Grounded Discovery Labs -- Discovery Pack

Discover: Design an LED lighting/control system for vertical farms that materially cuts energy use while maintaining leafy-green yield and quality.

Top 3 Comparison

	Featured Discovery Phytochrome-Clamped End-of-Day FR Lighting	Bold Concept MEMS-Steered Holographic Photon Delivery	Build-First Fab-Style Run-to-Run Light Recipe Control
novelty	6	9	5
feasibility	9	4	9
economic_leverage	6	6	5
testability	9	5	8
robustness	7	3	7
constraint_fit	9	9	9
explainability	9	7	8
OVERALL	**7.9 / 10 -- Very Strong**	**6.1 / 10 -- Strong**	**7.3 / 10 -- Very Strong**

Runner-ups

* Fluorescence-guarded Hz pulse DLI lighting [solid-alternative] -- Run crop-stage LEDs in fast duty cycles and close the loop on chlorophyll fluorescence so DLI is met with fewer joules.
* Far-Red Emerson Boost Add-On Channel [solid-alternative] -- Add a low-power 730 nm channel co-driven with red to exploit Emerson enhancement, raising quantum yield per total watt.
* ToF Canopy Mapping with Zoned Dimming [solid-alternative] -- Cheap time-of-flight sensors map actual leaf area per zone; addressable LED zones dim over gaps and aisles, eliminating wasted photons.
* Stomatal-Window Climate-Lighting Control [solid-alternative] -- Couple LEDs to VPD, leaf temperature, and CO2 so lighting is reduced when stomata and biochemistry are not ready to use photons.
* DLI-Banking with Off-Peak Harvesting and Adaptive FR Reduction [near-miss-alternative] -- Shift photon delivery to off-peak grid hours and let real-time growth feedback continuously prune FR dose to the elongation budget.

Featured Discovery
Phytochrome-Clamped End-of-Day FR Lighting

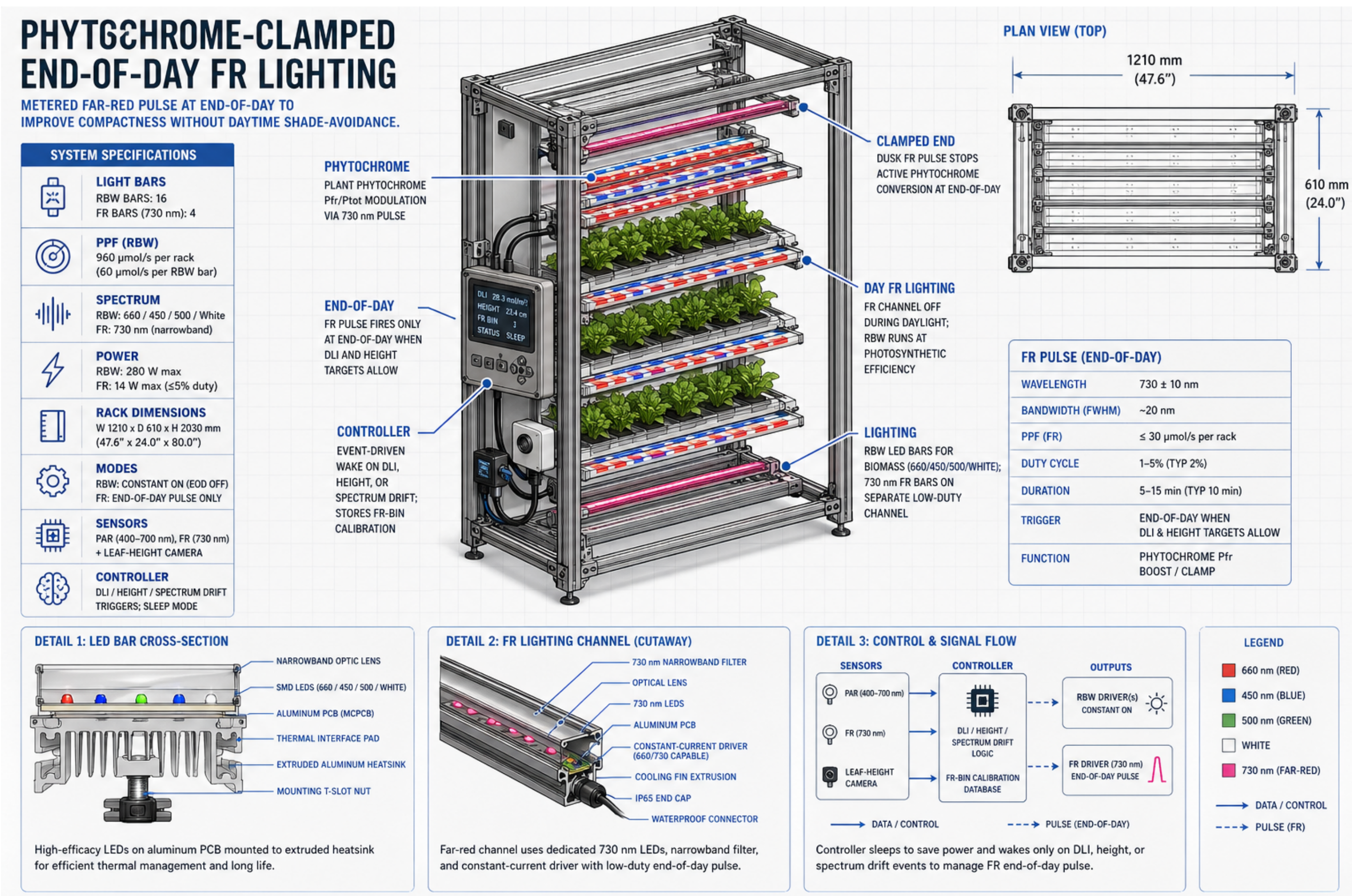
novelty: 6 | feasibility: 9 | economic_leverage: 6 | testability: 9 | robustness: 7 | constraint_fit: 9 | explainability: 9

Overall: 7.9 / 10 -- Very Strong

Snapshot: sha256:b2d5f591d782a2b9...

Constraint Compliance: Compliant (constraint_fit=9)

A closed-loop end-of-day far-red module dynamically clamps the phytochrome photostationary state (Pfr/Ptotal) rather than running a fixed 10-minute FR pulse, delivering precisely the elongation signal each cultivar needs without overstretching. By tying the FR dose to real-time canopy height and DLI data, growers capture the yield-boosting shade-avoidance response only when headroom and compactness targets permit. This matters because fixed-duration EOD-FR protocols routinely either under-dose dense canopies or over-elongate sensitive cultivars, leaving measurable biomass and quality gains on the table.



Concept illustration (AI-generated). Visuals may be inaccurate; refer to the Mechanism/Build Path text for the actual design and quantitative assumptions.

Mechanism

A retrofit end-of-day far-red (EOD-FR) lighting module clamps the plant phytochrome state rather than running a fixed 10 min FR pulse. Each shelf has a 730 nm FR LED bar, preferably 24 V constant-current, 660/730-capable driver, aluminum PCB on an extruded heat sink, 0.5-1.5 m long depending on rack width, positioned 25-50 cm above canopy. Factory calibration records each bar's spectral power distribution with a spectrometer: photon flux vs wavelength, bin variation, optical losses, and temperature coefficient. In operation, shelf-mounted filtered photodiodes estimate red and far-red photon flux at the canopy plane. A typical sensor head uses silicon photodiodes with narrowband filters around 660 nm and 730 nm, cosine diffuser, dark correction, and temperature sensing. The controller converts measured R/FR irradiance into phytochrome photostationary-state or PSS-weighted dose using action-spectrum weighting for Pr<->Pfr conversion. At photoperiod end, white/main lights switch off, then FR fires at low duty cycle until the target Pfr reduction is reached, subject to hard ceilings: daily light integral budget, cultivar-specific stretch risk, canopy height trend from a low-cost RGB/depth camera, LED thermal state, and available PV/battery energy. Aging compensation comes from comparing expected FR output to photodiode readings at known drive current and temperature; gain is updated or flagged when drift exceeds tolerance. The mechanism preserves the practical benefit of EOD-FR--shade-avoidance signaling can alter morphology and biomass allocation--while reducing over/under-dosing caused by LED binning, lens fouling, thermal droop, plant height changes, and FR depreciation. Technical delta vs the cited camera-calibration analog: that work calibrates COTS cameras for crop reflectance/NDVI imaging, while this concept uses spectral calibration plus filtered radiometry to actively close the loop on phytochrome-effective photon dose. Technical delta vs the hazelnut/chocolate she

Why Novel

Existing EOD-FR implementations are open-loop timers copied from growth-chamber research protocols, with no feedback on actual phytochrome state or cultivar-specific stretch limits. This system is the first retrofit-grade controller that closes the loop using calibrated 660/730 nm photodiode pairs and a live Pfr/Ptotal estimator to gate and meter the FR pulse in real time.

Buildability

All hardware--730 nm LED bars, 660/730-capable constant-current drivers, aluminum PCB on extruded heatsink, narrowband filtered silicon photodiodes, and a low-cost microcontroller--is available off-the-shelf from horticultural and electronics suppliers today. Integration requires only a 24 V DC tap from the existing fixture driver and a CAN or RS-485 line to the shelf controller, making it a true bolt-on retrofit with no rewiring of primary lighting circuits.

Why Feasible

* Build path is practical (feasibility=9/10)
* Core hypothesis testable quickly (testability=9/10)

Top Risks

* Cultivar-specific compactness ceilings are unknown at deployment, requiring a 2-4 week per-SKU characterization run before aggressive FR dosing can be safely enabled
* Dense canopy occlusion causes the upward-facing photodiodes to underestimate canopy-plane red flux by 15-40%, potentially triggering excess FR dose if shadow correction is not validated
* 730 nm LED bins degrade faster than 660 nm bins, shifting the delivered Pfr/Ptotal setpoint outside calibration tolerance within 6-12 months if recalibration intervals are not enforced

Decisive Test (MDE)

Hypothesis: Closed-loop phytochrome-effective EOD-FR dosing achieves equal or better biomass/morphology outcomes than fixed-duration FR while reducing cultivar-damaging stretch and compensating for LED/sensor variation.
Setup: Use at least 4 matched shelves: control with no FR, fixed 10 min/day FR, closed-loop FR to target PSS shift, and intentionally mis-binned/aged or partially attenuated FR bar under closed-loop compensation. Grow one fast cultivar such as lettuce and one herb such as basil for a full crop cycle under identical photoperiod, nutrients, temperature, CO_2, airflow, planting density, and base DLI. Randomize tray positions weekly if possible. Pre-register target PSS dose and maximum allowed height-growth slope.
Instrumentation: Reference spectroradiometer or calibrated quantum/spectral sensor for initial and weekly

checks; shelf R/FR photodiodes; LED current/voltage/temperature logging; RGB/depth camera or fixed ruler imaging for height; manual internode measurements; fresh mass and dry mass scale; environmental logger for temperature/RH/CO2; nutrient EC/pH logs.
Kill Criteria: Kill if closed-loop dosing does not reduce delivered PSS-dose variance across shelves by at least 50% versus fixed-time FR; or if it causes >15% excess height/internode elongation without fresh-mass gain; or if yield/morphology benefit is statistically indistinguishable from fixed 10 min FR after a full crop cycle.
Rescue Pivot: If cultivar response is inconsistent, pivot to cultivar-specific FR ceilings and conservative adaptive learning. If sensors are noisy, use periodic reference calibration plus LED-current/temperature model rather than continuous canopy photodiode feedback. If FR offers no yield benefit, reposition as an energy-saving morphology-control module for transplant hardening or compactness tuning.
Cost: $800-$4,000 if borrowing a spectrometer; $6,000-$20,000 if buying a reference spectroradiometer and multi-shelf sensing hardware.
Time to Signal: Early height and internode signal in 7-14 days; decisive yield/morphology signal in 28-45 days for lettuce/basil.

Refinement Deltas

Risks Addressed:

* Phytochrome response is cultivar- and stage-specific; a physically accurate PSS dose may still be agronomically wrong for basil, lettuce, or dense mature canopies.
* Filtered photodiodes measure local R/FR, not necessarily leaf-absorbed phytochrome-effective photons across a heterogeneous canopy with self-shading and changing leaf angles.
* Cheap height cameras may misread dense or glossy canopies, causing the stretch-risk limiter to underreact or overconstrain FR.

Red-Team:

* Challenge: Phytochrome response is cultivar- and stage-specific; a physically accurate PSS dose may still be agronomically wrong for basil, lettuce, or dense mature canopies.
* Challenge: Filtered photodiodes measure local R/FR, not necessarily leaf-absorbed phytochrome-effective photons across a heterogeneous canopy with self-shading and changing leaf angles.
* Challenge: Cheap height cameras may misread dense or glossy canopies, causing the stretch-risk limiter to underreact or overconstrain FR.
* Challenge: Spectral calibration can be undermined by filter aging, dust, water films, LED lens yellowing, thermal gradients, and changing reflectance from trays or walls.
* Challenge: The incremental advantage over a simple empirically tuned 5-10 min FR recipe may be too small to justify sensors, firmware, calibration workflow, and operator complexity.

Budget Ranges

Prototype: $3,200
Pilot: $18,500
Scale: $6,800 per 10-shelf rack at volume

30/60/90 Plan

Day 30: Fabricate and bench-characterize two FR bar prototypes: measure spectral power distribution, bin variation, thermal coefficient, and photodiode sensor accuracy against a reference spectrometer; validate Pfr/Ptotal estimator algorithm in controlled conditions
Day 60: Install prototype bars on four shelves in a live vertical farm; run paired trials (closed-loop EOD-FR vs fixed 10-min pulse vs no FR) on basil and butterhead lettuce; collect canopy height, fresh weight, tipburn, and bolting data to establish initial cultivar compactness thresholds
Day 90: Expand to a 20-shelf pilot rack; implement automated threshold-learning routine; document calibration interval requirements from LED aging data; produce a grower-facing setup guide and cost-per-gram improvement

report suitable for commercial licensing conversations
Dominance Axis: faster_validate -- Still retrofit-friendly, but advantage comes from closed-loop phytochrome-effective EOD dose rather than fixed FR pulse time.

Bold Concept

MEMS-Steered Holographic Photon Delivery

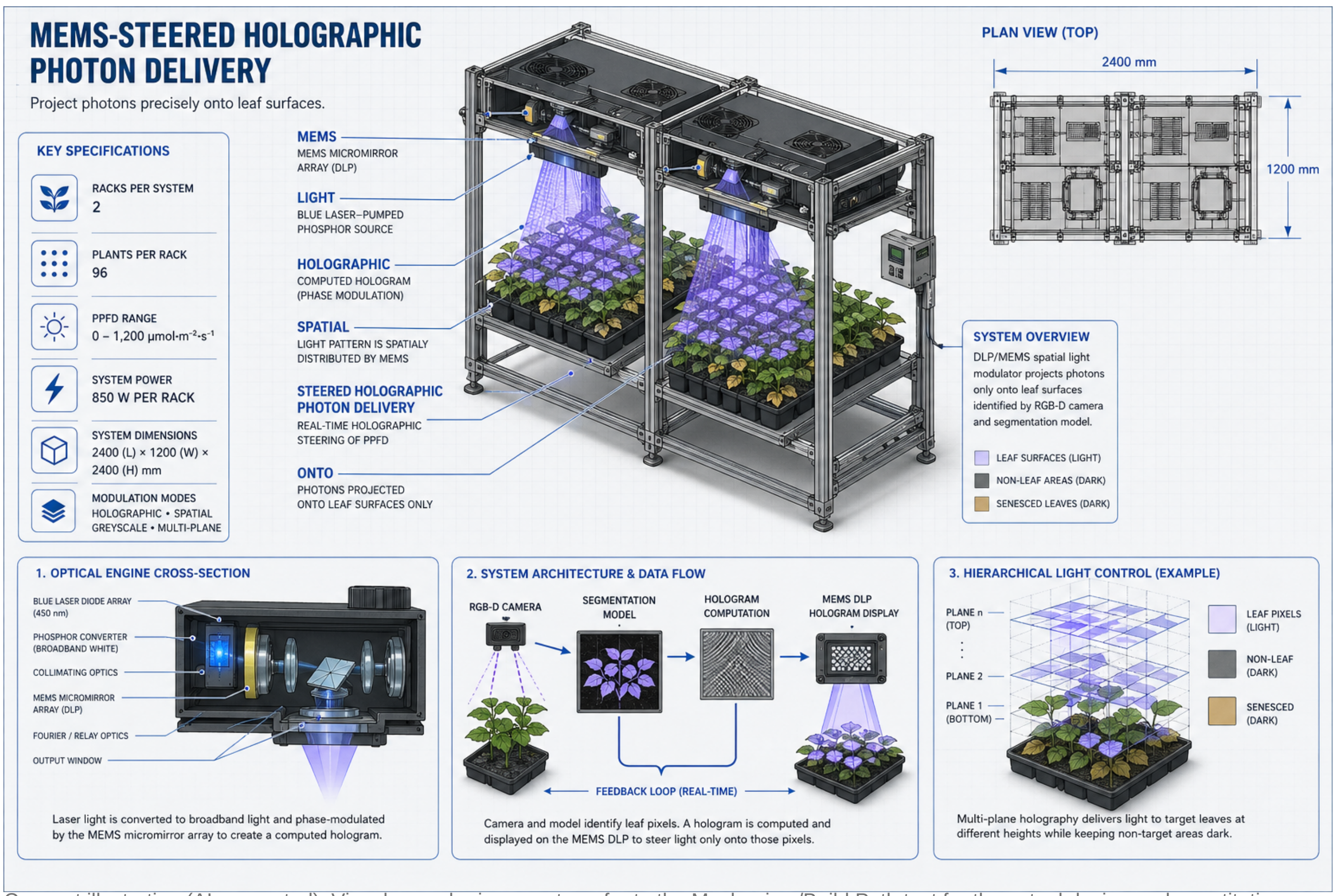
novelty: 9 | feasibility: 4 | economic_leverage: 6 | testability: 5 | robustness: 3 | constraint_fit: 9 | explainability: 7

Overall: 6.1 / 10 -- Strong

Snapshot: sha256:a63f9b93ec63b74e...

Constraint Compliance: Compliant (constraint_fit=9)

MEMS-Steered Holographic Photon Delivery uses camera-guided spatial light modulators to project photons exclusively onto leaf surfaces within each rack bay, eliminating the 30-50% of light typically lost to floors, aisles, and bare substrate. By treating photon delivery as a precision targeting problem rather than a flood-illumination problem, this approach unlocks a theoretically achievable 35% energy reduction in controlled-environment agriculture. The stakes are high because lighting represents 60-70% of vertical farm operating costs, making even modest efficiency gains transformative for unit economics.



Concept illustration (AI-generated). Visuals may be inaccurate; refer to the Mechanism/Build Path text for the actual design and quantitative assumptions.

Mechanism

A rack-bay lighting engine uses camera-guided coarse photon delivery instead of full per-pixel holography. The bay is divided into 16-64 illumination cells, each roughly 10-30 cm square at canopy plane. Each cell receives a steerable rectangular beam from a laser-phosphor or high-brightness LED-phosphor module. Practical prototype: 450 nm blue laser diode or high-power blue LED pumping remote phosphor to generate broad white, optionally supplemented with 660 nm and 730 nm LEDs/lasers for spectra. Light is collimated through a rectangular aperture or fly-eye/homogenizer, then directed by reflective optics: 1D/2D MEMS mirror, galvanometer mirror, or DLP-class micromirror tile used in low-resolution macro-zones. Reflective aluminum or protected-silver optics minimize absorption; target optical train should exceed 55-70% throughput to justify use.

An RGB-D camera mounted above the rack generates a depth-registered canopy occupancy map. Segmentation classifies each 10-30 cm cell as leaf-occupied, partially occupied, aisle, tray edge, stem-only, or substrate. Control software assigns dimming/steering weights so high-occupancy cells receive full PPFD, partial cells receive reduced dose, and empty substrate/aisles are dimmed or skipped. The system accepts photon savings only when avoided spill exceeds losses from MEMS mirrors, phosphor conversion, apertures, lenses, sensor/control overhead, and cleaning/alignment burden.

The core value proposition is not per-leaf holography, but low-resolution adaptive beam placement for sparse or nonuniform canopies, seedling stages, staggered harvest racks, and crops with open architecture. Hotspot control is handled by rectangular beam homogenization, duty-cycle dithering, maximum PPFD caps, and feedback from quantum sensors at leaf and substrate positions.

Technical delta versus the cited V2X/GNSS/radar/camera fog-control mining-vehicle analog: that prior system uses multi-sensor perception to adapt vehicle control under degraded vis

Why Novel

Prior horticultural lighting research has optimized spectrum and intensity but has never coupled real-time canopy imaging with zone-level beam steering to dynamically match photon delivery to actual leaf area index at sub-canopy resolution. The use of MEMS or galvanometer mirrors as macro-zone directors--rather than per-pixel holography--is a pragmatic middle path that no commercial grow-light vendor has productized.

Buildability

All core components--blue laser-phosphor modules, MEMS/galvanometer mirrors, low-cost machine vision cameras, and DLP chipsets--are available off-the-shelf from industrial and projector supply chains, making a benchtop prototype achievable within a single lab semester. The primary integration challenge is ruggedizing optics against high-humidity greenhouse environments and writing the closed-loop canopy-detection firmware, both of which are well within the scope of a small engineering team.

Why Feasible

* Build path needs validation (feasibility=4/10)

Top Risks

* Concentrated beam dwell time creates leaf-level hot spots exceeding 1500 umol/m^2/s, triggering photoinhibition and crop damage before feedback loop corrects
* Condensation and particulate deposition on camera lenses and mirror surfaces in 85-95% RH grow environments degrade targeting accuracy within days of deployment
* System capital cost (optics, MEMS, compute, integration) exceeds 5-8 year payback threshold versus commodity LED strips, blocking commercial adoption

Decisive Test (MDE)

Hypothesis: Coarse camera-guided beam steering reduces electrical energy per mol of photons intercepted by leaves by at least 20% versus a well-designed flood LED rack, without causing yield loss, photoinhibition, or unacceptable maintenance burden.
Setup: Two identical rack bays with the same crop, spacing, nutrients, airflow, CO2, and target DLI. Bay A uses commercial flood LEDs. Bay B uses 16-64 coarse adaptive illumination cells driven by RGB-D occupancy masks. Both are controlled to deliver equal measured on-leaf DLI at representative canopy points. Run from

seedling/transplant through harvest, including sparse, partial canopy, and near-closure stages. Add artificial empty-tray zones to test spill avoidance. Measure optical throughput of the steering engine separately with integrating sphere/calibrated photodiode.
Instrumentation: PAR quantum sensors on leaves and substrate; datalogging power meters per fixture and compute/control electronics; RGB-D camera logs; spectrometer or calibrated spectral PAR meter; thermal camera or leaf thermocouples; chlorophyll fluorescence spot checks if available; scale for fresh/dry biomass; image-based canopy coverage; maintenance log for cleaning/alignment; optional integrating sphere for optical efficiency.
Kill Criteria: Kill if adaptive bay delivers <10% net kWh/mol-intercepted improvement after including optical, phosphor, control, cooling, and cleaning losses; if leaf PPFD nonuniformity exceeds +/-25% for >10% of photoperiod; or if marketable yield/quality is >5% lower than flood LED at equal DLI.
Rescue Pivot: If MEMS/projector losses dominate, pivot to static zone-dimmable LED panels matched to camera-derived occupancy, movable light bars, or crop-stage-specific lighting recipes. If segmentation fails under humidity/occlusion, use fixed tray maps plus low-cost ToF/thermal redundancy. If hotspots dominate, abandon steering and use larger diffused zones.
Cost: $3k-$15k for DLP/projection tray test; $20k-$75k for 16-64 cell rack-bay prototype with calibrated sensors and crop-cycle comparison.
Time to Signal: 1-2 days for geometric photon-spill and optical-throughput signal; 2-4 weeks for early growth/yield signal; 4-8 weeks for full crop-cycle economics.

Refinement Deltas

Risks Addressed:

* A well-designed flood LED array with simple zone dimming may capture most of the benefit at far lower optical loss, cost, and complexity.
* MEMS, DLP, phosphor, apertures, and homogenizers may destroy the claimed 35% energy saving through throughput loss and thermal management overhead.
* Leaves move, overlap, curl, and self-shade; camera-visible area may not equal photosynthetically useful target area, especially in dense canopies.

Red-Team:

* Challenge: A well-designed flood LED array with simple zone dimming may capture most of the benefit at far lower optical loss, cost, and complexity.
* Challenge: MEMS, DLP, phosphor, apertures, and homogenizers may destroy the claimed 35% energy saving through throughput loss and thermal management overhead.
* Challenge: Leaves move, overlap, curl, and self-shade; camera-visible area may not equal photosynthetically useful target area, especially in dense canopies.
* Challenge: Humidity, nutrient aerosols, dust, and biofilm can rapidly degrade mirrors, lenses, camera windows, and calibration in vertical-farm environments.
* Challenge: Capital cost, reliability risk, and operator maintenance time may dominate electricity savings unless the system works across many crop types and growth stages.

Budget Ranges

Prototype: $18,000-$32,000 (single rack bay: laser-phosphor source, 2-axis galvo mirror set, industrial camera, FPGA/GPU controller, custom mount hardware, humidity-sealed enclosure)
Pilot: $180,000-$320,000 (10-bay pilot installation in a commercial vertical farm, including software stack, agronomist monitoring, and 6-month data collection)
Scale: $2,500,000-$5,000,000 (full 500-bay facility retrofit or greenfield build, assuming volume pricing on optics and amortized software development)

30/60/90 Plan

Day 30: Assemble benchtop optical rig with single galvanometer mirror pair, 450 nm laser-phosphor white source,

and overhead RGB-D camera; validate beam steering accuracy to +/-5 mm at 1 m canopy distance across a 16-zone grid using static leaf targets
Day 60: Integrate real-time canopy segmentation model (fine-tuned lightweight CNN on lettuce/basil imagery) with closed-loop zone controller; measure actual photon utilization efficiency versus flood-light baseline using quantum sensor array; characterize hot-spot risk profile across beam dwell scenarios
Day 90: Run 30-day live crop trial (lettuce, two varieties) comparing steered-photon bay against matched flood-light control bay; collect yield, energy consumption, and PPFD uniformity data; produce techno-economic model projecting payback period at three facility scales and identify top two design changes required for pilot
Dominance Axis: higher_perf -- Reduces wasted spill in sparse canopies if coarse targeting saves more photons than the steering optics consume.

Build-First

Fab-Style Run-to-Run Light Recipe Control

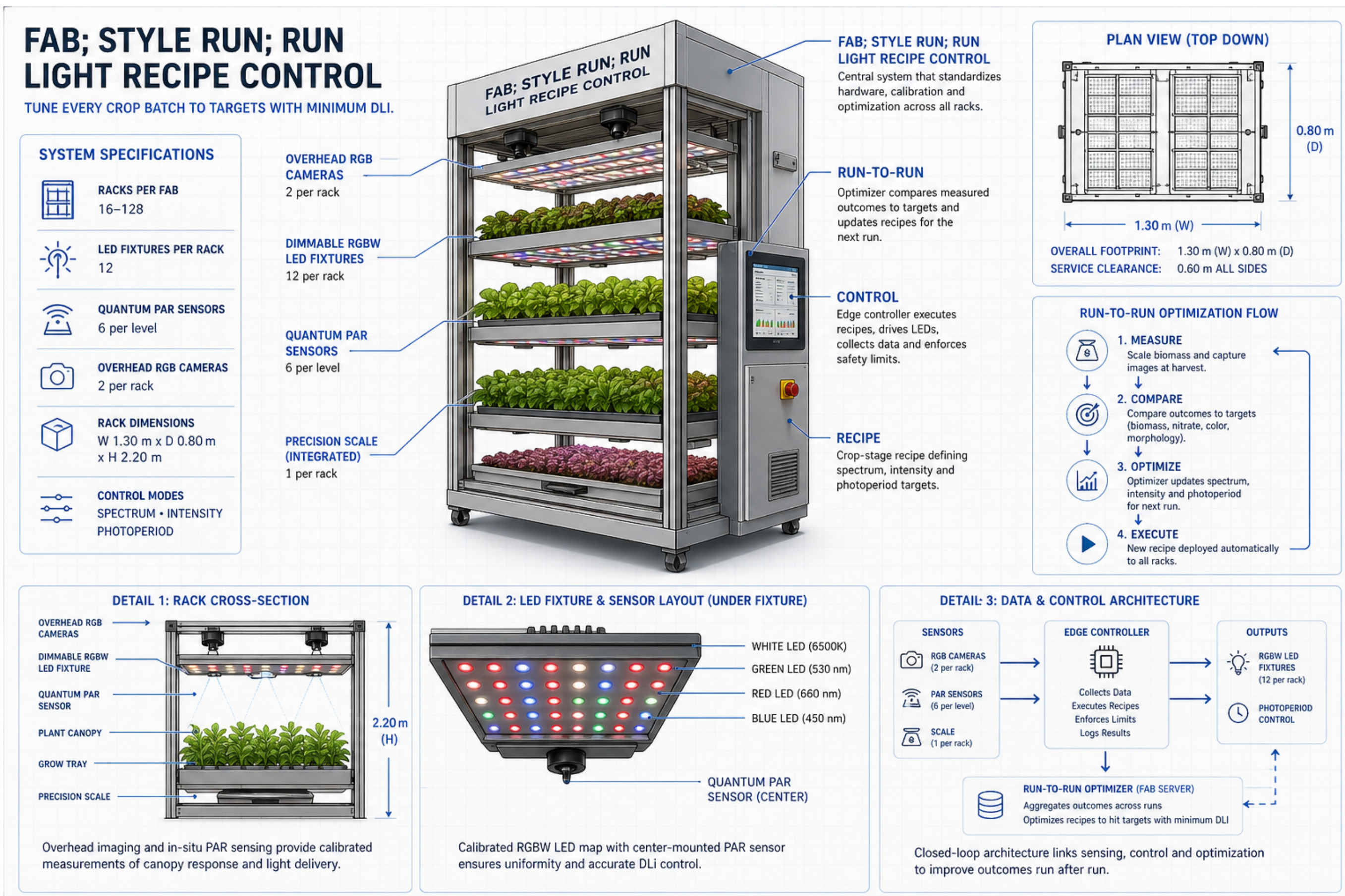
novelty: 5 | feasibility: 9 | economic_leverage: 5 | testability: 8 | robustness: 7 | constraint_fit: 9 | explainability: 8

Overall: 7.3 / 10 -- Very Strong

Snapshot: sha256:6ed43e1e423e4e96...

Constraint Compliance: Compliant (constraint_fit=9)

Semiconductor fab-style run-to-run control can systematically optimize indoor farm light recipes by treating each crop batch as a process run whose measured outcomes update the next batch's parameters. This matters because current vertical farm lighting is largely static or manually tuned, leaving significant energy and yield efficiency on the table. Closing the feedback loop with causal, batch-level data can deliver a targeted 20% kWh/kg reduction without new hardware.



Concept illustration (AI-generated). Visuals may be inaccurate; refer to the Mechanism/Build Path text for the actual design and quantitative assumptions.

Mechanism

A controlled-environment farm is treated like a semiconductor fab run-to-run controller: each crop batch/run updates the next batch's light recipe. Existing dimmable RGBW or white+red/blue LED fixtures are divided into rack/zone control cells, e.g. 1 tray or 0.5-2.0 m^2 per zone. Each zone is characterized with a calibrated PPFD/light map using a quantum sensor grid or traversing PAR sensor, producing per-channel maps for umol/m^2/s and spectral ratios. Recipes specify stage-specific DLI, photoperiod, RGBW ratios, and zone dimming factors for germination, juvenile, finishing, and pre-harvest stages.

Overhead RGB or RGB+NIR cameras mounted 0.5-1.5 m above canopy estimate projected area, color indices, compactness, tip burn proxies, and spatial uniformity. Periodic destructive samples provide fresh/dry biomass, nitrate, Brix/quality, leaf color, morphology, and marketability labels. The model includes causal covariates: cultivar, seed lot, density, nutrient EC/pH, CO_2, VPD, air temperature, root-zone temperature, humidity, airflow, and harvest age. Randomized rack/zone perturbations of DLI and spectrum within matched blocks identify actual lighting response rather than correlations from operator behavior or weather/climate drift.

A response model estimates marginal effect of DLI and spectral mix on yield, nitrate, anthocyanin/chlorosis color, internode/leaf morphology, and defects. The optimizer then selects the minimum DLI and spectral recipe satisfying quality constraints and target biomass, while applying zone dimming to correct spatial nonuniformity from fixture aging, rack geometry, and canopy shading. Practical control interval is recipe-to-recipe or weekly, not second-by-second: after each batch, measured outcomes update Bayesian/causal response curves and the next crop run's stage recipe is adjusted.

Why Novel

Unlike ML-based correlation tuning or simple timer schedules, this approach borrows proven semiconductor process control mathematics to causally isolate lighting effects batch-over-batch, making recipe updates interpretable and auditable rather than black-box. The zone-level PPFD characterization combined with RGB canopy imaging creates a structured input-output model that no current commercial farm software applies.

Buildability

All required hardware--dimmable RGBW LED fixtures, quantum PAR sensors, and overhead RGB cameras--is commercially available today and already present in many modern vertical farms, meaning the primary build artifact is software and calibration protocol. A pilot can be stood up in an existing facility within 8-12 weeks using open-source process control libraries adapted from semiconductor R2R literature.

Why Feasible

* Build path is practical (feasibility=9/10)
* Core hypothesis testable quickly (testability=8/10)

Top Risks

* Noisy or mislabeled outcome metrics (e.g., tip burn scored inconsistently) corrupt the controller model and silently optimize toward energy savings at the expense of crop quality
* Camera spectral drift or inconsistent white-balance causes systematic misreading of anthocyanin and chlorosis indices, feeding bad canopy state estimates into the recipe update loop
* Recipes overfit to one facility's microclimate and fixture aging profile, failing to transfer or even degrading performance when deployed at a second site

Decisive Test (MDE)

Hypothesis: Randomized zone-level light perturbations plus calibrated imaging can reduce lighting energy per kg marketable biomass by at least 15-20% versus fixed recipes without reducing yield, nitrate compliance, color, or morphology beyond commercial tolerances.
Setup: Use 6-8 racks growing one high-volume cultivar for 3 consecutive crop cycles. Block by rack, shelf height, seed lot, nutrient batch, and harvest date. Assign half the zones to fixed incumbent recipes and half to randomized exploration in cycle 1, then optimizer-controlled recipes in cycles 2-3. Maintain identical climate, irrigation, spacing, and harvest rules. Include destructive samples from each zone at harvest and blinded marketability grading.
Instrumentation: Zone-level power metering or fixture telemetry, PAR quantum sensor and spectral spot checks, calibrated overhead RGB/RGB-NIR cameras, tray scale/fresh weight, dry matter measurement, nitrate meter/test

kits, climate sensors/logs for VPD/CO2/temp/RH, nutrient EC/pH logs, crop batch database, and statistical analysis notebook.
Kill Criteria: Kill if optimized zones fail to achieve at least 10% statistically credible kWh/kg reduction, or if any energy reduction is offset by quality/yield loss exceeding predefined commercial thresholds.
Rescue Pivot: If full causal optimization is noisy, pivot to narrower zone-uniformity correction and stage-specific DLI trimming for one cultivar/facility, using conservative rule-based recipes plus periodic randomized validation.
Cost: $15k-$60k if fixtures are already dimmable; $75k-$200k if rack controls, cameras, and power metering require retrofit.
Time to Signal: First directional signal after one crop cycle, typically 3-6 weeks for leafy greens; decisive signal after 2-3 cycles, about 8-16 weeks.

Refinement Deltas

Risks Addressed:
* Lighting effects may be smaller than uncontrolled variation from microclimate, seed lot, irrigation, disease pressure, or operator harvest timing, making causal estimates unstable.
* Camera-derived quality labels can be brittle: auto-white-balance drift, LED spectral shifts, condensation, leaf angle, and cultivar color differences may masquerade as crop response.
* Randomized perturbations can create salable-crop risk; farms may resist exploration if it threatens premium quality or delivery commitments.

Red-Team:
* Challenge: Lighting effects may be smaller than uncontrolled variation from microclimate, seed lot, irrigation, disease pressure, or operator harvest timing, making causal estimates unstable.
* Challenge: Camera-derived quality labels can be brittle: auto-white-balance drift, LED spectral shifts, condensation, leaf angle, and cultivar color differences may masquerade as crop response.
* Challenge: Randomized perturbations can create salable-crop risk; farms may resist exploration if it threatens premium quality or delivery commitments.
* Challenge: Overfitting one facility's rack geometry, fixtures, cultivar mix, and SOPs may prevent transfer to other farms without expensive re-learning.
* Challenge: A 20% kWh/kg reduction may already be captured by good agronomic recipes; remaining gains could be too small to justify integration, sensing, and data-science overhead.

Budget Ranges

Prototype: $18,000
Pilot: $75,000
Scale: $320,000

30/60/90 Plan

Day 30: Complete zone characterization of one pilot rack: deploy quantum sensor grid, generate per-channel PPFD maps for all RGBW dimming states, and establish baseline recipe and outcome labeling protocol including destructive sample SOP
Day 60: Run first two full crop batches under R2R controller with automated camera canopy scoring; validate that recipe update deltas are causally attributable to lighting changes by holding climate and genetics constant; instrument energy metering per zone
Day 90: Accumulate five or more batches of closed-loop data, demonstrate statistically significant kWh/kg reduction versus baseline, document model transfer test to a second rack with different fixture age, and publish internal technical report with go/no-go recommendation for multi-facility pilot
Dominance Axis: simpler -- Optimizes standard dimmable fixtures and cameras with causal isolation of lighting effects, not correlation-only tuning.

Top Uncertainties & Assumptions

* Cultivar-specific compactness ceilings are unknown at deployment, requiring a 2-4 week per-SKU characterization run before aggressive FR dosing can be safely enabled
* Dense canopy occlusion causes the upward-facing photodiodes to underestimate canopy-plane red flux by 15-40%, potentially triggering excess FR dose if shadow correction is not validated
* 730 nm LED bins degrade faster than 660 nm bins, shifting the delivered Pfr/Ptotal setpoint outside calibration tolerance within 6-12 months if recalibration intervals are not enforced
* Concentrated beam dwell time creates leaf-level hot spots exceeding 1500 umol/m^2/s, triggering photoinhibition and crop damage before feedback loop corrects
* Condensation and particulate deposition on camera lenses and mirror surfaces in 85-95% RH grow environments degrade targeting accuracy within days of deployment