Biomass Yield, Morphological Characteristics, Energy Balance, and Water-Use Efficiency of Red Lettuce (Lactuca sativa L.) Cultivation under Various Artificial Light Spectra

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Indrawan Cahyo Adilaksono[1], Samuel Balapradana Simanjuntak[1], Joseph Batara Sibarani[1], Rian Albar Insani[1], Aep Supriyadi[1], Ayano Ito[2], Laras Putri Wigati[3], Agus Dana Permana[1], Anriansyah Renggaman[1]

[1] Agricultural Engineering Study Program, SITH ITB, Indonesia | [2] Graduate School of Agriculture, Kyoto University, Japan | [3] Microbial Biotechnology Research Group, SITH ITB, Indonesia

Abstract

Artificial lighting strongly influences crop productivity and resource demand in plant factories. This study compared five high-power LED spectra—warm white (WW, 3000 K), pure white (PW, 6000 K), cool white (CW, 8000 K), red:blue 1:1, and red:blue 3:1—for red lettuce (Lactuca sativa L.) under an equal daily light integral (DLI) of 12 mol·m^{-2}·d^{-1}. A completely randomized design with four replications was conducted in a hydroponic deep-water culture system. WW produced the greatest biomass (20.48 g FW; 1.47 g DW) and leaf expansion (414.20 cm² total leaf area), while achieving the highest light-use efficiency (1.61%) and water-use efficiency (49.29 g FW·L^{-1}). The 3R:1B spectrum achieved the highest electrical energy-use efficiency (9.91 g FW·kWh^{-1}) and energy conversion efficiency (0.29%). Thus, broad-spectrum WW maximized growth and water productivity, whereas red-dominant narrow-band lighting improved electrical energy utilization.

Keywords: Artificial lighting; red lettuce; biomass; energy-use efficiency; water-use efficiency

Introduction

Controlled-environment agriculture (CEA) and plant factories with artificial lighting (PFAL) enable year-round crop production, but lighting remains a major operational input. LED technology offers precise spectral control and opportunities to improve energy efficiency. Indoor cultivation commonly uses red–blue combinations because these wavelengths are strongly absorbed by chlorophyll; however, broad-spectrum white LEDs also provide green photons that can penetrate deeper into the canopy. Red lettuce is responsive to spectral cues, making it a useful model for evaluating biomass and canopy development. This study compared three white spectra with two red–blue configurations at a standardized DLI to identify lighting strategies that balance crop yield, morphology, water use, and energy performance.

Research Method

A completely randomized design (CRD) was employed to evaluate five LED spectral treatments: warm white (WW, 3000 K), pure white (PW, 6000 K), cool white (CW, 8000 K), red-to-blue ratio of 1:1 (1R:1B), and red-to-blue ratio of 3:1 (3R:1B) as shown in **Figure. 1**, with four replications per treatment. Red lettuce seedlings were cultivated in a deep-water culture (DWC) hydroponic system, with 12 plants per basin. The plants received an AB Mix nutrient solution maintained at an electrical conductivity (EC) of 2 mS cm^{-1}. To ensure comparable light exposure, all treatments were maintained at the same daily light integral (DLI) of 12 mol m^{-2} d^{-1}, while photosynthetic photon flux density (PPFD) was measured using a spectroradiometer and the photoperiod was adjusted accordingly. Plants were harvested at 31 days after sowing (DAS). The evaluated parameters included biomass production, and morphological characteristics, water consumption, electrical energy consumption, and biomass energy content.

The experimental data were analyzed using analysis of variance (ANOVA), followed by appropriate post-hoc tests.

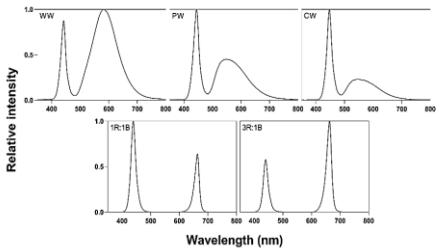
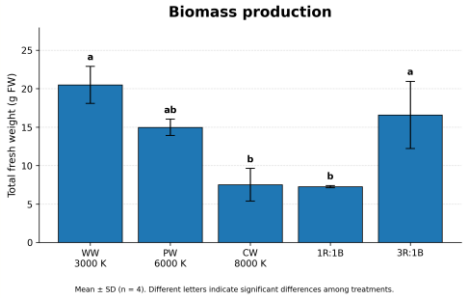
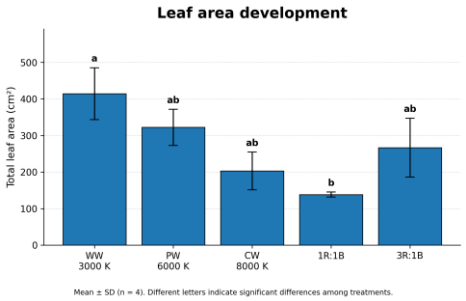


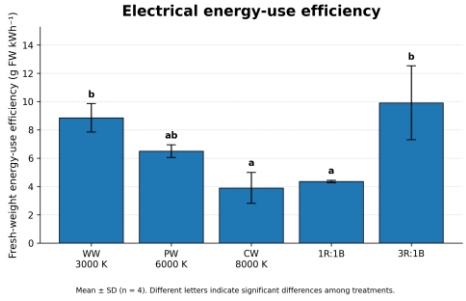
Figure 1. Relative spectral distribution of the five LED treatments.

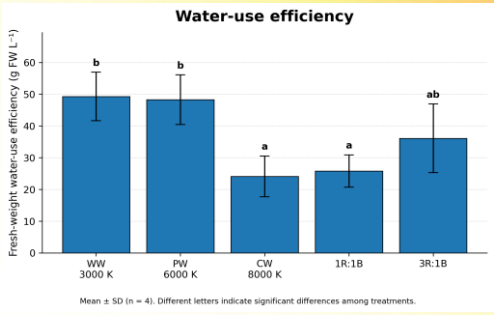
Discussion & Result

The results demonstrate a trade-off between maximizing crop growth and minimizing lighting electricity demand. Broad-spectrum warm white light supported stronger canopy expansion and biomass accumulation, likely through the combined contribution of red photons to carbon assimilation and green photons to deeper canopy penetration. In contrast, narrow-band red-dominant 3R:1B lighting required less electrical input and converted electricity into biomass energy more efficiently. Blue-dominant 1R:1B lighting consistently produced the lowest biomass and leaf area. Therefore, spectrum selection should be matched to the production priority: harvest mass and water productivity, or electrical energy efficiency.









Among the five treatments, broad-spectrum warm white (WW, 3000 K) consistently promoted the greatest plant growth, producing the highest total fresh weight (20.48 ± 2.41 g) and dry weight (1.47 ± 0.26 g). This superior biomass accumulation was accompanied by the largest total leaf area (414.20 ± 70.83 cm²) and projected leaf area (260.72 ± 41.59 cm²), indicating more extensive canopy expansion under WW lighting. In contrast, the 1R:1B treatment resulted in the lowest biomass production, with only 7.26 ± 0.15 g fresh weight and 0.48 ± 0.03 g dry weight. Although spectral quality affected canopy expansion, no significant differences were observed in leaf number, leaf thickness, tissue water content, or root-to-shoot ratio, suggesting that the primary morphological response was associated with leaf area development rather than changes in other measured plant characteristics. In terms of resource-use efficiency, WW also achieved the highest water-use efficiency, reaching 49.29 ± 7.62 g FW L^{-1} and 3.53 ± 0.69 g DW L^{-1}, together with the highest light-use efficiency of 1.61 ± 0.07%. These findings indicate that WW lighting not only enhanced biomass accumulation but also improved water and light utilization under the tested hydroponic conditions. However, the highest electrical energy-use efficiency was obtained under red-dominant 3R:1B lighting, which achieved 9.91 ± 2.61 g FW kWh^{-1} and 0.69 ± 0.18 g DW kWh^{-1}, as well as the highest energy conversion efficiency of 0.29 ± 0.08%. This suggests that 3R:1B lighting converted electrical energy into plant biomass more efficiently, despite not producing the highest absolute biomass. Overall, the results demonstrate a trade-off between maximizing crop productivity and optimizing electrical energy utilization.

Conclusion

At a standardized DLI of 12 mol·m^{-2}·d^{-1}, LED spectral quality strongly influenced red lettuce biomass accumulation and canopy expansion. Warm white (3000 K) was the most effective treatment for maximizing fresh and dry biomass, leaf area, light-use efficiency, and water-use efficiency. By comparison, red-dominant 3R:1B lighting achieved the highest electrical energy-use and overall energy conversion efficiencies. These findings indicate that broad-spectrum white LEDs are suitable when maximizing harvest yield and water productivity is the priority, while red-dominant narrow-band LEDs offer an advantage when reducing electricity use per unit biomass is critical. Optimizing LED spectra can therefore improve resource efficiency in controlled-environment vegetable production.