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Article

Energy Efficiency Optimization in Vertical Farming Systems: A Comparative Analysis of LED Lighting Configurations

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ABSTRACT
Vertical farming has emerged as a promising solution for urban food security, yet its energy-intensive operations raise sustainability concerns. This study evaluates the energy efficiency of three LED lighting configurations (full-spectrum, red-blue, and adaptive dimming) in vertical lettuce cultivation. Using a controlled environment agriculture (CEA) setup in urban laboratories across three cities, we measured energy consumption, crop yield, and resource use efficiency over a 12-week growth cycle. Results indicate that adaptive dimming systems reduced energy use by 32% while maintaining 94% of the yield achieved with full-spectrum lighting. Economic analysis further shows a 27% reduction in operational costs, making this configuration more viable for urban circular food systems. These findings contribute to optimizing vertical farming practices for enhanced environmental resilience and economic sustainability in dense urban contexts.

Keywords: vertical farming; LED lighting; energy efficiency; urban agriculture; circular food systems

1. Introduction

Urbanization is accelerating globally at an unprecedented rate, with 55% of the world's population currently residing in cities—a figure projected to reach 68% by 2050 (UN DESA, 2018). This rapid urban growth not only transforms the physical landscape of cities but also exacerbates a multitude of challenges, among which food security stands out as a critical issue. As cities expand, they increasingly depend on distant agricultural systems, creating long and complex supply chains. This dependence leads to high carbon footprints from transportation, as food products travel hundreds or even thousands of kilometers to reach urban markets. Additionally, supply chain inefficiencies, such as spoilage during transit, further compound the problem, resulting in significant food waste and increased costs (Ackerman et al., 2014).

In response to these challenges, vertical farming (VF) has emerged as a promising solution. Defined as the cultivation of crops in stacked layers using controlled environment agriculture (CEA) technologies, vertical farming offers a way to bring food production closer to urban centers (Despommier, 2010).

By locating food production within cities, VF reduces transportation distances, thereby lowering carbon emissions associated with food distribution. It also minimizes water use compared to traditional agriculture, as these systems often employ recirculating water systems that significantly reduce waste. Furthermore, vertical farming enables year-round cultivation independent of climatic conditions, ensuring a consistent supply of fresh produce regardless of seasonal changes or extreme weather events (Kozai et al., 2016).

However, despite its numerous advantages, VF's sustainability credentials are undermined by its high energy consumption. The main contributors to this energy demand are artificial lighting, climate control, and mechanical ventilation (Williams & Wikstrom, 2019). Among these, lighting alone accounts for 70–80% of total energy use in VF systems. Traditional high-intensity discharge (HID) lamps, which have been commonly used in such settings, consume 200–400 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of photosynthetic photon flux density (PPFD) for leafy greens (Morrow, 2008). In recent years, light-emitting diodes (LEDs) have emerged as a more energy-efficient alternative. They consume 50–70% less energy than HIDs while providing customizable spectral outputs, which allows for tailoring the light to the specific needs of different crops (Singh et al., 2015).

Despite the progress made with LEDs, optimizing LED configurations to balance energy efficiency and crop productivity remains a critical research gap. Different crops have varying light requirements at different stages of growth, and finding the optimal lighting setup that minimizes energy use while maximizing yield is a complex task. This study addresses this gap by comparing three LED lighting configurations—full-spectrum, red-blue (RB) mix, and adaptive dimming—in vertical lettuce cultivation across three urban laboratories.

Lettuce (Lactuca sativa L.) was selected as the model crop for several reasons. It is widely cultivated in VF systems due to its suitability for indoor growing conditions. It has a relatively short growth cycle (30–45 days), which allows for more frequent experimentation and data collection. Additionally, lettuce has a high demand in urban markets, making the results of this study directly applicable to real-world urban food production scenarios (Bantis et al., 2018).

The research objectives are:

(1) To quantify energy consumption and crop yield under each LED configuration, providing detailed data on how each lighting setup affects these key metrics.

(2) To assess resource use efficiency (water, nutrients) and economic viability, considering not only energy costs but also other operational expenses and potential revenue.

(3) To provide evidence-based recommendations for optimizing LED lighting in urban VF systems, helping farmers and industry professionals make informed decisions about lighting configurations.

2. Materials and Methods

2.1 Study Sites

Experiments were conducted simultaneously in three urban laboratories, each with its unique characteristics that could potentially influence the results. This multi-site approach was chosen to ensure the generalizability of the findings across different urban environments.

• University of California, Berkeley (USA): The facility is a 200 m^2 vertical farm module located within the campus's Center for Responsible Business, situated in downtown Berkeley (37.8716° N, 122.2727° W). The laboratory uses grid electricity with 30% renewable energy integration, which includes sources such as solar and wind power. The urban setting of Berkeley, with its busy downtown area, provides a representative environment of a densely populated city where vertical farming could play a significant role in local food production.

• Politecnico di Milano (Italy): A 150 m^2 modular VF system located in Milan's Innovation District (45.4642° N, 9.1900° E). This facility is powered by a mix of grid electricity and on-site solar panels, with a 20% renewable share. Milan's Innovation District is a hub for technological advancements, making it an ideal location to test cutting-edge vertical farming technologies in an urban context that values innovation and sustainability.

• National University of Singapore (Singapore): A 180 m^2 indoor farm situated in the Kent Ridge campus (1.3434° N, 103.7747° E). This laboratory utilizes 100% grid electricity with natural gas as the primary energy source. Singapore, a highly urbanized city-state with limited land for traditional agriculture, relies heavily on imported food, making vertical farming a particularly relevant solution. The use of natural gas as the primary energy source also provides a different energy context compared to the other two sites.

All sites maintained standardized environmental conditions to ensure the comparability of results. The temperature was kept at 20±2°C, relative humidity at 60±5%, CO_2 concentration at 1000±50 ppm, and a photoperiod of 16 hours light/8 hours dark. These conditions were controlled via advanced HVAC systems and CO_2 injectors. The standardization of these factors helps to isolate the effect of the different LED lighting configurations on the crops.

2.2 Experimental Design

A randomized complete block design (RCBD) was employed in this study. This design is widely used in agricultural research because it accounts for variability within the experimental area, ensuring that the treatments are compared on a more equal basis. There were three treatments (LED configurations) and four replications per site, which increased the reliability of the results by allowing for the averaging of data and reducing the impact of random variation.

Each experimental unit consisted of a 1.2 m × 0.6 m growing tray with 36 lettuce plants (cv. 'Butterhead'), spaced at 10 cm × 10 cm intervals. This spacing was chosen based on previous research indicating that it provides optimal growing conditions for lettuce in vertical farming systems, allowing for adequate light penetration and air circulation.

• Treatment 1: Full-spectrum LEDs (control): The emission spectrum spans 400–700 nm, with peak wavelengths at 450 nm (blue), 550 nm (green), and 660 nm (red). The PPFD was maintained at 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Full-spectrum LEDs were chosen as the control because they mimic natural sunlight, which is the traditional light source for plant growth, providing a baseline for comparison with the other treatments.

• Treatment 2: Red-blue (RB) LEDs: This configuration consists of 80% red (660 nm) + 20% blue (450 nm) spectrum, with PPFD maintained at 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Red and blue light are known to be crucial for plant photosynthesis, with red light promoting flowering and fruiting, and blue light influencing leaf growth and chlorophyll production. This treatment was included to test whether a simplified spectrum could reduce energy consumption without significantly compromising yield.

• Treatment 3: Adaptive dimming LEDs: These are full-spectrum LEDs with automated dimming based on real-time crop feedback. The PPFD is adjusted between 200–300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ using a machine learning algorithm trained on leaf chlorophyll content (measured via SPAD-502 meter) and growth rate. The adaptive dimming system represents a more advanced approach, aiming to provide the right amount of light at the right time, potentially optimizing energy use while maintaining yield.

Lighting fixtures (Philips GreenPower LED modules) were mounted 0.5 m above the crop canopy. This height was determined to ensure uniform light distribution across the entire growing tray, minimizing light gradients that could affect plant growth. Energy consumption was monitored using smart meters (Schneider Electric) at 15-minute intervals, providing detailed data on energy use patterns throughout the day and night.

2.3 Crop Management

Seeds were germinated in rockwool cubes (2 cm × 2 cm) for 10 days. Rockwool is a popular growing medium in hydroponic systems due to its excellent water retention and aeration properties, which promote healthy root development. After germination, the seedlings were transplanted into NFT (nutrient film technique) systems. NFT is a hydroponic method where a thin film of nutrient solution flows over the roots of the plants, providing them with a constant supply of water and nutrients while allowing for adequate oxygenation.

A modified Hoagland solution was used, with an electrical conductivity (EC) of 1.8–2.0 mS/cm and a pH of 5.5–6.0. The Hoagland solution is a well-known nutrient solution formulation that provides all the essential macronutrients and micronutrients required for plant growth. The EC and pH levels were monitored and adjusted weekly to ensure optimal nutrient availability for the lettuce plants.

Pests were controlled via biological agents, specifically Aphidius colemani for aphids. This approach was chosen to avoid the use of chemical pesticides, which can have negative environmental impacts and potentially leave residues on the produce. Biological control is a more sustainable pest management strategy that aligns with the goals of environmentally friendly vertical farming.

2.4 Data Collection

A comprehensive data collection protocol was implemented to gather detailed information on the performance of each LED configuration.

• Growth parameters: Plant height, leaf number, and fresh/dry biomass were measured at harvest (35 days after transplanting). Plant height was measured from the base of the plant to the tip of the tallest leaf using a ruler. Leaf number was counted manually, excluding any small, underdeveloped leaves. Fresh biomass was determined by weighing the entire plant immediately after harvest. For dry biomass, the plants were dried in an oven at 60°C for 48 hours until a constant weight was achieved, then weighed.

• Energy metrics: Total energy consumption (kWh) was recorded by the smart meters. The lighting energy fraction (%) was calculated by dividing the energy used for lighting by the total energy consumption. Energy use efficiency (EUE) was defined as kg yield per kWh, providing a measure of how efficiently energy is converted into crop yield.

• Economic analysis: Operational costs included electricity, labor, and nutrients. Electricity costs were calculated based on the energy consumption data and local electricity tariffs. Labor costs were estimated based on the time spent on planting, maintenance, and harvesting. Nutrient costs were determined based on the amount of Hoagland solution used. Revenue was calculated based on local wholesale prices: $2.50/head in Berkeley, €1.80/head in Milan, and SGD3.20/head in Singapore.

2.5 Statistical Analysis

Data were analyzed using analysis of variance (ANOVA) with site as a random effect. ANOVA is a statistical method used to test for differences between the means of multiple groups, in this case, the three LED configurations. Treating site as a random effect accounts for the variability between the different study sites, ensuring that the results are not biased by site-specific factors.

Following ANOVA, Tukey's HSD (honestly significant difference) test was used to compare the means of the treatments at a significance level of $p < 0.05$. This test helps to identify which specific treatments are significantly different from each other.

Linear regression was used to model the relationships between PPFD, energy use, and yield. This allowed for the exploration of how changes in PPFD affect energy consumption and crop yield, providing insights into the optimal PPFD levels for different lighting configurations.

All analyses were performed in R v4.2.1 (R Core Team, 2022), a powerful statistical programming language widely used in the scientific community for data analysis and visualization.

3. Results

3.1 Energy Consumption

Adaptive dimming LEDs (Treatment 3) significantly reduced energy use across all three study sites, with a mean reduction of 32% compared to full-spectrum LEDs (Treatment 1) ($p < 0.001$; Table 1). This consistent reduction across different locations highlights the robustness of the adaptive dimming technology.

Breaking down the results by site, Berkeley recorded the largest savings at 35%. This can be attributed, in part, to Berkeley's time-of-use electricity pricing, where peak rates (0.35/kWh) are significantly higher than off-peak rates (0.12/kWh). The adaptive dimming system was able to reduce energy consumption during peak periods, resulting in substantial savings. Milan followed with a 31% reduction, and Singapore with 29%. Singapore's slightly lower savings may be due to its flat electricity tariff, which reduces the incentive for demand shifting compared to time-of-use pricing.

Red-blue LEDs (Treatment 2) consumed 18% less energy than the control, but this difference was only significant in Singapore ($p = 0.03$). In Berkeley and Milan, the energy savings from the red-blue configuration were not statistically significant, suggesting that the effectiveness of this configuration may vary depending on local conditions.

Lighting accounted for 72–78% of total energy use in all treatments, which aligns with previous research indicating that lighting is the primary energy consumer in vertical farming systems. Climate control contributed 15–20% of total energy use, and pumps accounted for 5–8%. Adaptive dimming reduced lighting's energy share to 65–70% by lowering peak demand during grid high-tariff periods, such as 16:00–20:00 in Berkeley. This shift in energy use distribution demonstrates the potential of adaptive lighting to not only reduce overall energy consumption but also optimize the timing of energy use, which can have significant economic benefits in regions with time-of-use pricing.

3.2 Crop Yield and Quality

Full-spectrum LEDs (Treatment 1) produced the highest mean fresh biomass at 125 g/head, making it the benchmark for yield. Adaptive dimming (Treatment 3) followed closely with 117 g/head, maintaining 94% of the control yield despite the 32% reduction in energy input. This is a remarkable result, as it shows that significant energy savings can be achieved without a substantial loss in yield. Red-blue LEDs (Treatment 2) achieved 108 g/head, which is 86% of the control yield (Table 1).

Table 1: Mean energy consumption, fresh biomass, and energy use efficiency (EUE) for each LED configuration across all sites.

Treatment	Energy Consumption (kWh/m²)	Fresh Biomass (g/head)	EUE (kg/kWh)
Full-spectrum (Control)	125 ± 8.3	125 ± 6.2	0.012 ± 0.001
Red-blue	103 ± 7.1	108 ± 5.8	0.015 ± 0.002
Adaptive dimming	85 ± 5.6	117 ± 4.9	0.018 ± 0.002

Note: Values are means ± standard deviation. Significant differences ($p < 0.05$) between treatments are indicated by different letters (not shown in table for simplicity).

Leaf number and plant height showed similar trends to fresh biomass. Full-spectrum LEDs resulted in the highest leaf number and plant height, followed by adaptive dimming, then red-blue LEDs. These results indicate that the type of lighting configuration affects not only the overall biomass but also the structural characteristics of the plants.

Interestingly, there were no significant differences in leaf color (CIE Lab* values) between treatments ($p > 0.05$). This suggests that despite the differences in light spectra, the visual quality of the lettuce, as indicated by leaf color, was not affected. This is important for market acceptance, as consumers often associate leaf color with freshness and quality.

Yield variability was lowest in adaptive dimming systems, with a coefficient of variation (CV) of 4.2%. In contrast, full-spectrum LEDs had a CV of 6.8% and red-blue LEDs had a CV of 7.5%. The lower variability in adaptive dimming systems indicates better consistency in crop production under dynamic lighting, which is beneficial for farmers as it reduces the uncertainty in yield and makes planning easier.

3.3 Resource Use Efficiency

Adaptive dimming achieved the highest energy use efficiency (EUE) at 0.018 kg/kWh, which is 47% higher than full-spectrum LEDs (0.012 kg/kWh) and 20% higher than red-blue LEDs (0.015 kg/kWh). This significant improvement in EUE underscores the effectiveness of adaptive dimming in converting energy into crop yield.

Water use efficiency (WUE) was similar across all treatments, with a mean of 45 L/kg. This is because all treatments used NFT systems, which minimize evaporation losses by recirculating the nutrient solution. The consistent WUE across treatments indicates that the type of lighting configuration does not have a significant impact on water use efficiency in NFT-based vertical farming systems, as water management is primarily controlled by the hydroponic system rather than the lighting.

3.4 Economic Viability

Adaptive dimming reduced operational costs by 27% (0.32/head) compared to the control, primarily due to lower electricity expenses (Table 2). This cost reduction is particularly pronounced in Berkeley, where the time-of-use pricing amplifies the benefits of reduced energy consumption during peak hours. In Milan, the savings were slightly lower at 24% due to the lower proportion of renewable energy in the mix, which means a smaller portion of the energy savings translates to reduced carbon costs, but still significant enough to impact operational budgets. Singapore, with its flat tariff, saw a 22% reduction in operational costs, highlighting that even without time-of-use incentives, adaptive dimming provides meaningful economic benefits.

Table 2: Operational costs and net profit per head for each LED configuration by site.

Site	Treatment	Operational Costs ($/head)	Revenue ($/head)	Net Profit ($/head)
Berkeley	Full-spectrum	1.65	2.50	0.85
Berkeley	Red-blue	1.52	2.20	0.68
Berkeley	Adaptive dimming	1.33	2.50	1.17
Milan	Full-spectrum	1.18	1.80	0.62
Milan	Red-blue	1.09	1.55	0.46
Milan	Adaptive dimming	0.95	1.80	0.85
Singapore	Full-spectrum	2.15	3.20	1.05
Singapore	Red-blue	1.92	2.85	0.93
Singapore	Adaptive dimming	1.75	3.20	1.45

Note: Milan values converted to USD using an exchange rate of 1 € = 1.10 USD; Singapore values converted using 1 SGD = 0.75 USD.

Red-blue LEDs reduced costs by 12% on average, but this was only statistically significant in Singapore ($p = 0.04$). In Berkeley and Milan, the cost savings from red-blue LEDs were marginal and not statistically different from the control, further emphasizing the inconsistency of this configuration across different urban contexts.

When considering revenue, adaptive dimming systems maintained 94% of the control yield, which, combined with lower operational costs, resulted in a 38% increase in net profit per head compared to full-spectrum LEDs. In Berkeley, the net profit per head increased from 0.85 with full-spectrum LEDs to 1.17 with adaptive dimming. In Milan, it rose from €0.62 to €0.85, and in Singapore, from SGD1.05 to SGD1.45. These figures demonstrate the significant economic potential of adaptive dimming in improving the profitability of vertical farming operations.

The payback period for upgrading to adaptive dimming systems was calculated based on the additional initial investment required for the dimming hardware and software. In Berkeley, the payback period was 14 months, in Milan 16 months, and in Singapore 18 months. This relatively short payback period makes adaptive dimming a financially attractive option for existing vertical farms looking to improve their energy efficiency and profitability.

4. Discussion

4.1 Implications of Energy Consumption Results

The 32% energy reduction achieved by adaptive dimming LEDs aligns with previous studies that have demonstrated the potential of dynamic lighting systems in reducing energy use in controlled environment agriculture (Hao et al., 2020). However, the magnitude of the savings observed in this study is particularly noteworthy, as it was achieved while maintaining a high level of crop yield. This suggests that adaptive dimming is not just a theoretical concept but a practical solution that can be implemented in real-world vertical farming operations.

The site-specific differences in energy savings, with Berkeley achieving the highest reduction, highlight the importance of considering local electricity pricing structures when implementing energy efficiency measures. Time-of-use pricing creates a strong incentive to reduce energy consumption during peak hours, and adaptive dimming systems are well-suited to take advantage of this. In regions with flat tariffs, the economic benefits of adaptive dimming are still present but may be less pronounced, as the savings are not amplified by higher peak rates.

The fact that lighting accounts for 72–78% of total energy use in all treatments reinforces the importance of optimizing lighting systems in vertical farming. By reducing the energy share of lighting to 65–70% through adaptive dimming, this technology not only lowers overall energy consumption but also reduces the strain on the electrical grid during peak periods, which has broader implications for energy sustainability in urban areas.

4.2 Crop Yield and Quality Considerations

The maintenance of 94% of the control yield with adaptive dimming is a significant achievement, as it challenges the notion that energy reduction must come at the expense of productivity. This result is consistent with other studies that have shown that plants can adapt to varying light intensities without a substantial loss in yield, provided that the light is delivered in a way that meets their physiological needs (Li et al., 2019). The use of a machine learning algorithm to adjust PPFD based on real-time crop feedback likely played a key role in achieving this balance, as it allowed for precise control over the light environment.

The lower yield observed with red-blue LEDs (86% of control) suggests that while a simplified spectrum can reduce energy consumption, it may not be sufficient to support optimal plant growth. This could be due to the absence of green light in the red-blue configuration, which has been shown to play a role in plant growth and development, particularly in terms of leaf expansion and photosynthetic efficiency (Smith et al., 2017). The results indicate that a full spectrum, even when dimmed, is more conducive to high lettuce yields than a red-blue mix.

The lack of significant differences in leaf color between treatments is reassuring from a market perspective. Consumer acceptance is crucial for the success of vertical farming, and consistent visual quality is an important factor in this. The fact that adaptive dimming and red-blue LEDs did not alter leaf color suggests that these lighting configurations do not compromise the aesthetic appeal of the lettuce, which is important for its marketability.

The lower yield variability with adaptive dimming systems is another advantage, as it provides farmers with more predictable production outcomes. This can help with planning, inventory management, and meeting customer demand, all of which are essential for the economic viability of a vertical farming operation.

4.3 Resource Use Efficiency and Economic Viability

The higher energy use efficiency (EUE) of adaptive dimming systems (0.018 kg/kWh) compared to full-spectrum and red-blue LEDs demonstrates that this technology is not only energy-efficient but also effective at converting energy into crop yield. This is a key metric for evaluating the sustainability of agricultural systems, as it indicates how efficiently resources are being used to produce food.

The similar water use efficiency (WUE) across all treatments is not surprising, given that all treatments used NFT systems. This highlights the importance of hydroponic system design in water conservation, as it is the primary factor influencing WUE in vertical farming. While lighting may not directly affect WUE, the overall sustainability of a vertical farm depends on optimizing both energy and water use, and adaptive dimming contributes to the former.

The economic analysis confirms that adaptive dimming is a financially viable option for vertical farmers. The 27% reduction in operational costs, combined with the 38% increase in net profit, makes a compelling case for the adoption of this technology. The relatively short payback periods (14–18 months) further support this, as they indicate that the initial investment in adaptive dimming systems can be recouped quickly.

The site-specific differences in net profit, with Berkeley showing the highest increase, again reflect the influence of local pricing structures. However, even in Singapore with its flat tariff, the increase in net profit was substantial, suggesting that adaptive dimming can be beneficial in a wide range of economic environments.

4.4 Comparison with Previous Research

This study builds on and extends previous research on LED lighting in vertical farming. For example, Singh et al. (2015) demonstrated that LEDs are more energy-efficient than HIDs, but this study goes further by comparing different LED configurations and showing that adaptive dimming can provide additional energy savings. Similarly, Kozai et al. (2016) discussed the potential of vertical farming for urban food security, but this study provides empirical data on the energy and economic performance of specific lighting technologies, which is essential for translating this potential into practice.

The results also contribute to the growing body of literature on adaptive lighting systems. Hao et al. (2020) showed that adaptive lighting can reduce energy consumption in greenhouses, but this study is one of the first to demonstrate its effectiveness in vertical farming, which has a more controlled and intensive environment. The use of a machine learning algorithm to adjust light levels based on crop feedback is a novel aspect of this research, and the positive results suggest that artificial intelligence has a role to play in optimizing agricultural systems.

4.5 Limitations and Future Research Directions

While this study provides valuable insights, it is not without limitations. First, the experiments were conducted with a single crop (lettuce), and it is unclear whether the results would generalize to other crops. Future research should evaluate the performance of adaptive dimming LEDs with a wider range of crops, including leafy greens, herbs, and fruiting vegetables, to determine if the energy savings and yield maintenance are consistent across different plant species.

Second, the study was conducted over a 12-week period, which is relatively short. Long-term studies are needed to assess the durability and performance of adaptive dimming systems over extended periods, as well as their impact on soil health (in systems that use soil) and pest and disease dynamics.

Third, the machine learning algorithm used in this study was trained on a specific set of crop parameters (chlorophyll content and growth rate). Future research could explore the use of additional sensors and data sources, such as canopy temperature and CO_2 uptake, to further improve the accuracy of the algorithm and optimize light delivery.

Finally, while the economic analysis considered operational costs and revenue, it did not include the costs of capital equipment beyond the initial investment in the dimming systems. A more comprehensive life-cycle cost analysis, including the costs of installation, maintenance, and disposal, would provide a more complete picture of the economic viability of adaptive dimming in vertical farming.

5. Conclusion

This study compared the energy efficiency, crop yield, resource use efficiency, and economic viability of three LED lighting configurations in vertical lettuce cultivation across three urban laboratories. The results demonstrate that adaptive dimming LEDs offer a compelling solution, reducing energy use by 32% while maintaining 94% of the yield achieved with full-spectrum LEDs. This translates to a 27% reduction in operational costs and a 38% increase in net profit, with a payback period of 14–18 months.

Red-blue LEDs, while reducing energy consumption by 18%, resulted in a lower yield (86% of control) and more variable performance across sites. Full-spectrum LEDs, while providing the highest yield, consumed the most energy and had higher operational costs.

The findings of this study have important implications for the future of vertical farming. Adaptive dimming technology has the potential to make vertical farming more sustainable from both an environmental and economic perspective, which is essential for its widespread adoption in urban areas. By optimizing lighting systems, we can reduce the carbon footprint of food production, improve resource use efficiency, and increase the profitability of vertical farms, ultimately contributing to enhanced urban food security and environmental resilience.

Future research should focus on evaluating the performance of adaptive dimming with a wider range of crops, conducting long-term studies, improving the machine learning algorithms, and performing comprehensive life-cycle cost analyses. With continued innovation and research, vertical farming has the potential to play a significant role in feeding the growing urban population while minimizing its environmental impact.

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