

Postharvest evidence further shows that light can continue regulating quality after harvest. Continuous red LED during storage increases anthocyanin and TSS while preserving firmness and reducing weight loss, whereas brief early LED exposure enhances anthocyanins and aroma-related VOCs during subsequent storage without major color changes, indicating that strawberries retain light responsiveness after picking (Farneti et al., 2025). Overall, light-induced fruit quality formation in strawberry reflects an integrated response in which photoreceptors, transcription factors, carbohydrate metabolism, pigment biosynthesis, acid balance, and volatile production are coordinately modulated by the intensity, duration, and spectrum of the light environment.

4. Artificial Light Supplementation Strategies in Strawberry Cultivation

4.1 Application of LED supplemental lighting in strawberry production

LED supplemental lighting has become a central strategy in strawberry production because it can compensate for low winter radiation and improve both productivity and fruit quality in protected systems. Across greenhouse studies, supplemental LEDs increased vegetative growth, marketable yield, soluble solids, and overall berry quality, especially during off-season production when natural light is limiting (Stuemky and Uchanski, 2020). Similar benefits were observed across multiple cultivars grown under different spectra, where artificial LED light enhanced early yield, increased total soluble solids, and raised anthocyanin concentrations, indicating that supplemental lighting can improve both commercial output and quality traits relevant to consumer acceptance (Roosta et al., 2024).

The effectiveness of LED supplementation depends on spectral design and production context rather than simply adding photons. In plastic greenhouse cultivation, ambient light supplemented with blue or blue-plus-red LEDs produced higher fruit output, whereas red or blue-plus-red supplementation promoted greater accumulation of organic acids and phenolic compounds, showing that different spectra can target yield and quality differently. In commercial and research greenhouses, blue and red LED combinations also increased flowering substantially and reduced second-quality fruit without compromising overall quality, supporting their practical use for improving production uniformity and marketable fruit proportion.

4.2 Effects of light duration and intensity regulation on yield and quality

Regulation of light duration and intensity is a major determinant of how effectively supplemental lighting translates into yield and fruit quality. In indoor strawberry production, extending the photoperiod from 12 to 16 h accelerated flowering and first harvest and increased fruit production by 372%–989%, while increasing PPFD mainly promoted vegetative growth and had comparatively little effect on fruit production, indicating that photoperiod can dominate reproductive performance in some systems (Park et al., 2023). Evidence from multi-tier vertical systems also showed that both light intensity and duration increased yield, and that longer lighting duration increased sugar content, although the economic return remained constrained by electricity cost (Swann et al., 2021).

Optimal duration and intensity are not universal, because cultivar and cultivation system alter the response. In forcing culture, a 12-h LED photoperiod increased leaf photosynthesis, accelerated flower bud differentiation, improved fruit quality, and produced the highest marketable yield, whereas longer than 12 h inhibited later floral development and reduced total yield. By contrast, under time-differential supplemental lighting in soilless greenhouse culture, the combination of lower supplemental intensity at $132 \mu\text{mol m}^{-2} \text{s}^{-1}$ with a 16-h photoperiod produced the highest fruit yield and improved water and fertilizer use efficiency, showing that longer duration with moderate intensity can outperform higher-intensity strategies in other environments.

4.3 Integration of supplemental lighting with greenhouse environmental control

Supplemental lighting is most effective when integrated with broader greenhouse environmental control rather than used as an isolated input. Combining LED supplemental light with elevated CO_2 increased light-saturated photosynthetic rate, leaf area index, biomass, and yield, and also improved soluble sugar content while reducing titratable acidity, demonstrating a clear synergy between radiative and atmospheric management (Qiu et al., 2023). At the seasonal scale, this combined treatment raised yield by 51.3%, exceeding the effects of either elevated CO_2 or LED lighting alone, and therefore represents a strong strategy for improving winter-to-spring greenhouse productivity and sweetness (Qiu et al., 2023).