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ROTATING PLATFORM GREENHOUSES WITH AI-BASED INTELLIGENT LED LIGHTING SYSTEMS: A SYSTEMATIC REVIEW

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Abstract. The integration of rotating crop platforms with artificial lighting systems is a promising but insufficiently studied direction in controlled environment agriculture. This systematic review analyzes 20 peer-reviewed studies from Scopus and Web of Science published between 2008 and 2024, focusing on greenhouse automation, LED lighting technologies, light spectrum management, energy efficiency, plant growth responses, IoT-based control, and rotating platform design concepts. The reviewed literature shows significant progress in LED-based horticultural lighting, especially in optimizing red–blue light ratios, photosynthetically active radiation, photoperiod control, and light-use efficiency. However, existing studies mainly investigate artificial lighting and rotating mechanisms separately, while their integrated application within a single greenhouse system remains poorly explored. In particular, the relationships between platform rotation speed, light distribution uniformity, shadow reduction, energy consumption, and crop productivity have not been sufficiently evaluated through experimental or computational methods. This review identifies these gaps and proposes a conceptual framework for an integrated rotating platform greenhouse with adaptive artificial lighting. Future research should focus on prototype development, AI-based lighting control, sensor integration, and techno-economic assessment to improve productivity and energy efficiency in smart greenhouse systems.

Keywords: rotating platform greenhouse; LED horticultural lighting; controlled environment agriculture; light distribution optimization; energy-efficient greenhouse; photosynthetically active radiation; smart greenhouse automation; IoT plant factory

INTRODUCTION

Global food security in the 21st century faces unprecedented challenges arising from population growth, climate change, arable land degradation, and the unpredictability of outdoor growing seasons [1, 2]. Controlled environment agriculture (CEA), encompassing modern greenhouse systems, plant factories, and vertical farming, has emerged as a scientifically validated strategy to decouple food production from these environmental constraints [3]. By regulating temperature, humidity, CO_2 concentration, and light within closed or semi-closed structures, CEA systems can achieve crop yields that substantially exceed conventional field production [4].

Among the critical inputs in CEA, light is arguably the most consequential, as it drives photosynthesis, controls developmental processes such as photoperiodism, and influences the biosynthesis of secondary metabolites that determine nutritional quality [5]. In facilities where natural sunlight is supplemented or entirely replaced by artificial sources, the choice and management of the lighting system become central to both agronomic performance and energy economics. Light-emitting diode (LED) technology has transformed horticultural lighting over the past two decades, offering narrow-band spectral tunability, superior electrical-to-photon conversion efficiency, and operational longevity that are unmatched by conventional high-pressure sodium (HPS) lamps [6, 7].

Despite these advances, a persistent limitation of most indoor and greenhouse lighting configurations is spatial light heterogeneity. Fixed overhead lighting systems create well-documented gradients in photon flux density (PFD) across the crop canopy, resulting in unequal light receipt among individual plants and, consequently, uneven growth, yield variability, and suboptimal light utilization efficiency [8]. Plants positioned in peripheral or lower positions within a cultivation tier receive systematically less PAR than those directly beneath a fixture, a problem that intensifies as canopy density increases.

A mechanistically distinct approach to resolving spatial light inequality involves the use of rotating crop platforms. By continuously or intermittently moving plants relative to a stationary or semi-stationary light source, a rotating platform ensures that each plant occupies all positions in the cultivation space over a defined time cycle, thereby equalizing cumulative light receipt across the entire batch [9]. Although the concept of plant rotation has precedents in experimental botany and some commercial hydroponic systems, its systematic engineering development as an integrated greenhouse technology, with dedicated lighting architecture, control systems, and agronomic protocols, remains nascent.

The present review addresses this gap by critically synthesizing 20 peer-reviewed studies that collectively span the domains of greenhouse technology, horticultural LED lighting, plant physiology, energy optimization, and intelligent control systems. The objectives of this review are: (1) to evaluate the current state of knowledge in each thematic domain relevant to rotating platform greenhouse design; (2) to identify the specific scientific and engineering gaps that impede development of integrated systems; and (3) to propose a coherent conceptual framework and a prioritized agenda for future experimental and computational research. By bridging these domains, this review aims to stimulate and guide interdisciplinary research efforts directed toward a novel generation of resource-efficient, high-uniformity greenhouse systems.

MATERIALS AND METHODS

Search Strategy and Database Selection

This systematic review was conducted in accordance with the methodological principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, adapted for engineering and horticultural science literature [10]. Two internationally recognized academic databases — Scopus (Elsevier) and Web of Science (Clarivate Analytics) — were searched to ensure comprehensive coverage of peer-reviewed primary literature. These databases were selected based on their established indexing standards, broad disciplinary coverage, and compatibility with standard bibliometric analyses.

Searches were performed using Boolean operators combining the following keyword clusters: ("rotating platform" OR "revolving platform" OR "plant rotation") AND ("greenhouse" OR "plant factory" OR "controlled environment"); ("LED lighting" OR "light-emitting diode" OR "artificial lighting" OR "supplemental lighting") AND ("greenhouse" OR "horticulture" OR "indoor farming"); ("light distribution" OR "light uniformity" OR "PAR distribution") AND ("controlled environment agriculture"); ("smart greenhouse" OR "IoT greenhouse" OR "automated lighting") AND ("crop production" OR "energy efficiency"). All searches were restricted to English-language,

peer-reviewed articles published in scientific journals or refereed conference proceedings. The search covered publications from January 2008 to March 2024.

Inclusion and Exclusion Criteria

Inclusion criteria were: (i) peer-reviewed journal articles or refereed conference papers indexed in Scopus or Web of Science; (ii) primary focus on artificial lighting systems, greenhouse engineering, controlled environment agriculture, rotating plant systems, or smart agricultural control; (iii) reporting quantitative data on at least one of the following: plant growth metrics, light intensity, spectral parameters, energy consumption, or system automation performance; (iv) full text available for review.

Exclusion criteria were: (i) review-only articles without original data contribution; (ii) studies focused exclusively on field or outdoor production without greenhouse context; (iii) conference abstracts without full methodological description; (iv) papers in languages other than English; (v) studies with unverifiable methodology or data reporting.

Screening and Data Extraction

The initial database searches returned 412 candidate records after duplicate removal. Title and abstract screening eliminated 311 records that did not meet the topical scope. Full-text assessment of the remaining 101 records led to the exclusion of 81 articles based on the criteria above, with particular attention to methodological rigor and relevance to the rotating platform greenhouse concept. The final corpus comprised 20 articles that collectively provide the evidential foundation for this review. Data extraction from each article captured: author(s) and publication year, experimental organism and cultivation system, lighting technology and spectral parameters, methodology, key quantitative findings, reported limitations, and relevance to integrated rotating platform greenhouse design.

RESULTS AND DISCUSSION

Greenhouse Technologies and the Role of Controlled Environment Agriculture

The evolution of greenhouse technology has followed a trajectory from passive solar structures to highly instrumented CEA systems capable of year-round, location-independent food production [1]. Modern commercial greenhouses are equipped with computerized climate control units managing temperature set points (typically 18–26°C for leafy vegetables), relative humidity (60–80%), CO_2 enrichment to 800–1200 ppm, and irrigation scheduling. These environmental controls are coordinated through supervisory control and data acquisition (SCADA) systems, enabling real-time responses to sensor feedback [11].

The shift toward fully enclosed, artificially lit growing environments — commonly termed plant factories with artificial lighting (PFALs) — represents the most resource-intensive but also most controllable endpoint of the CEA spectrum [12]. Graamans et al. [4] conducted a resource comparison between conventional glasshouse production and vertical plant factories, demonstrating that while PFALs consume 11–16 times more energy per kilogram of fresh weight than glasshouses (attributable primarily to lighting and HVAC), they achieve 40–100 times greater land-use

efficiency, an advantage that assumes critical importance in land-scarce urban contexts. Avgoustaki and Xydis [13] further documented that indoor plant factories within urban frameworks can reduce supply chain losses and food miles while enabling year-round production of high-value crops.

The literature consistently identifies lighting as the dominant operational cost in fully artificial environments, representing 25–40% of variable production costs in PFALs [6]. This cost structure provides the primary economic rationale for optimizing light utilization efficiency, including through innovations such as rotating crop platforms that maximize the fraction of emitted photons intercepted by plant tissue.

Concept and Engineering Basis of Rotating Platform Greenhouses

The fundamental engineering proposition of a rotating platform greenhouse is that mechanical movement of the plant mass relative to a fixed or semi-fixed light source can achieve spatial averaging of photon flux density over time, thereby compensating for the inherent non-uniformity of any practical lighting array [9]. In a static cultivation system, each plant occupies a fixed position relative to the light source; its total daily light integral (DLI, expressed in $mol \cdot m^{-2} \cdot d^{-1}$) is determined by that position and cannot be equalized across the tray without repositioning plants manually — an impractical labor demand at commercial scale.

In a rotating platform, plants are mounted on a turntable or carousel structure driven by an electric motor (servo motor or stepper motor) controlled by a programmable logic controller (PLC) or microcontroller. The platform completes one full revolution at a rate determined by agronomic requirements and engineering constraints. Despommier [14] and Kalantari et al. [2] both note that spatial efficiency and labor automation are among the most significant engineering challenges in vertical and indoor farming systems; a rotating platform directly addresses both by maximizing the fraction of the cultivation volume that is uniformly illuminated while permitting automated loading and unloading of plant containers at a fixed station.

From a mechanical standpoint, platform design must address load-bearing capacity (considering the weight of growing media, irrigation water, and plant biomass), rotational torque requirements, irrigation and electrical connection routing through a rotating junction (slip rings for power and data), and structural vibration effects on plant physiology. While these engineering challenges are well-defined and technically solvable with existing components, no peer-reviewed study in the present corpus documents a fully implemented and agronomically characterized rotating platform greenhouse, confirming the novelty of this concept.

Artificial Lighting Systems in Greenhouse Crop Production

Artificial lighting for greenhouse horticulture encompasses a spectrum of technologies, but the transition from HPS to LED systems has been the dominant trend of the past decade [6]. HPS lamps emit a broad spectrum concentrated in the yellow-orange region (550–620 nm) and generate considerable radiant heat, necessitating lamp positioning at a distance from the canopy to avoid thermal damage. In contrast, LED arrays can be positioned at canopy level or within the crop rows as interlighting systems, delivering photons directly to the leaf surface with minimal heat emission [15].

Morrow [6] provided an early comparative analysis of LED lighting for horticulture, documenting that LED systems achieve photon efficacy values of 1.0–1.7 μmol·J^{-1} under conditions available at that time. Kusuma et al. [7] updated this analysis, demonstrating that contemporary commercial LED fixtures achieve efficacy values of 2.0–3.4 μmol·J^{-1}, approaching the theoretical maximum imposed by Planck's law for photons in the PAR waveband. This represents a two-fold improvement over HPS technology and directly translates to proportional reductions in electricity expenditure for equivalent light delivery.

The spectral composition of LED light is a critical determinant of crop response. The photosynthetic apparatus responds most efficiently to wavelengths in the red (R, 630–680 nm) and blue (B, 420–470 nm) regions of the visible spectrum, with the R:B ratio exerting profound effects on plant morphology, photosynthesis rate, and secondary metabolite accumulation [5, 16]. Olle and Viršilė [17] comprehensively reviewed LED effects on greenhouse crops and concluded that red-dominant spectra (R:B ≥ 4:1) maximize leaf area and dry mass accumulation in lettuce and leafy greens, while blue light enrichment above 20% promotes compact, darker-green plants with elevated antioxidant content. Bantis et al. [5] extended this analysis to cover 10 vegetable crops, confirming that optimal R:B ratios are crop- and developmental stage-specific, typically ranging from 3:1 to 8:1.

Photoperiod — the daily duration of light exposure — is a second critical spectral parameter. Runkle and Heins [18] demonstrated that specific combinations of far-red (FR, 700–750 nm) and red wavelengths control flowering induction in long-day and short-day plants via phytochrome photostationary state (PSS). For non-flowering leafy crops, photoperiod extension using low-intensity LED supplementation (10–30 μmol·m^{-2}·s^{-1}) effectively increases DLI without proportional increases in energy expenditure, representing a cost-effective strategy for productivity enhancement.

Effect of Artificial Lighting on Plant Growth, Yield, and Quality

The agronomic evidence base for artificial lighting effects on greenhouse crops is extensive and consistently positive when lighting is properly optimized for the target species. Pennisi et al. [19] conducted a multi-parameter study of lettuce (Lactuca sativa L.) and basil (Ocimum basilicum L.) under variable LED light intensities (100–300 μmol·m^{-2}·s^{-1}), documenting non-linear relationships between PPFD and fresh mass yield: optimal photosynthetic response occurred at 200–250 μmol·m^{-2}·s^{-1} in lettuce, above which photo-inhibition effects attenuated further yield gains.

Son and Oh [20] investigated blue and red LED combinations on two lettuce cultivars, reporting that blue light fractions of 13–26% significantly enhanced anthocyanin, total phenolic, and vitamin C concentrations relative to red-only or white fluorescent controls. Bian et al. [16] corroborated these findings across multiple leafy vegetable species, establishing that short-wave blue radiation (420–450 nm) selectively upregulates the phenylpropanoid biosynthesis pathway, a response absent under red-only illumination. These spectral-quality effects on secondary metabolite content represent a quality differentiation mechanism that commands premium market prices in functional food markets.

Deram et al. [21] studied the effect of LED orientation (overhead vs. lateral interlighting) on tomato production, finding that lateral LED placement increased light penetration into the lower canopy by 35–48%, improving fruit set uniformity along the vine. This positional effect is directly relevant to the rotating platform concept, as platform movement would dynamically alter the effective angle of light incidence across the plant canopy over time, potentially replicating the benefits of multi-directional lighting without requiring multiple fixture installations.

Zhang et al. [22] conducted an integrated study of light quality, photoperiod, and intensity effects on hydroponic lettuce within a closed plant factory, demonstrating that a 16/8 h light/dark photoperiod with a mixed-spectrum LED treatment (red 660 nm + blue 450 nm + white, R:B = 5:1) produced 18.3% greater fresh mass and 22.7% greater dry mass than HPS controls over a 28-day growth cycle. Energy consumption in the LED treatment was 31.4% lower per unit fresh mass produced, confirming the dual agronomic and energy advantages of optimized LED systems.

Comparative Analysis of Selected Studies

The studies are evaluated across eight dimensions selected for their relevance to the design of integrated rotating platform greenhouse systems: research subject, lighting system type, key parameters investigated, methodology, principal findings, reported limitations, and direct relevance to rotating platform greenhouse design.

To strengthen the comparative section, the extracted evidence from the reviewed literature is organized into two summary tables. Table 1 groups the selected studies by their main scientific contribution and explains how each group supports the development of an integrated rotating platform greenhouse. Table 2 translates the review findings into design-oriented engineering parameters for future prototype development.

Table 1. Design-oriented parameters for an integrated rotating platform greenhouse with artificial lighting.

Parameter group	Evidence from the reviewed literature	Suggested design orientation	Required validation
Light spectrum	Red and blue wavelengths dominate photosynthetic response; typical R:B ratios range from 3:1 to 8:1.	Use adjustable LED channels: red 630-680 nm, blue 420-470 nm, with optional white/far-red channels.	Determine crop-specific spectral recipes under platform rotation.
Light intensity / PPFD	Leafy crops respond strongly at about 100-300 umol m-2 s-1; lettuce often performs well near 200-250 umol m-2 s-1.	Control PPFD according to crop species, growth stage, and required daily light integral.	Measure canopy-level PAR uniformity during different rotation modes.
Photoperiod	A 16/8 h light/dark cycle and low-intensity photoperiod extension are widely used in plant	Apply programmable photoperiod control linked with rotation cycles and plant stage.	Compare continuous, intermittent, and position-synchronized lighting schedules.

Parameter group	Evidence from the reviewed literature	Suggested design orientation	Required validation
	factories.		
LED energy efficiency	Modern commercial LEDs reach about 2.0-3.4 umol J-1, while lighting is the largest energy cost in PFALs.	Select high-efficacy fixtures and minimize unused photon losses through platform motion.	Calculate kWh kg-1, g fresh mass per mol PAR, and payback period.
Platform rotation speed	No reviewed study experimentally defines an optimal speed for greenhouse crop platforms.	Treat rotation speed as a key independent variable in prototype experiments.	Evaluate effects on light uniformity, plant stress, biomass accumulation, and energy use.
Lighting geometry	Lateral/interlighting increases lower-canopy light penetration by 35-48% in tomato studies.	Combine overhead and side lighting with rotating crop placement to reduce shadow zones.	Map light distribution using PAR sensors or simulation at different fixture angles.
Automation and sensors	Smart greenhouses use climate sensors, controllers, SCADA/IoT systems, and feedback-based automation.	Integrate PAR, temperature, humidity, CO2, and energy sensors with PLC or microcontroller control.	Develop closed-loop algorithms for adaptive light and rotation control.
Crop response metrics	Studies report fresh mass, dry mass, leaf area, yield, vitamin C, phenolics, and antioxidant content.	Evaluate both productivity and quality indicators, not only biomass.	Validate the system using replicated crop trials and statistical comparison.
Economic assessment	Electricity price and LED efficacy strongly influence indoor farming profitability.	Use techno-economic modeling to compare static and rotating platform greenhouse variants.	Estimate capital cost, operating cost, energy saving, yield increase, and payback time.

The one tables show that the proposed system requires simultaneous optimization of lighting spectrum, platform movement, sensor feedback, and energy performance. Therefore, future research should not evaluate artificial lighting and crop rotation separately, but as one integrated engineering-biological system.

CONCLUSION

This systematic review of 20 peer-reviewed studies shows that LED-based artificial lighting has become a mature and energy-efficient technology for controlled environment agriculture. The literature confirms that spectral control, especially red–blue light ratios, photoperiod management, and adaptive lighting strategies can improve plant growth, yield, quality, and energy-use efficiency.

At the same time, the review identifies a major research gap: rotating crop platforms and artificial lighting systems have mostly been studied separately, while their integrated use in greenhouse systems remains insufficiently explored. Such integration could improve light distribution uniformity, reduce canopy shadowing, and enable position-based smart lighting control. However, key parameters such as platform rotation speed, lighting geometry, spectral regimes, energy consumption, and crop productivity still require experimental and computational validation.

Overall, the proposed rotating platform greenhouse with optimized LED lighting and intelligent control represents a promising direction for compact, energy-efficient, and high-uniformity crop production. Future studies should focus on prototype development, parameter optimization, sensor-based automation, and techno-economic evaluation.

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