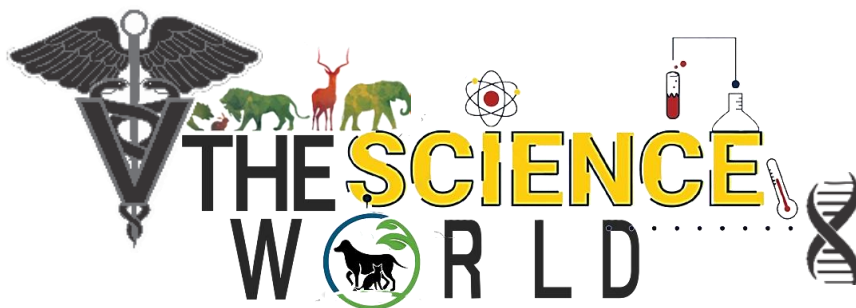




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Dynamic Lighting: Programming Light Like a Fertilizer

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Abstract

For most of agricultural history, light has been treated as a condition rather than an input. Farmers could manage seed, water and fertilizer, but sunlight arrived on its own terms. Controlled-environment agriculture is changing that relationship. Modern LED systems can regulate not only how much light a crop receives, but also its colour spectrum, duration, timing, direction and distribution across the canopy.

This approach—dynamic lighting—treats light almost like a programmable fertilizer. A greenhouse controller can increase light when a crop can use it efficiently, reduce it when sunlight is sufficient, alter the spectrum during flowering or fruit development, and apply short finishing treatments to influence colour, flavour or nutritional compounds. Sensors, weather forecasts, crop models and electricity prices can all help determine the programme.

Research already shows meaningful results. Carefully designed far-red supplementation has increased tomato yield by up to 16% in a controlled greenhouse study, while a commercial-scale practice trial reported an 11% improvement under a particular interlighting treatment. Dynamic schedules can also lower peak electricity demand and avoid expensive lighting hours. Yet photons cannot replace nitrogen, water or sound agronomy. The opportunity is not simply to install brighter lamps, but to develop crop-specific, locally validated light prescriptions that combine plant physiology with energy economics.



Introduction

When Light Becomes a Farm Input

A grower standing inside a modern greenhouse at dawn may see something unusual. The lamps do not all switch on together. One section brightens gradually. Another remains dim because the weather forecast promises strong morning sun. Blue light increases over a nursery bench to keep seedlings compact. Far-red light reaches the middle of a tomato canopy. Later, the system reduces output as electricity prices rise. The greenhouse is not merely illuminated. It is being programmed.



Fig 1. A representative image for Dynamic Greenhouse Lighting Powered by Operating System

Plants use light as both food and information. Light supplies energy for photosynthesis, but it also tells a plant whether it is in open sun or beneath competing leaves, whether the day is lengthening, and when it should germinate, stretch, flower or form protective pigments.

This is why two lamps drawing the same electrical power may not produce the same crop. What matters is the number and wavelength of photons reaching the leaves, the hours over which they arrive, their position in the canopy and the crop's ability to use them at that moment.

Dynamic lighting brings these variables under active control. Instead of running lamps at one intensity for a fixed number of hours, it changes the treatment in response to sunlight, species, cultivar, crop stage, plant condition, carbon dioxide, humidity, electricity tariffs and the grower's production target.

A Useful Analogy: Fertilizer is matched to soil condition, crop demand and growth stage. Dynamic lighting aims to do something similar with photons. But light supplies energy and signals—not mineral nutrients—and more is not automatically better.

Understanding the Light Dose

Intensity

Photosynthetic photon flux density (PPFD) describes the number of photosynthetically useful photons reaching one square metre every second. Its common unit is micromoles per



square metre per second ($\mu\text{mol m}^{-2} \text{s}^{-1}$). PPFD tells us how strong the light is at a particular moment.

Daily light integral

Daily light integral (DLI) adds those photons over the entire day. It is measured in moles per square metre per day. A constant PPFD of $250 \mu\text{mol m}^{-2} \text{s}^{-1}$ for 16 hours supplies a DLI of $14.4 \text{ mol m}^{-2} \text{day}^{-1}$. The same daily total can be delivered through a long gentle photoperiod or a shorter intense treatment, but the biological effects need not be identical.

$$\text{DLI} = \text{PPFD} \times \text{lighting seconds} \div 1,000,000$$

Spectrum

Plants perceive a broad spectrum. Each band has overlapping but distinct roles, which is why a dynamic fixture may contain several independently controlled LED channels.

Light band	Approx. range	Important plant responses
Ultraviolet-A	315–400 nm	Protective compounds, colour and stress responses; excessive exposure can injure tissue.
Blue	400–500 nm	Stomatal regulation, compactness, chlorophyll formation and pigmentation.
Green	500–600 nm	Penetrates relatively deeply into dense canopies and supports visual inspection.
Red	600–700 nm	Efficiently drives photosynthesis and is generally efficient to produce with LEDs.
Far-red	700–800 nm	Can alter extension growth, canopy architecture, flowering and biomass allocation.

Timing and direction

Plants respond to sequence as well as total dose. A short pre-harvest blue treatment is not necessarily equivalent to spreading the same blue

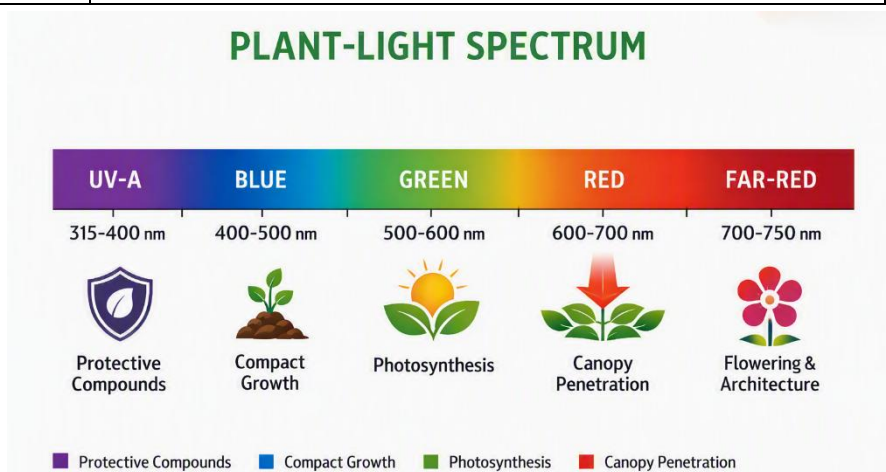


Fig 2. Representative Image for Distribution of Plant Light Spectrum



photons evenly through the day. Likewise, overhead lighting and interlighting may produce different results because leaves intercept them differently. The practical question becomes: which photons should arrive, where, at what intensity, for how long, and at which stage of the crop's day and life?

Technological Advancement: From Grow Lamp to Light Operating System

1. Multi-channel, dimmable LEDs

Modern fixtures may contain separately controlled blue, green, red and far-red channels, with ultraviolet available in specialised systems. Electronic dimming allows smooth intensity changes without replacing the fixture. LEDs also send less radiant heat toward the crop than high-pressure sodium lamps, although driver and fixture heat must still be managed.

2. Sunlight-responsive supplementation

Quantum sensors measure light at crop level while a controller estimates accumulated DLI. Lamps dim when sunlight is adequate and increase output during dull periods. Forecast-based systems can reserve electrical lighting when strong sunlight is expected later.

3. Crop feedback

The next generation watches the crop through chlorophyll fluorescence, leaf temperature, canopy imaging, carbon-dioxide exchange, water uptake and growth rate. In a closed loop, the system applies light, observes the response and adjusts the next dose.

4. Growth-stage recipes

A seedling does not need the same treatment as a fruiting plant. Programmes can be divided into germination, establishment, vegetative growth, canopy shaping, flowering, fruit filling and pre-harvest finishing.

5. Spatial lighting

Individually controlled zones, movable fixtures and canopy maps can reduce photons wasted on empty floor. In tall crops, interlighting delivers light to lower leaves that overhead fixtures may not reach effectively.

6. Energy-aware control

Lighting can be shifted away from peak tariffs, coordinated with rooftop solar and batteries, and prevented from switching on all at once. Biological limits remain decisive: the cheapest electricity schedule is not always the most profitable crop schedule.



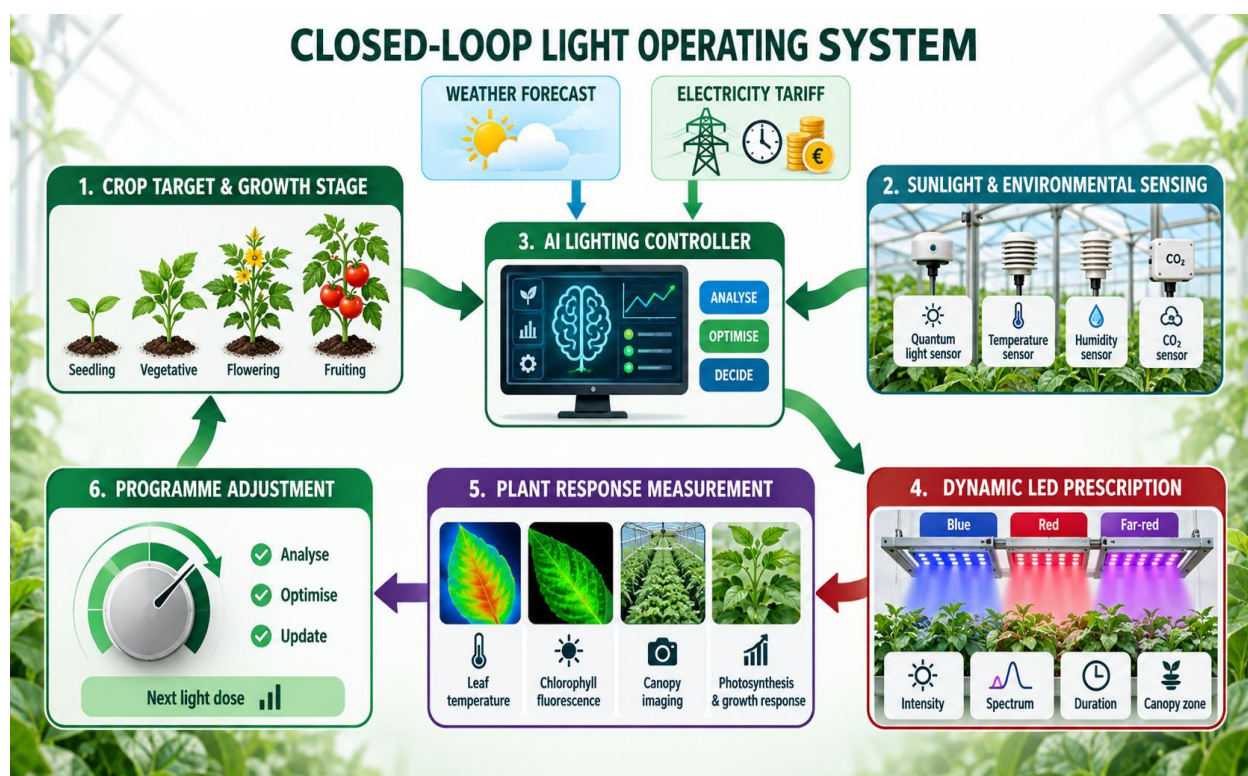


Fig 3. Closed loop Work flow of Dynamic Light Operating System in a Green house

Applications

Greenhouse vegetables: Tomato, cucumber, sweet pepper and strawberry can use supplementary light during winter, cloudy weather or monsoon periods. Dynamic control maintains DLI, reaches dense canopies and supports year-round scheduling.

Leafy greens and herbs: Lettuce, spinach, kale, basil, coriander and microgreens have short cycles and high visual-value requirements. Recipes may target yield, compactness, colour, antioxidant accumulation, aroma and shelf quality.

Seedlings and nurseries: Light can help produce compact, uniform, transplant-ready plants and synchronise batches for dispatch.

Floriculture: Photoperiod and spectrum can influence flowering time, branching, stem length and market scheduling.

Tissue culture and propagation: Programmable light provides uniform artificial conditions for multiplication, rooting and acclimatisation while limiting heat close to culture vessels.

Vertical farming: Nearly every crop photon may be electrical, so spectral flexibility is valuable and efficiency is critical. Lighting must be designed with air conditioning, dehumidification and crop density.

Seed production and breeding: Controlled photoperiods can synchronise flowering and accelerate breeding generations.

Space agriculture: NASA's Veggie and Advanced Plant Habitat show why controllable LEDs matter where energy, volume, crew time and natural sunlight are constrained.

Benefits and Wider Impact

Higher and more consistent production: Lighting reduces variation caused by cloudy days and seasons, making production easier to schedule.

Improved quality: Spectrum can influence architecture, colour, dry matter, flavour-related chemistry and secondary metabolites. Claims remain crop- and cultivar-specific.

Better use of electricity: LED conversion can lower lighting demand, while dimming avoids output when sunlight is adequate. Whole-system analysis must include heating and cooling.

Lower peak demand: Staggered programmes can reduce contracted demand, grid stress and exposure to peak prices.

More production per unit of land: Controlled lighting supports close spacing and vertical stacking, but environmental performance depends on energy source, crop choice and avoided supply-chain losses.

A new service economy: Light-recipe services can combine verified programmes, monitoring and seasonal optimisation instead of selling fixtures alone.

Statistics of Adoption

No dependable worldwide census counts farms using genuinely dynamic, sensor-controlled lighting. Market reports often combine fixed LEDs, dimmable fixtures and software-controlled systems. Their figures indicate direction, not the percentage of farms operating closed-loop light recipes.

- A 2026 commercial estimate reported that LEDs represented 86.13% of horticultural-lighting market revenue by technology in 2025. Greenhouses represented 49.21% of application revenue, while vertical farms were forecast as the fastest-growing application through 2031.
- The same estimate placed Europe at 32.94% of 2025 market revenue and projected an Asia-Pacific compound annual growth rate of 13.42% through 2031.
- An India-focused commercial estimate placed lighting at 29% of India's vertical-farming component market in 2025. This is a revenue share, not an installation count.
- The Government of India reported that 2.51 lakh hectares of additional area came under protected cultivation from 2014–15 to 2021–22 through MIDH. Not all of this area uses artificial light, but it is an infrastructure base for later precision-lighting adoption.



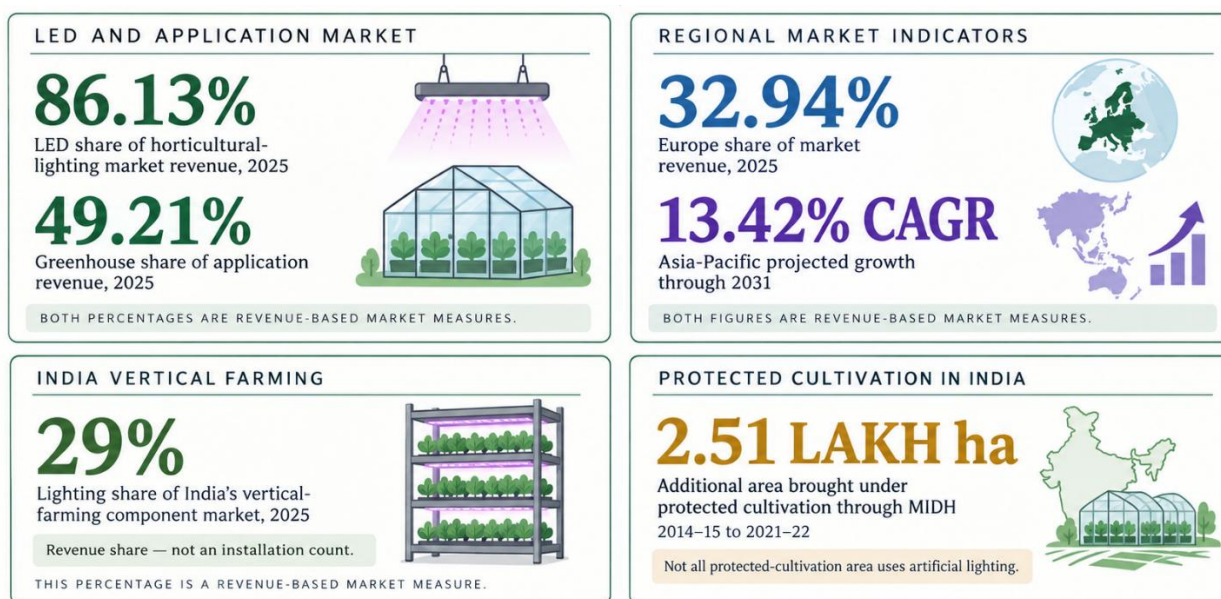


Fig 4. Representative image for Key Statistics of horticultural lighting and protected cultivation

Policy and Government Support

India

India does not yet have a major national subsidy category dedicated specifically to dynamic horticultural lighting. Support is mostly indirect through protected cultivation, hydroponics, automation, research and renewable energy.

The 2025 Mission for Integrated Development of Horticulture guidelines promote greenhouses, hydroponics and aeroponics, circulation fans and sensor-based fertigation. Precision Farming Development Centres located in agricultural universities, ICAR institutes and IIT Kharagpur are expected to validate and disseminate region-specific technologies.

Under the guidelines, selected components receive 50% assistance subject to limits. Sensor-based fertigation automation, for example, has a cost norm of ₹4 lakh per unit with 50% assistance for a qualifying protected-cultivation area. This supports the control infrastructure surrounding dynamic lighting, although grow lights are not expressly identified as a separate national subsidy component.

A practical Indian promotion programme should include:

- crop- and cultivar-specific light trials through ICAR institutes, agricultural universities and PFDCs;
- regional studies for high-radiation, cloudy and monsoon conditions;



- dimmable horticultural LEDs and quantum sensors as approved protected-cultivation add-ons;
- performance-linked support based on photon efficacy, crop-level uniformity and verified dimming;
- integration with rooftop solar, storage and time-of-day tariffs;
- common reporting standards for spectra, PPFD maps, fixture life and degradation;
- demonstration farms for nurseries, floriculture, leafy vegetables and high-value fruiting crops.

United States

The USDA National Institute of Food and Agriculture operates an Urban, Indoor and Emerging Agriculture programme supporting research, education and extension. Its 2026 funding opportunity listed estimated total funding of US\$4 million, with awards from US\$50,000 to US\$500,000 and no matching requirement. NASA's long investment in efficient crop lighting has also produced terrestrial spin-offs.

Netherlands and European Union

Dutch policy has explicitly supported energy-efficiency investments in greenhouse horticulture. A 2025 Dutch programme allocated €40 million to greenhouse energy efficiency and applied technical requirements to eligible LED equipment, including efficacy and dimming. The approach is instructive: policy can reward measurable efficiency and controllability rather than any lamp labelled horticultural.

Research Proofs and Case Studies

1. Far-red dose and tomato yield

A 20-week Wageningen greenhouse experiment maintained 250 $\mu\text{mol m}^{-2} \text{s}^{-1}$ supplementary PPFD and a 16-hour photoperiod while varying far-red fraction. At a far-red fraction of 0.40, two cluster-tomato cultivars produced approximately 16% more fruit yield. The response did not increase indefinitely, showing the importance of an optimum dose.

2. Commercial-scale interlighting

A Wageningen practice trial reported that 30 $\mu\text{mol m}^{-2} \text{s}^{-1}$ of far-red interlighting increased tomato yield by 11% and improved measured quality and shelf-life attributes. A lower 10 $\mu\text{mol m}^{-2} \text{s}^{-1}$ treatment had little effect.



3. Duration versus timing

A 2024 high-wire tomato study found that supplementary far-red increased fruit dry weight per cultivation area by 23–25%. The benefit was related more to duration of exposure than to whether light was supplied in the first or second half of the photoperiod.

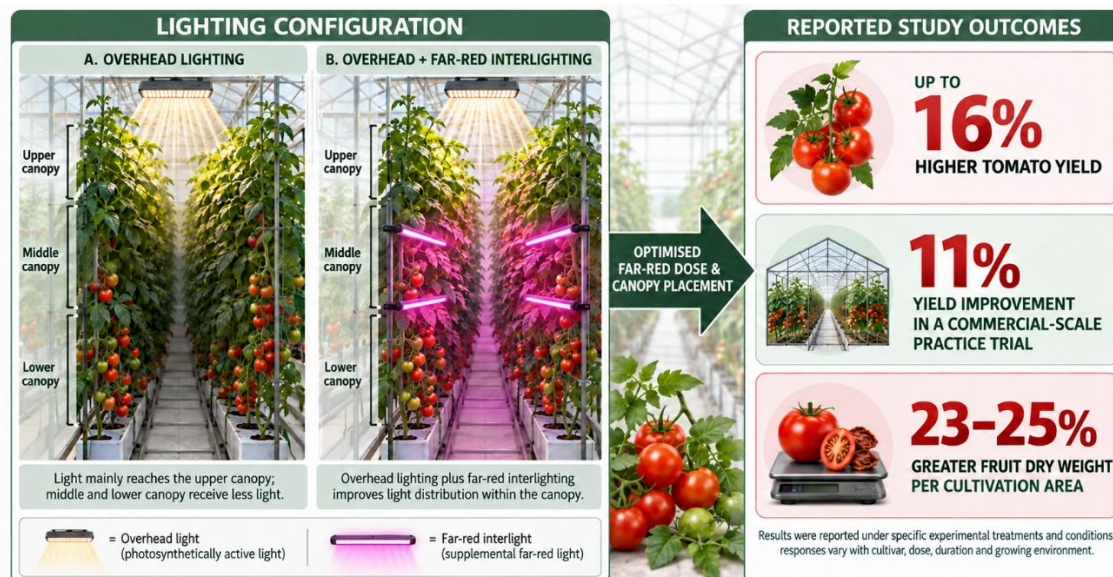


Fig 5. Representative image for effect of Lighting in Tomato Crop under Green house

4. Energy efficiency and fruit quality

A study comparing intracanopy red and red-plus-far-red LEDs with overhead high-pressure sodium lighting reported LED energy-use efficiency about five times higher under its experimental conditions, together with improvements in some fruit quality attributes. The magnitude should not be generalised beyond that crop and geometry.

5. Dynamic interruption has limits

Wageningen research found that tomato plants tolerated a two-hour morning lighting interruption under the tested conditions, but a four-hour interruption reduced chlorophyll, light absorption, photosynthesis and production. Sensors detected the decline early.

6. Space research to terrestrial farming

NASA's Advanced Plant Habitat combines extensive environmental sensing with controllable LED lighting. Experiments investigate how intensity and spectrum affect growth, metabolites, flavour, nutrition and development—the same questions faced by high-performance controlled-environment farms on Earth.



The Remaining Challenges

There is no universal light recipe. Responses vary with species, cultivar, plant age, season, temperature, carbon dioxide, nutrition and water. A treatment that increases yield may also change plant height, harvest uniformity or shelf life.

Electrical savings at the fixture do not tell the whole story. LEDs send less radiant heat toward the crop than high-pressure sodium lamps. A cold-climate greenhouse may need additional heating, while an indoor farm must remove lamp and dehumidification heat.

Measurement practices remain inconsistent. Growers need crop-level PPFD maps, spectral distributions, photon efficacy, uniformity, dimming curves and long-term degradation—not nominal wattage alone.

Light is a biological stressor as well as an energy source. Excess intensity, poorly timed ultraviolet exposure or an unsuitable photoperiod can cause bleaching, photoinhibition and lower productivity.

Finally, many so-called intelligent recipes are trained on small experiments or simulated data. Commercial deployment should start with conservative, measurable adjustments and control plots. A controller needs agronomic boundaries and a manual override.

Conclusion

Dynamic lighting changes the meaning of illumination in agriculture. Light is no longer simply switched on above a crop. It can be measured, divided into wavelengths, distributed across the canopy and delivered according to time, growth stage, weather and plant response. Programming light like a fertilizer captures the central idea: photons can be prescribed. But the best programme will not be the brightest, most colourful or most complicated. It will be the one that produces a measurable crop benefit for the lowest combined cost of electricity, cooling, heating, equipment and risk.

For researchers, the priority is to turn promising experiments into reproducible crop- and cultivar-specific protocols. For governments, the need is to support efficient, dimmable and measurable systems rather than hardware alone. For growers, the starting point is simple: measure natural light, define the crop target, add only the photons that create value, and watch how the plant responds.

The future greenhouse may not have a fixed day. It will have a negotiated one—written jointly by sunlight, sensors, the electricity grid and the crop itself.

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- Note:** AI tools Assistance were taken Judiciously for language refinement and Visual representations

