

8 Future Perspectives and Conclusions

Future strawberry production will likely move from fixed supplemental lighting schedules to precision systems that regulate spectrum, intensity, and timing in response to plant demand and greenhouse conditions. Recent work on controlled environments identifies optimized spectral quality and spatial distribution as a promising route to improve yield, fruit quality, and resource-use efficiency, while emphasizing that dynamic and spatially adaptive lighting solutions will be essential for modern sustainable horticulture. This direction is reinforced by broader photobiology reviews showing that LEDs allow growers to tailor spectrum and intensity to crop needs and developmental stages, creating a practical basis for more precise regulation of strawberry growth and quality.

A second priority is the development of sensor-based and model-driven lighting control. Hourly light integral control has already shown that real-time monitoring of PPFD and temperature can determine when supplemental lighting should be applied or withheld, improving yield, soluble solids, and sugar-acid ratio under commercial greenhouse conditions. More advanced frameworks are now pointing toward remote monitoring, weather-linked forecasting, and centralized smart control, suggesting that future strawberry systems will combine sensor networks with predictive algorithms to regulate light proactively rather than reactively.

Stage-specific lighting is another major future direction because strawberry responses differ across vegetative growth, flowering, fruit development, and postharvest storage. Recent synthesis work argues that current reviews have often treated only part of the crop cycle and that a full developmental framework is needed to design stage-specific lighting strategies that improve both yield and quality. Consistent with this view, earlier review evidence identified unresolved questions on cultivar-dependent wavelength effects, blue:red ratios during vegetative and flowering phases, and flavonoid retention during storage and transport, all of which remain highly relevant for precision recipe design.

An additional frontier is dynamic lighting aligned with biological rhythms rather than static daily light delivery. Recent review evidence on circadian regulation shows that spectrum-tunable LEDs can now enable real-time control of light quality, intensity, and timing, and that dynamically combining these factors can coordinate biological rhythms with light-energy use more effectively than simple adjustments of intensity or spectrum alone. This suggests that future strawberry lighting systems should not only meet daily photon targets, but also test whether circadian-aligned light programs can improve sugar accumulation, metabolite balance, and energy efficiency in ways that fixed schedules cannot.

Future light management strategies will also need to fit within broader sustainability goals, because greenhouse production is energy-intensive and lighting is one of its most consequential inputs. Energy reviews show that greenhouses have substantial energy consumption and greenhouse gas emissions, and that energy-saving strategies in design and operation are therefore essential for sustainable crop production. Within that context, light regulation should be evaluated not only by its effect on yield and quality, but also by its contribution to whole-system energy conservation, carbon footprint, and environmental performance.

Low-carbon optimization provides a concrete framework for this integration. Multi-objective modeling work shows that supplemental lighting can be regulated against both photosynthetic performance and carbon-emission targets, reducing carbon emissions by as much as 14.85% while maintaining 95.49% of the net photosynthetic rate relative to light-saturation objectives. For strawberry systems, this implies that future lighting recipes should be selected by balancing fruit quality gains against electricity demand and carbon cost, rather than simply maximizing photon delivery.

Sustainable integration also includes combining light regulation with other resource-management practices. In greenhouse strawberry, supplemental light increased fruit polyphenols and sugars under both full and deficit irrigation, and the combination of silicate spray with LED lighting was recommended as a route to produce high-quality fruit while allowing deficit irrigation for water conservation. More broadly, informed management of sunlight through materials, structures, and monitoring can improve food quality and yield while potentially reducing water, energy, and pesticide use, indicating that artificial and natural light management should be treated as part of the same sustainability framework.