ICPA
17th INTERNATIONAL CONFERENCE ON PRECISION AGRICULTURE
ConBAP 2026
CONGRESSO BRASILEIRO DE AGRICULTURA DE PRECISÃO E DIGITAL
13-16 July 2026 | Porto Alegre, Brazil
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COMPARATIVE ANALYSIS OF TECHNICAL AND ECONOMIC FEASIBILITY OF PEPPER (*CAPSICUM ANNUUM*) CULTIVATION UNDER ARTIFICIAL LIGHTING VS. PROTECTED ENVIRONMENT

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A paper from the Proceedings of the

17th International Conference on Precision Agriculture and 11th Brazilian Congress on Precision and Digital Agriculture

13-15 July 2026

Porto Alegre, Brazil

Abstract.

Contemporary agriculture is undergoing a technological disruption marked by the transition from natural biological dependence to an industrial precision science. At the heart of this shift, the cultivation of pepper (Capsicum annuum) in Controlled Environment Agriculture (CEA) settings utilizes artificial lighting to transform electromagnetic radiation into a programmable input, eliminating solar variability. This study conducted a comparative technical and economic feasibility analysis between conventional greenhouse cultivation (T_0) and a fully LED-controlled system (T_1), simulating a 500 m² unit in Minas Gerais, Brazil. The methodology employed deterministic modeling and a completely randomized design. The T1 system utilized state-of-the-art Full Spectrum LED fixtures (3.0 µmol/J), with optimized Daily Light Integral (DLI) for the vegetative and reproductive stages. The initial investment for the indoor system was estimated at R$ 750,000.00, a value five times higher than that of the conventional greenhouse (R$ 150,000.00). The cost analysis focused specifically on the Energy Operational Expenditure (OpEx), considering the demand from the fixtures and the thermal load of the climate control system required to neutralize sensible heat and evapotranspiration. Results demonstrated that the T_1 system achieves an indisputable biological superiority, with an 80% increase in annual yield (14,850 kg compared to 8,250 kg in T_0). This performance is attributed to light stability and spectral precision, which maintains the photosynthetic rate at its theoretical maximum. However, the energy cost in T_1 proved to be a monumental obstacle, totaling R$ 106,857.90 per year — a value 1,627% higher than the conventional system. In the CEA model, approximately 45% of the gross revenue is consumed by the electricity bill, whereas in the greenhouse, this impact is less than 10%. Consequently, the Return on Investment (ROI) for the indoor system (11.3%) was lower than that of the greenhouse (21.6%) under current electricity tariffs. The payback period for the controlled environment was estimated at 8.8 years. The feasibility of the T_1 system depends critically on a premium sales price (R$ 16.00/kg), justified by pharmaceutical-grade standardization and the absence of chemical residues. It is concluded that investment in LED technology is favorable only if production stability absorbs the risk of high OpEx, making the integration of on-site photovoltaic generation imperative to reduce tariff dependence and maximize profitability in Minas Gerais.

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Keywords.
Controlled Environment Agriculture (CEA); LED Lighting; Economic Feasibility; Precision Agriculture; Energy OpEx.

1. INTRODUCTION

Modern agriculture is experiencing a technological disruption: the transition from natural biological dependence to an industrial precision science. At the center of this shift, indoor artificial lighting eliminates solar variability a historically uncontrollable variable transforming electromagnetic radiation into a programmable input. Technologies such as LEDs and HID lamps provide the essential Photosynthetically Active Radiation (PAR). Unlike the human eye, which is sensitive to lumens, plants process photons; thus, Photosynthetic Photon Flux Density (PPFD) becomes the core metric to ensure a consistent energy supply (Bugbee, 2016).

The scientific interest lies in the manipulation of controlled photomorphogenesis. Through the electromagnetic spectrum, plant morphology is dictated: blue light (400-500 nm) induces vegetative robustness, while red light (600-700 nm) signals flowering (Gupta; Agarwal, 2021). Beyond physical growth, "light recipes" and UV radiation allow for the alteration of the plant's internal chemistry, boosting secondary metabolites such as antioxidants and terpenes (Mattos et al., 2020). This results in a chemically standardized end product, something unachievable under the variable solar spectrum of the open field.

This evolution responds to global pressures such as accelerated urbanization, scarcity of arable land, and climate change. Investors see artificial lighting as the key to urban food security and the rise of Controlled Environment Agriculture (CEA) (Kozai; Niu; Takagaki, 2015). This model enables cultivation within metropolises, reducing waste and the logistical carbon footprint. Consequently, the horticultural lighting market is growing rapidly, driven by the demand for "clean" products and pharmaceutical standardization.

However, the sector faces a monumental obstacle: high energy costs. Lighting is the largest component of operational expenditure (OpEx), frequently surpassing labor costs. Although LEDs achieve efficacies exceeding 3.0 µmol/J (Bugbee, 2016), the electrical load required to reach the Daily Light Integral (DLI) in high-performance crops remains massive. This scenario demands that engineering maximizes photon delivery per Watt to guarantee both the environmental and financial sustainability of the projects.

Given this challenge, economic feasibility studies comparing production with and without artificial lighting become imperative. While sunlight has zero cost, its intermittency limits predictability. Conversely, artificial light offers absolute control but requires an investment that can render low-value crops non-viable. This justifies the analysis of Return on Investment (ROI) and energy efficiency (g/kWh) to validate the business model (Kim et al., 2023).

In short, artificial lighting is a tool of sovereignty that transforms the plant into a programmable *biofactory*. This work seeks to bridge the gap between the biological potential of photomorphogenesis and the reality of energy costs, evaluating whether the qualitative and productive increase justifies the exclusion of sunlight in modern industrial agriculture. In light of this scenario, the objective of this work was to simulate and compare the productive performance and economic viability of sweet pepper cultivation in a fully controlled environment versus a conventional greenhouse, quantifying the trade-off between biological gain and energy cost.

2. MATERIAL AND METHODS

2.1. Experimental Design and Study Unit

The study is based on deterministic modeling for sweet pepper (*Capsicum annuum*) cultivation, simulating a unit with an effective production area of 500 m². The experimental design is completely randomized (CRD), comparing two production systems:

- T_0 (Control): A conventional greenhouse (gothic-arch model, galvanized steel) equipped with a 200-micron diffusing plastic film and passive climate control.

- T_1 (Treatment): A Controlled Environment Agriculture (CEA) indoor facility, thermally insulated with polyurethane panels and 100% artificial lighting (Horticultural Full Spectrum).

The adopted planting density is 3.0 plants/m², totaling 1,500 plants per system, grown using fertigation in an inert substrate.

2.2. Lighting System Specification (T_1)

For the indoor system, the use of state-of-the-art horticultural LED fixtures with a photon efficacy of 3.0 μmol/J will be simulated. The lighting design aims to provide an optimized Daily Light Integral (DLI):

- Vegetative Phase: PPFD of 450 μmol/m²/s (18-hour photoperiod).

- Reproductive Phase: PPFD of 750 μmol/m²/s (12-hour photoperiod).

- Spectrum: Full Spectrum with peaks in the blue (450 nm) and deep red (660 nm) regions to maximize photomorphogenesis.

2.3. Cost Modeling (Capital and Operational Expenditure)

Economic viability will be measured by comparing implementation costs and large-scale operational costs.

2.3.1. Capital Expenditure (CapEx):

- T_0: Estimated at R$ 150,000.00 (R$ 300/m²), comprising the steel structure and basic irrigation automation, located in Minas Gerais, Brazil.

- T_1: Estimated at R$ 750,000.00 (R$ 1,500/m²), where the LED lighting represents 60% of the cost and the HVAC (climate control) system accounts for 20%, located in Minas Gerais, Brazil.

2.3.2. Operational Expenditure for Energy (OpEx):

The total energy consumption (E_{total}) will be quantified by the power demand of the lighting fixtures (Watt) (P_L) added to the thermal load of the air conditioning system (Watt) (P_{AC}), which is required to neutralize the sensible heat generated by the LEDs and the evapotranspiration (Graamans et al., 2018):

$$E_{total}\,(\mathrm{kwh}) = \sum \frac{P_L + P_{AC}}{1000} \times t \qquad (1)$$

where t = time (h).

2.4. Quantitative Analysis and Efficiency

Yield will be estimated via Radiation Use Efficiency (RUE), assuming a harvest index of 0.65. The production differential will be evaluated using the Photon Efficiency Break-Even Point, determining the yield increase required in T1 to offset the marginal cost of electricity.

2.5. Statistical Procedures

The simulated data from five consecutive cycles will be subjected to:

- Student's t-test: To compare the means of yield (kg/m²) and dry mass between T_0 and T_1 ($\alpha = 0.05$).

- Sensitivity Analysis: A Monte Carlo simulation to evaluate the impact of fluctuations in electricity tariffs (R$/kWh) and fruit market prices on the Return on Investment (ROI).

- Payback Period Calculation: The estimated time required to recover the investment in both scenarios.

3. RESULTS AND DISCUSSION

Below, we present the consolidated data comparing the productive and financial performance between the conventional greenhouse system (T_0) and the indoor LED system (T_1).

Table 1. Comparative Analysis of Productive and Financial Indicators

Indicator	T_0 (Greenhouse)	T_1 (Indoor LED)	Difference (%)
Annual Yield (kg)	8,250	14,850	+80.0%
Annual Energy Cost (R$)	R$6,186.51	R$106,857.90	+1.627%
Average Market Price (R$/kg)	R$8.00	R$16.00	+100.0%
Annual Gross Revenue (R$)	R$66,000.00	R$237,600.00	+260.0%
Annual Net Operational Profit	R$ 32,400.00	R$84,742.10	+161.5%
Capital Expenditure (CapEx)	R$150,000.00	R$750,000.00	+400.0%
Return on Investment (ROI)	21.6%	11.3%	-10.3 p.p.
Payback Period (years)	4.6	8.8	+91.3%

3.1. Biological Efficiency vs. Environmental Control and Sovereignty Costs

The simulation confirms that the T_1 (Indoor) treatment achieves an indisputable biological superiority, with an 80% increase in yield. This results from the stability of the DLI and spectral precision (peaks at 450 nm and 660 nm), which maintain the photosynthetic rate at its theoretical maximum without the drops in solar radiation common in Minas Gerais (MG) due to cloud cover or seasonality.

However, the annual energy cost of R$ 106,857.90 reveals the heavy burden of "artificial sunlight." At an electricity tariff of 0.93735 R$/kWh, electricity ceases to be a secondary input and becomes the project's largest cash drain. In T1, for every R$ 1.00 of revenue, approximately R$ 0.45 is consumed solely by the electricity bill (45%), whereas in T0 this value is under R$ 0.10 (10%). This high-consumption scenario for sustaining the microclimate and lighting reflects the logistical and energy resource bottlenecks already mapped out by Graamans et al. (2018).

3.2. ROI and Payback Analysis under the Minas Gerais Tariff

The 11.3% ROI in the Indoor system is positive but lower than that of the greenhouse system (21.6%). This occurs because, although the absolute profit is higher in the Indoor system (R$ 84,000.00 vs. R$ 32,000.00), the initial investment of R$ 750,000.00 is highly capital-intensive. The 8.8-year payback period for the indoor system is within the useful lifespan of the LEDs (>10 years), but it is considered a slow return for the fresh produce sector, which demands high liquidity.

3.3. Quality and Value-Added: The Viability Factor

The viability of T1 depends critically on the premise that indoor sweet peppers will be sold at R$ 16.00/kg (approximately double the greenhouse price). This pricing is justified by the absence of chemical residues, extreme visual standardization, and guaranteed supply during scarcity windows, allowing the producer to capture market niches willing to absorb this price premium (Gupta; Agarwal, 2021). Without this price premium, the T1 system would exhibit a negative ROI under the simulated energy tariff. Physiologically, sweet peppers cultivated under the exact balance provided by the lighting fixtures achieve a high, homogenous commercial standard, which is validated by controlled-spectrum experiments in indoor environments (Claypool; Lieth, 2018; Zhang et al., 2024).

3.4. Viability Conclusion: Is the Investment Worth It?

The investment is justifiable under specific conditions:

- Food Security and Logistics**:** If the project is established in dense urban centers where transportation costs are drastically reduced and there is a high demand for pesticide-free products.

- Energy Mitigation**:** To render the project fully viable in Minas Gerais, it is imperative to couple it with a Photovoltaic Solar Generation system. Reducing reliance on the heavy 0.93 R$/kWh grid tariff would transform the indoor system's ROI, shortening the payback period to approximately 4 to 5 years an energy integration strategy considered vital by Silva, Santos, and Souza (2023) to make vertical farming and CEA systems viable within the Brazilian energy market.

4. CONCLUSION

The study concludes that the transition to the indoor system (T_1) guarantees productive sovereignty, providing an 80% increase in the annual yield of sweet peppers through spectral control. However, the energy cost under the tariff of R$ 0.93735/kWh poses a severe challenge, being 17 times higher than that of the conventional greenhouse system (T_0). Although T_1 generates superior quality fruits with higher market value (R$ 16.00/kg), the high initial capital investment of R$ 750,000.00 results in an ROI of 11.3% and a payback period of 8.8 years.

Comparatively, the greenhouse (T_0) presents a faster return (4.6 years), despite its vulnerability to seasonality. Investing in a state-of-the-art LED system pays off strategically for high-value-added markets, but its full viability depends on mitigating electrical costs, preferably through on-site renewable generation. Thus, the trade-off favors the technology only if productive stability and "pharmaceutical-grade" quality can absorb the financial risk of high energy OpEx.

ACKNOWLEDGEMENTS

The authors thank FAPEMIG (Fundação de Amparo à Pesquisa do Estado de Minas Gerais) for the financial support for the project (Grant PPE-00095-23) and for providing the research fellowships (Grant BIP-00150-23), and EPAMIG ITAP for the support in conducting the research.

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