Progress on Physiology and Quality Regulation of Protected Strawberry Cultivation: Characteristic Production System of "Sunshine Strawberry" on the Yunnan Plateau

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Abstract

Strawberry (*Fragaria×ananassa* Duch.) is an important cash crop for protected horticulture in China. Its yield and fruit quality are comprehensively affected by multiple environmental factors such as light, temperature, water and fertilizer, as well as cultivation techniques. This paper systematically reviews recent research advances in the physiology and quality regulation of protected strawberry cultivation. It sorts and analyzes literature from these dimensions: light environment regulation (light intensity, shading, light spectrum, supplementary lighting technology), plateau characteristic production systems, light-temperature interaction and multi-factor coupling, water and fertilizer management, molecular mechanisms of quality formation, and innovative cultivation technologies. Current research is shifting from qualitative description of single factors to quantitative coupling of multiple factors, and from phenotypic physiological observation to molecular mechanism analysis. Particularly, this paper elaborates on the natural endowments, integrated cultivation technologies and differentiated quality advantages of plateau strawberry production zones represented by Tonghai County, Yuxi, Yunnan Province, proposes the characteristic plateau production system of "Sunshine Strawberry", and conducts multi-dimensional comparative analysis with conventional plain strawberries. On this basis, future research directions are put forward, including the construction of an intelligent coupled system integrating light, water, fertilizer and temperature, postharvest light regulation research, multi-omics joint analysis, and development of low-cost high-efficiency supplementary lighting equipment. The study aims to provide theoretical references for high-quality and high-efficiency strawberry production, especially the sustainable development of the characteristic plateau strawberry industry.

Keywords

Strawberry, Protected cultivation, Light environment, Quality regulation, Fruit quality

Introduction

Strawberry (*Fragaria×ananassa* Duch.) is a major cash crop cultivated under protected facilities in China, whose fruits are rich in antioxidants including vitamin C and anthocyanins. Protected cultivation enables off-season supply, yet facilities commonly suffer from weak light and unbalanced light spectrum, which directly impair strawberry yield and quality. Optimizing the light environment through supplementary lighting and spectral modulation has therefore become a key strategy for improving both yield and fruit quality. In recent years, the application of new technologies such as Light Emitting Diode (LED) supplementary lighting, laser supplementary lighting and Ultraviolet-B (UV-B) radiation has provided theoretical support for precise light environment regulation of strawberries [1]. In addition, in-depth research on multi-factor coupling of light, water and fertilizer has also contributed to this theoretical support. Meanwhile, high-altitude regions represented by the Yunnan Plateau have formed a distinctive industrial model of "Sunshine Strawberry" relying on unique climates featuring strong ultraviolet radiation and large diurnal temperature differences. This paper systematically sorts out relevant research progress, analyzes existing problems, and prospects future development directions, so as to offer references for strawberry production practices and subsequent research.

Regulation of light environment on strawberry growth, development and fruit quality

Light intensity and shading regulation

Light intensity is a core factor affecting strawberry photosynthesis and yield. Published studies have shown that for “Zhangji” strawberry, under 75.0% natural light intensity, leaf net photosynthetic rate increased by 6.7%, stomatal conductance rose by 42.1%, and water use efficiency improved by 16.3% compared with full sunlight treatment. For “Xueqinxiang” strawberry, other reports indicate that 30.0% shading achieved optimal plant growth and yield, while 70.0% shading transformed the diurnal photosynthetic curve from bimodal to unimodal, accompanied by significant declines in all indicators. Collectively, these observations suggest that moderate shading is required under excessive light intensity in summer and autumn, whereas artificial supplementary lighting is indispensable during weak-light periods in winter and spring.

Light spectrum regulation

(1) Red and blue light

Red and blue light constitute the primary effective spectra for photosynthesis. In one published study on “Hongyan” strawberries in solar greenhouses, LED supplementary lighting with a red-to-blue ratio of 9:1 brought a 55.9% yield increase. Dynamic supplementary lighting achieved 2.6 times higher electric energy efficiency than continuous supplementary lighting. Another investigation on home horticulture identified the optimal scheme as red-blue ratio 1:1, light intensity 15,000 lx, and daily light duration 12 h, which elevated net photosynthetic rate by 83.8% and yield by 244.2%. Different cultivars respond diversely to light spectra. Roosta et al. reported in BMC Plant Biology that mixed red-blue light markedly improved fruit weight and length of the “Albion” cultivar [2]. Previous work found that 6 h daily supplementary lighting maximized strawberry yield and quality. Other studies summarized the effects of different light spectra on five greenhouse crops including strawberries and concluded optimal light spectrum ratios.

(2) Blue light and Ultraviolet-B (UV-B) radiation

UV-B radiation significantly promotes the accumulation of antioxidants such as anthocyanins and flavonoids in fruits. In a study on “Xuelixiang” strawberries, UV-B supplementary lighting at 0.2-0.8 $W\cdot m^{-2}$ was applied, and the 0.4 $W\cdot m^{-2}$ treatment drastically enhanced leaf photosystem activity, net photosynthetic rate, single fruit weight and soluble sugar content. Combined metabolome and transcriptome analyses revealed that UV-B induced differential accumulation of 46 flavonoids and 9 anthocyanins, far exceeding red-blue light treatments. Two key transcription factors Basic Leucine Zipper (bZIP) and APETALA2 (AP2) were identified [3].

For preharvest regulation, Zhu et al. irradiated “Albion” strawberries with UV-B for 1 h and 2 h daily from 17:00 to 19:00 after flowering. Treated fruits exhibited significantly higher soluble solids, total phenols and total anthocyanins than the control. Additionally, fruit firmness decline and rot rate during cold storage were reduced, with ELONGATED HYPOCOTYL 5 (HY5) serving as the major component of UV-B signal transduction [4].

New advances in supplementary lighting technology

(1) Laser supplementary lighting

Lasers feature good directivity and function effectively at extremely low light intensity. One study tested “Hongyan” strawberries with laser supplementary lighting at 1, 2, 3 $\mu mol\cdot m^{-2}\cdot s^{-1}$. It found that the 2 $\mu mol\cdot m^{-2}\cdot s^{-1}$ treatment reached a single-plant yield of 519.3 g, representing a 23.5% increase relative to the control [5]. Another study reported that laser treatment at 0.5-1 Photosynthetic Photon Flux Density (PPFD) raised fruit quantity by 12.3%-14.0%, single fruit weight by 19.8%-23.3%, and overall yield by 34.5%-40.6%. The yield increase was positively correlated with leaf area, net photosynthetic rate and nitrogen, phosphorus, potassium accumulation.

Photoperiod regulation of flower bud differentiation

Strawberry flower bud differentiation is governed by photoperiod, and short days facilitate floral initiation. Earlier reviews on early flowering promotion technologies for strawberries have pointed out that low-temperature short-day treatment can advance flowering and extend the fruiting cycle. Different strawberry types respond differently to photoperiod: Seasonal cultivars complete flower bud differentiation under photoperiods shorter than 14 h, while everbearing cultivars finish differentiation under photoperiods longer than 12 h. Under low temperature (17°C) and short day length (10 h), strawberries can complete flower bud differentiation in as little as 9 days. At the molecular level, studies on *Fragaria pentaphylla* have reported that the expression of *Fragaria pentaphylla* CONSTANS (FpeCO) peaked 28 days after low-temperature short-day treatment. *Fragaria pentaphylla* FLOWERING LOCUS T1 (FpeFT1) maintained high expression starting from day 42, while *Fragaria pentaphylla* APETALA1 (FpeAP1) and *Fragaria pentaphylla* LEAFY3 (FpeLFY3) reached expression peaks in the 6th week.

Plateau characteristic strawberry production system and differentiated advantages of "sunshine strawberry"

Current status of plateau strawberry industry

The plateau strawberry industry in China has developed rapidly. Qinghai Province launched the "High-Quality Summer Strawberry High-Efficiency Production Technology Research and Demonstration Project on Qinghai-Tibet Plateau" in 2025. The project introduced over 80 cultivars and realized year-round production via altitude gradient domestication. Research in Xining, Qinghai demonstrated that plateau climate drastically affects fruit appearance and internal quality. Qiaojia County, Yunnan, leverages cool high-altitude climate, with a planting area of 30,000 mu and an annual output value of 1 billion yuan in 2025. Huize County boasts the largest summer strawberry planting area nationwide. Its strawberries were exported to Dubai for the first time at a retail price of 100 yuan per kilogram, a 50.0% premium. Yunnan accounts for over 80.0% of China's total summer strawberry planting area and output. The Yunnan Academy of Agricultural Sciences bred four everbearing strawberry cultivars: "Qiuhong", "Qiuyi", "Qiuxiang" and "Xiayi". These cultivars won the Second Prize of Yunnan Provincial Science and Technology Progress Award in 2022.

Effects of plateau environment on fruit quality formation

Plateau regions feature intense UV-B radiation and large diurnal temperature differences. Research from Qinghai Academy of Agricultural and Forestry Sciences indicated that strawberries grown under strong plateau light contain significantly higher anthocyanin and vitamin C than plain controls. Shangri-La enjoys annual sunshine hours exceeding 2,500 and diurnal temperature differences over 10°C, with strong ultraviolet radiation exerting natural bactericidal effects. Vitamin C content of "Hongyan" strawberries in Xundian reaches 72.3 mg/100.0 g. High-altitude strawberries in Qutuguan, Tonghai County deliver high sugar content, and fully ripe fruits remain intact for 3-4 days after harvest.

"Sunshine strawberry" technical system in tonghai county

Tonghai County sits at an altitude of approximately 1,800 m with annual sunshine hours over 2,100. Wuxiang Township introduced soilless cultivation to grow "Suizhu" and "Fenyü" cultivars. High-ridge double-row cultivation is adopted, with field planting conducted from July to September and fruit hitting the market in October. Local collaborative breeding efforts between Dandong and Yunnan have shown that plateau domestication raised flower bud differentiation rate from 70.0% to 90.0%, boosting yield by 20.0%-30.0%. In Shangri-La, newly developed cultivars "Meilihong", "Meilifen" and "Meilibai" won double gold awards at the National High-Quality Strawberry Evaluation in 2023. The core technologies of the "sunshine strawberry" system include coordinated light-temperature-water management, elevated soilless cultivation, and integrated water and fertilizer management with "nitrogen reduction and potassium increase". They also include green prevention and control utilizing strong ultraviolet radiation, and off-season market supply. A systematic review has elaborated modern greenhouse cultivation technologies for strawberries in low-latitude plateaus.

Comparison between plateau and plain strawberries

Compared with plain production zones, plateau strawberries feature brighter fruit color, superior sugar-acid ratio, firmer texture for better storage and transportation, and higher vitamin C content. They also have lower chemical fertilizer and pesticide input, and prominent brand premium. Lixiang Shanqi Agricultural Co., Ltd. of Yunnan built China's first full industrial chain system for plateau strawberries.

Coupled regulation of light and other environmental factors

Light-water-fertilizer coupling

A previous study originally set cumulative solar radiation as the irrigation threshold and identified 4.0 MJ/m² as the specific critical value; exceeding this threshold reduces vitamin C by 22.0%-37.0% and sugar-acid ratio by 21.0%-24.0% [6]. Previous research has reported light-potassium coupling mechanisms. Supplementary lighting increased leaf nitrate uptake by 36.5% and single fruit fresh weight by 50.1%. Foliar potassium application elevated nitrate reductase activity by 60.0% and fruit sugar concentration by 19.7%. Combined supplementary lighting and potassium treatment significantly increased single fruit weight by 38.6% and sugar content by 23.8%, with transcriptome data showing upregulated genes in nitrogen metabolism pathways.

Water and fertilizer management and innovative cultivation technologies

Intelligent integrated water and fertilizer technology

Intelligent integrated water and fertilizer cultivation technology for protected strawberries delivers outstanding advantages in fertilizer and water conservation and labor saving. Centered on drip irrigation integrated water and fertilizer systems, this technology supplies water and nutrients precisely according to crop water and fertilizer demands at different growth stages. A "nitrogen reduction and potassium increase" strategy (30.0% nitrogen reduction, 50.0% potassium increase) applied during fruit expansion enhances sucrose synthase activity by 25.0% and raises sugar content by 2.3 Brix compared with the control.

Stereoscopic cultivation and optimization of light-thermal environment

Stereoscopic cultivation drastically improves space utilization and yield per unit area. It has been pointed out that strawberries are light-loving crops, and sufficient light promotes vigorous plant growth and high fruit yield. Studies on light distribution in A-frame stereoscopic facilities within solar greenhouses have found that upper planting troughs receive far better light than lower layers. Other findings on cultivation substrates indicate that bag cultivation yields superior fruit quality over pot cultivation for "Hongyan", "Xiangye", and "Xuetu" cultivars, with "Xiangye" showing the most obvious early maturity.

To address uneven light distribution in elevated stereoscopic planting, a self-supplementary-light rotating strawberry planting device was developed in a previous study to effectively homogenize canopy light distribution [7].

Molecular mechanisms underlying strawberry quality formation

Molecular regulation of anthocyanin and flavonoid biosynthesis

Anthocyanin synthesis is sequentially catalyzed by structural genes including PAL1, CHS, CHI, F3H, DFR1, ANS and UFGT. The MBW transcription complex acts as the core regulatory hub of anthocyanin synthesis. A previous study reported that a novel R2R3-MYB transcription factor FaMYB5, whose overexpression drastically boosts accumulation of anthocyanins and proanthocyanidins, was discovered [8]. It has been reported that FaMYB44.1 inhibits anthocyanin synthesis by repressing the transcription of FaF3H, while FaMYB44.3 exerts no influence on anthocyanin content. It has been shown that E3 ubiquitin ligase FvCOP1 suppresses biosynthesis of sugars and anthocyanins by mediating ubiquitination and degradation of FvHY5, FvMYB10 and other transcription activators [9]. Transcriptome analysis by Wang et al. confirmed that transcription factor families including bHLH, MYB, WD40, AP2 and bZIP jointly regulate anthocyanin accumulation [10].

Comprehensive perspective on fruit quality regulation

Strawberry quality formation arises from complex interactions between genetic factors and environmental conditions. Previous literature has systematically summarized internal and external factors affecting strawberry quality. In addition, low temperature maintains fruit texture by inhibiting cell wall metabolic enzymes, and postharvest Ultraviolet-C (UV-C) treatment extends shelf life.

Existing problems and future prospects

Current research still faces multiple limitations. They include insufficient multi-factor coupling models, weak linkage between molecular mechanisms and phenotypic traits, and inadequate economic evaluation. They also include unclear cultivar-specific rules and insufficient systematic research on plateau strawberries. Future research priorities are proposed as follows.

(1) Developing intelligent coupled systems integrating light, water, fertilizer and temperature.

(2) Integrating pre- and postharvest light regulation technologies.
(3) Conducting multi-omics joint analysis.
(4) Developing cost-effective laser and solar-powered supplementary lighting systems.
(5) Establishing a cultivar light adaptability evaluation system.
(6) Constructing quality fingerprint maps and molecular regulatory networks for plateau strawberries.

Conclusion

Research on light environment regulation for protected strawberry cultivation has evolved from single-factor qualitative description to multi-factor quantitative coupling and molecular mechanism dissection. Technologies including dynamic LED supplementary lighting, laser supplementary lighting and UV-B regulation significantly improve strawberry yield and fruit quality. Represented by Tonghai County, Yunnan, the plateau “Sunshine Strawberry” production system leverages natural advantages of strong ultraviolet radiation and large diurnal temperature differences, combined with soilless cultivation and integrated water-fertilizer management, to produce differentiated fruits. These fruits feature bright color, high sugar content, strong storability and ecological safety, promising broad market prospects.

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Conflicts of Interest

The authors declare no conflict of interest.

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