), as plants can only process so much light at once[2]. A more effective approach is to extend the lighting duration rather than increasing intensity[3]. Joint studies by Singapore Food Agency (SFA) and Wageningen University (WUR) on Xiao Bai Cai confirmed this. They found that longer lighting periods produced better yields than higher light intensity, even when using the same DLI. This method also proved more efficient in converting light into plant growth.

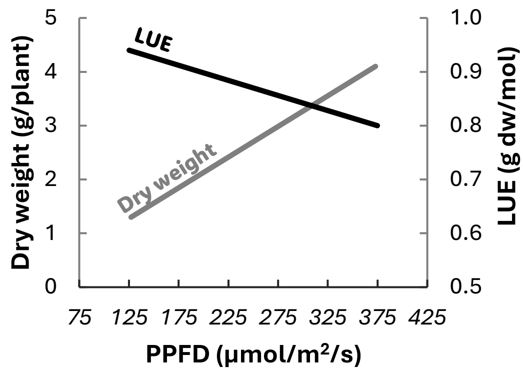


Figure 2: Increase in PPFD led to 3-fold increase in dry weight but 15% reduction in LUE. Adapted from Mayorga-Gomez et al (2024)[3].

Include some far-red light to improve yield and LUE

Far-red (FR) light acts together with red (R) to further drive photosynthesis and help leaves expand to capture more light. For some green lettuce varieties, this can improve yield and LUE by up to 23%. However, be careful - some varieties may develop thin leaves with poorer quality and shorter shelf life[4].

FR light offers an interesting solution for red lettuce varieties. While these varieties typically need higher blue (B) light for proper red colour development, this reduces yields. Adding FR can improve LUE and growth rate by ~13% while producing an acceptable red colour (Figure 3D)[5]. Hence, this could be used as a static light treatment for red lettuces.

Research on Asian leafy varieties show promising results. FR improved Choy Sum biomass, indicating possible enhancement of LUE[6]. Joint studies by SFA and WUR found that the addition of FR improved both yield and LUE in Xiao Bai Cai.

Note: B = Blue light (400 – 500 nm); G = Green light (500 – 600 nm); R = Red light (600 – 700 nm); FR = Far-red light (700 – 800 nm) W = White light (400 – 700 nm)

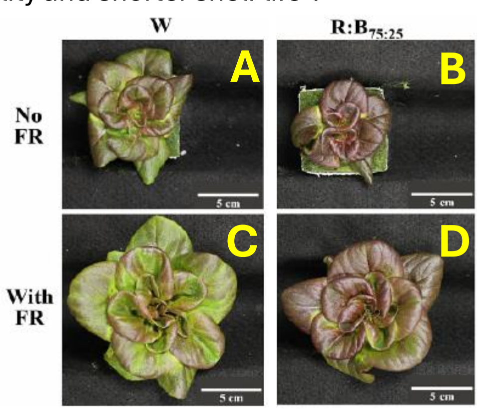


Figure 3: Adding FR to RB (**D**) improves yield and colour compared to standard W (**A**), adapted from Brenk et al, 2024.

Minimise the use of white LEDs

White (W) LEDs are cheaper but less energy-efficient, and contain much green (G) light in their spectrum. Some G light is reflected, some is absorbed and is transmitted to lower parts of the canopy. But when small amounts of G light is present with high R light, this can lead to better growth for some varieties. For instance, a spectrum of 73% R and 19% G had similar or slightly better LUE than various RB lights for a red lettuce variety[5]. An added benefit of including G light: it makes it easier to spot pests and diseases.

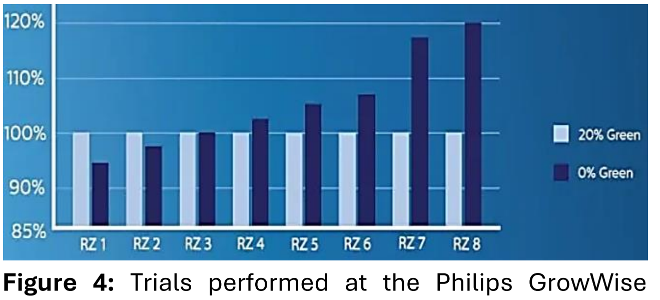


Figure 4: Trials performed at the Philips GrowWise Center show some lettuce varieties (RZ 1-2) display slightly higher relative productivity from having some G light (grey bars), compared to RB-only spectrum (blue bars)[7]. Note that G light is obtained from parts of the W LEDs' spectrum in these trials.

Improving light-use efficiency (LUE) through effective crop management and design

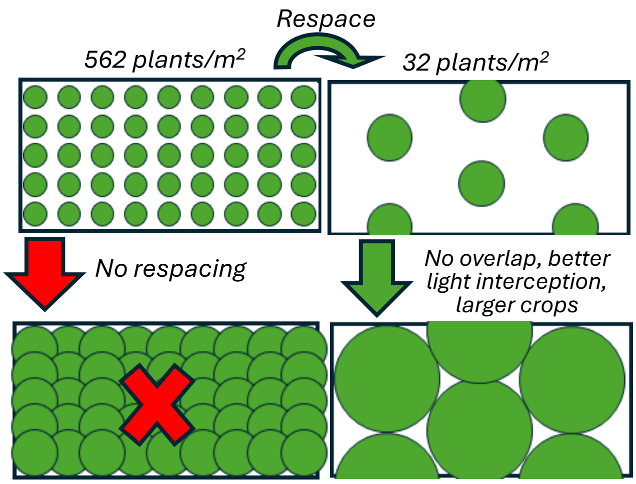
Recapturing light through reflection

Use white surfaces to promote diffuse reflection of light within the growing area. Seedlings in the bottom left image receive twice the amount of light as installed levels due to reflection. Image to the right shows same plants grown to the point just prior to respacing (see section below). Images from Janssen et al (2019)[1].

Redirect light escaping from the rack edges back to growing area using reflectors. A study showed 14% increase in seedling biomass with the use of reflectors. See image below from Huang et al (2023)[10].

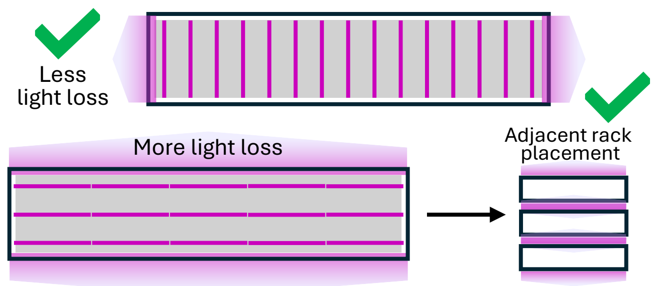
Respacing

Respacing reduces the chance of crops overlapping as they grow larger, thereby maximising light interception. It also avails more reflective surface to improve light recapture. Note that without automation, respacing requires labour and time. Ideal planting density depends on the volume and desired harvest weight of the crop[4]. For reference, the final stage plant density can range between 20–50 plants/m^2 for lettuces.



Good arrangement of LEDs on rack

Avoid arranging LEDs parallel to length of rack. Review potential light loss and use reflectors, or place adjacent racks to recover lost light.

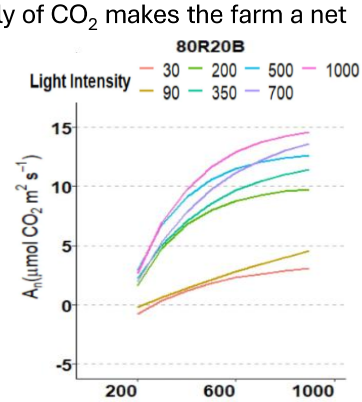


Give space for LEDs above crop canopy (~20 cm): too close results in the formation of excessively bright spots (light stress) and dark spots (lost opportunity for growth). Air flow is compromised, leading to higher temperatures, uneven growth, tipburn and diseases[1].

CO_2 dosing

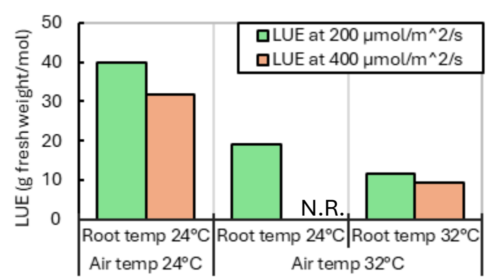
Higher CO_2 levels (800 – 1200 ppm) can enhance carbon assimilation under increased light intensity. Beware that oversupply of CO_2 makes the farm a net carbon emitter.

Right: Tomato seedlings grown under RB LEDs showing higher net photosynthetic rate with increasing CO_2 concentration and light intensity (adapted from Moratiel et al)[9].



Optimising air and root zone temperature

Allowing the plant to grow in the best environment allows it to make best use of incoming light. For lettuce, LUE diminishes drastically moving from 24 to 32°C. Cooling the root zone can help moderate higher air temperatures.



Above: Adapted from Carotti et al[8].

Conclusion: Driving Profitability Through Light and Energy-Use Efficiency

There are many ways to improve LUE, which in turn will also improve EUE of lighting. Since less waste heat is generated, this lowers total energy needed for cooling. Therefore, overall cost of production is reduced.

Key Takeaways for Growers

- ❑ Use the following KPIs to track, gain insights and take action: i) productivity (kg/m^2/year), ii) light-use efficiency (g/mol) and iii) energy-use efficiency (g/kWh).
- ❑ For better results, run lights for a longer duration (e.g. 200 μmol/m^2/s for 18 h) at lower intensity than shorter duration at high intensity (for same DLI).
- ❑ Adding far-red light can help improve LUE for leafy vegetables. It can also help with biomass accumulation, and boosts yield when used in conjunction with high % blue spectrum for red lettuces.
- ❑ Avoid broad-white spectrum, opt for higher % red spectrum. But small amounts of white may be beneficial when mixed with majority red spectrum, depending on the crop.
- ❑ Using multi-colour dynamic lighting control system allows you to easily adjust light recipes and improve LUE or productivity based on your needs.
- ❑ Optimize growing conditions to improve LUE: maintain proper CO_2 levels, control temperatures (both air and root zone), optimise plant spacing, and keep a good distance between lights and plant canopy.
- ❑ Use reflective materials to enhance light capture and light interception by plant for better LUE.

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Local farms can tap on the Agri-Cluster Transformation (ACT) Fund with the enhanced Energy Efficiency Programme (EEP) to build capabilities and capacities that drive higher productivity in a sustainable and resource-efficient manner. Farms can tap on co-funding under the EEP to undergo an energy efficiency audit which would establish their baseline energy consumption and identify potential areas for improvements. Farms can also leverage the enhanced Capability Upgrading component to adopt resource and energy-efficient equipment and technologies from SFA's prequalified list. All licensed farms can apply for co-funding under the EEP.

About the author:

Craig D'Souza is a part of the Agri-Technology & Food Innovation Department, which provides technical advice to farms to optimise or improve production. He gained critical experience in horticulture lighting for indoor farms and greenhouses from a global horticulture LED company, and also spent some time as a nursery manager growing a variety of crops. His current topics of interest include adapting lighting and climate control strategies for farms located in tropical climates.

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