

补光对设施栽培樱桃果实成熟和糖分积累的影响

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摘要:【目的】探究不同补光处理对樱桃果实的影响, 筛选设施栽培樱桃最佳人工补光方案。【方法】以设施栽培的中国樱桃诸暨短柄与黑珍珠为材料, 从果实硬核期到采收期间, 分别使用不同功率的LED灯光源、白炽灯光源、商品补光灯光源进行补光, 以自然光照作为对照, 对果实内源激素、相关酶活性与基因表达进行测定。【结果】发现采用红蓝光比例6:1的LED光源补光显著促进了果实成熟进程, 能够使果实成熟过程中内源激素动态变化趋势较对照组提早出现, 并且显著提高了成熟软化与糖合成基因的表达, 使果实蔗糖合成酶活性比同期对照组提高18.75%以上。【结论】功率36 W的LED补光处理效果最好, 显著促进了果实成熟进程, 提高樱桃糖分积累量, 值得在樱桃生产中应用和推广。

关键词: 樱桃; 补光; LED; 成熟; 糖分积累

中图分类号: S662.5

文献标志码: A

文章编号: 1009-9980(2023)10-2183-12

Effects of supplementary light on ripening and sugar accumulation of cherry under protected cultivation

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Abstract: 【Objective】 Because of the subtropical monsoon climate in most areas of southern China, the protected cultivation is widely applied in cherry production to reduce the impact of the large precipitation in spring. There are still problems such as weak light intensity, short light duration and uneven light distribution in protected cultivation environment. Therefore, improving the light environment of facility cultivation through artificial light supplement technology has important practical significance for regulating the growth and development and improving yield and quality of cherry. In this study, different supplementary light measures were compared and the best scheme for protected cultivation of cherry was selected. 【Methods】 The Chinese cherry cultivars Zhujidianbing and Heizhenzhu were used as materials in this study. Four different types of light sources were used: LED lamp (36 W, RB 6:1), LED lamp (50 W, RB 6:1), commodity plant growth lamp (12 W, RB 2:1, G101) and incandescent lamp (36 W), with no artificial light as the control (CK). All the groups were treated with mulching the ground with reflective film. The distance between the lights was 3 m, and the height from the top of the tree was 50 cm. Time of light supplement was set to 05:00—10:00, 16:00—19:30 on sunny days and 5:00—19:30 on rainy days. The contents of endogenous hormones GA_s, IAA and ABA, the percentage of soluble solids, and the enzyme activities of peroxidase (POD), sucrose synthase (SS) and sucrose phosphate synthase (SPS) in cherry flesh were measured from the color transition stage to the harvest stage. The expression levels of genes related to ripening, softening, and sugar synthesis in fruits were also measured in the harvest stage. 【Results】 Each supplementary light treatment caused the dynamic change of endogenous hormones in the fruit earlier than control, and promoted the fruit development and maturation process of the two varieties. The comprehensive effect of LED light treatment was the best, resulting in the

收稿日期: 2023-03-31

接受日期: 2023-07-30

基金项目: 浙江省农业新品种选育重大科技专项(2021C02066-9)

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changing process of endogenous hormones GA_s and ABA in the fruit earlier than control. Supplementary light treatments also increased the TSS contents of two cherry cultivars at harvest time. LED light treatments had the most significant effect on improving TSS content, which made the TSS of Zhujiduanbing fruit reach 17.63%, and made the TSS of Heizhenzhu fruit reach 14.67%. The increase of sucrose synthase activity in the fruit of each supplementary light treatment was earlier than control, thus promoting the accumulation of sugar in the fruit. Among them, LED supplementary light treatments had the most obvious promotion effect. LED 36 W treatment made the sucrose synthase vitality of Zhujiduanbing fruit reach a peak 3 days before harvest, which was 69.17% higher than the control during the same period, and increased the sucrose synthase activity of Heizhenzhu fruit by 18.75% compared to control during harvest. Overall, LED 36 W treatment had the best effect, and gene expression levels were measured for this treatment. It was found that the expression of the ABA synthase gene *NCED1* was significantly higher with LED 36 W treatment than that with control, which regulated the levels of endogenous hormones related to fruit ripening at the molecular level. The relative expression levels of polygalacturonase gene *PG1* and xylanase gene *XYL1*, which can regulate cell wall degradation, were also significantly higher with this treatment than those with the control, indicating that this treatment could promote fruit softening by positively regulating the process of cell wall degradation. The determination of anthocyanin synthesis pathway genes *PAL*, *CHS*, *ANS* and transcription factor *MYB10* in the pericarp during harvest showed that the expression levels of *CHS*, *ANS* and *MYB10* in Zhujiduanbing pericarp treated with LED 36 W were significantly higher than the control. And in Heizhenzhu pericarp, the expression levels of all four genes with LED 36 W treatment were significantly higher than those with the control. LED 36 W treatment activated the synthesis of anthocyanins in cherry pericarp by activating high-level expression of synthesis pathway genes and transcription factors at the molecular level, thereby promoting the coloring of cherry pericarp. The relative expression levels of sucrose synthase genes *SSI*, *SS6* and sucrose phosphate synthase gene *SPSA1* in fruit during harvest were also analyzed. The results showed that with the two cherry cultivars, LED 36 W treatment significantly increased the expression level of *SSI* gene in fruit compared to the control, indicating that *SSI* played a major role in responding to supplementary light treatment. LED 36 W treatment positively regulated the synthesis of sucrose synthase by activating the expression of *SSI*, thereby promoting sugar accumulation in cherry fruits through sucrose synthase. **【Conclusion】** All supplementary light treatments promoted the dynamic changes of endogenous hormones during cherry fruit ripening, and increased the level of soluble solids content in the fruit. Among them, LED (36 W, RB 6: 1) supplementary light treatment could advance the endogenous hormone change process of two Chinese cherry cultivars by 3 to 9 days, increase the activity of sucrose synthase in the fruit by more than 18.75% compared to the control during the same period, and significantly improve the expression of genes related to fruit ripening and softening, sugar synthesis, and anthocyanin synthesis at the molecular level, which had the best effect on promoting cherry ripening and improving fruit quality. It is worthy of application and promotion in cherry practical production.

Key words: Cherry; Supplemental light; LED; Ripeness; Sugar accumulation

中国樱桃 (*Prunus pseudocerasus* L.) 是蔷薇科李亚科李属植物, 起源于中国, 是世界四大樱桃栽培种之一^[1], 果实富含多种维生素和矿质元素^[2], 深受消费者的喜爱。在浙江省等中国南方地区樱桃生产

中, 广泛采用设施栽培以减轻高温多雨环境对樱桃生长的影响^[3]。传统设施栽培可以调控环境因子, 但相对于自然条件还存在设施环境下光照度弱、光照时间短、光照分布不均^[4]等问题。光照条件不足

会导致作物营养生长受限^[5]、果实发育缓慢^[6]。因此,通过人工补光技术改善设施栽培的光照条件,对于调节作物的生长发育、提高产量、改善果实品质等具有重要的实践意义^[7-9]。目前关于中国樱桃设施栽培中的补光技术研究尚未见报道。

研究表明,光照条件是影响植物的生长发育过程的重要环境因子^[10],光照不仅为光合作用提供能量以促进植物营养生长,还影响植物生殖生长的整个阶段,参与调控作物品质形成等诸多方面^[11-13]。目前,在蔬菜和柑橘等果树的设施栽培中,传统光源和LED新型光源的补光技术对有效延长光照时间、调控光质具有积极作用,能够促进果实的发育成熟,并提升其产量和品质^[14-16]。此外,LED补光光源还能够影响作物的内源激素含量,显著提高葡萄、水稻等作物的产量和抗逆性^[17-18]。光照环境差是影响浙江省樱桃生产的关键问题,当地春季梅雨季节降水量大,连续阴雨天气和避雨栽培所使用的薄膜等材料对设施透光率的影响,导致樱桃果实发育过程中自然光照条件不足,果实品质与产量受到影响。因此,开发合适的人工补光技术改善光照环境是樱桃生产中的迫切需求,该技术能有效提高设施内光照度,有利于促进果实发育成熟,增产增收。

诸暨短柄与黑珍珠是浙江省中国樱桃主栽品种^[19],笔者在本研究中以诸暨短柄与黑珍珠为试验材料,选择传统白炽灯、商品补光灯“G101型激光植物生长灯”与红蓝光LED灯作为补光处理手段,探究不同的补光处理对果实成熟和糖分积累的影响,以期为开发设施栽培樱桃补光技术提供理论参考依据。

1 材料和方法

1.1 供试材料

试验于2022年4月在浙江省杭州市桐庐县桃园进行。供试品种为设施栽培的中国樱桃诸暨短柄和黑珍珠。诸暨短柄樱桃是由浙江省农业科学院等单位从中国樱桃地方品种中选育出的优株,1992年通过品种审定。黑珍珠樱桃是中国樱桃的芽变优株,1993年由重庆南方果树研究所选出。

1.2 试验设计

补光光源采用4种不同的补光灯类型:LED灯(36 W, RB 6:1)、LED灯(50 W, RB 6:1)、G101型激光植物生长灯(12 W, RB 2:1)和白炽灯(36 W),以

不补光为对照(CK)。补光灯间距3 m,距离树顶高度50 cm,地表铺设反光膜。补光时间设置为晴天每天05:00—10:00、16:00—19:30,阴雨天每天05:00—19:30。

1.3 测定方法

于2022年4月13—21日两种供试材料果实转色期至采收期,间隔3~6 d取样,每次取样随机选取各处理3株植株共9个果实,用高效液相色谱法测定果肉GA_s、IAA、ABA含量,3次重复,取平均值。用手持糖度计测定可溶性固形物含量。POD、SS、SPS酶活性的测定参照Solarbio公司的试剂盒说明书进行。

樱桃果皮与果实总RNA的提取采用优化的CTAB-LiCl法,合成cDNA第一链参照Beyotime公司的反转录试剂盒说明书进行。根据NCBI上查找到的同源性较高的樱桃的*NCED1*、*PGI*、*XYLI*、*PAL*、*CHS*、*DFR*、*ANS*、*UFGT*、*MYB10*、*Riant*、*SSI*、*SS6*与*SPSA1*,利用Primer 5.0软件设计特异引物(表1),使用实时荧光定量RT-PCR测定樱桃在采收期各基因的表达量。

1.4 数据统计分析

采用Excel 2013进行数据初步处理,采用SPSS 18.0进行差异显著性分析($p < 0.05$)。

2 结果与分析

2.1 补光处理对果实成熟进程的影响

2.1.1 补光处理对单果质量变化的影响 补光处理对樱桃的果实单果质量增加具有促进作用(表2)。其中LED 36 W补光处理效果最好,使两个品种中国樱桃果实单果质量上升幅度大、采收期单果质量高。该处理下诸暨短柄单果质量在采收期达到2.91 g,比对照组高18.29%,黑珍珠单果质量在采收期达到2.48 g,比对照组高23.38%。

2.1.2 补光处理对果实内源激素含量的影响 内源激素含量是标志成熟进程的重要指标,研究中发现两个樱桃品种果实发育后期,果实内源激素GA_s/IAA/ABA总体呈现上升趋势,补光处理对两个品种樱桃的内源激素含量动态变化进程具有不同程度的促进作用(图1)。在诸暨短柄果实中,内源GA_s与ABA含量在采收前持续上升,两种LED补光灯与G101型激光植物生长灯处理的果实中GA_s与ABA含量在采收前9 d内持续高于对照组。而LED补光

表 1 本研究所需的引物信息
Table 1 Primers used in this study

引物名称 Primer names	引物序列(5'-3') Primer sequences (5'-3')
Actin-F (XM_021972676.1)	CCAAAGGCTAATCGGGAGAA
Actin-R (XM_021972676.1)	ACCACTGGCGTAGAGGAAAG
PaNCED1-F (XM_021978487.1)	CATGTCGAGGACGACTTGCCGT
PaNCED1-R (XM_021978487.1)	GCGCCGTCTGGAGAGACGTGGA
PaPG1-F (XM_021951033.1)	ATCACCTTCCGCATTGCTG
PaPG1-R (XM_021951033.1)	TCACCTTAATGTTGTTGGAG
PaXYL1-F (XM_021966588.1)	ACAACCTGGAACGGTGTGCGAT
PaXYL1-R (XM_021966588.1)	TCCTGGTGTAATGTTGCTCG
PaPAL-F (XM_021948624.1)	GCCTCACCAGGCAACAAGAGCA
PaPAL-R (XM_021948624.1)	TCTGGCCATCTGGTCCAACAGC
PaCHS-F (XM_021960902.1)	GTATGTGCGAGTACATGGCA
PaCHS-R (XM_021960902.1)	GCTTAGTGAGCTGATAGTC
PaDFR-F (XM_021975874.1)	CTGCACCGAGTGTTCATGT
PaDFR-R (XM_021975874.1)	CTGGTGCTCTTCGACGTTAC
PaANS-F (XM_021947877.1)	ATCTCCGATGAGCTCATGG
PaANS-R (XM_021947877.1)	CTCAATGTAATCAGCAGGTG
PaUFGT-F (XM_021949694.1)	CAGATCCGATGATTGAA
PaUFGT-R (XM_021949694.1)	ATTCTAATGTTGAGGCTAAT
PaMYB10-F (XM_021956273.1)	CTGCTAACATACAACGAT
PaMYB10-R (XM_021956273.1)	TTCAACCACCTTAGTCTA
PaRiant-F (XM_021968160.1)	GCTATCTGGCTGGAGAAG
PaRiant-R (XM_021968160.1)	GCTATCTGGCTGGAGAAG
PaSS1-F (XM_021949164.1)	ACGGCCTGGTGTGGGAGTA
PaSS1-R (XM_021949164.1)	GAAATAGCCGTGGGGAGAAAGAT
PaSS6-F (XM_021946051.1)	GCAAGACAGATGGGGACTAT
PaSS6-R (XM_021946051.1)	GCTGCTGCTGTTCTGCTTCTC
PaSPSA1-F (XM_021953379.1)	GCAAACCAAGGCATCCACAAT
PaSPSA1-R (XM_021953379.1)	GAACCCTACAGAGCCTTCAGT

表 2 樱桃果实单果质量

Table 2 Single fruit mass of cherry g

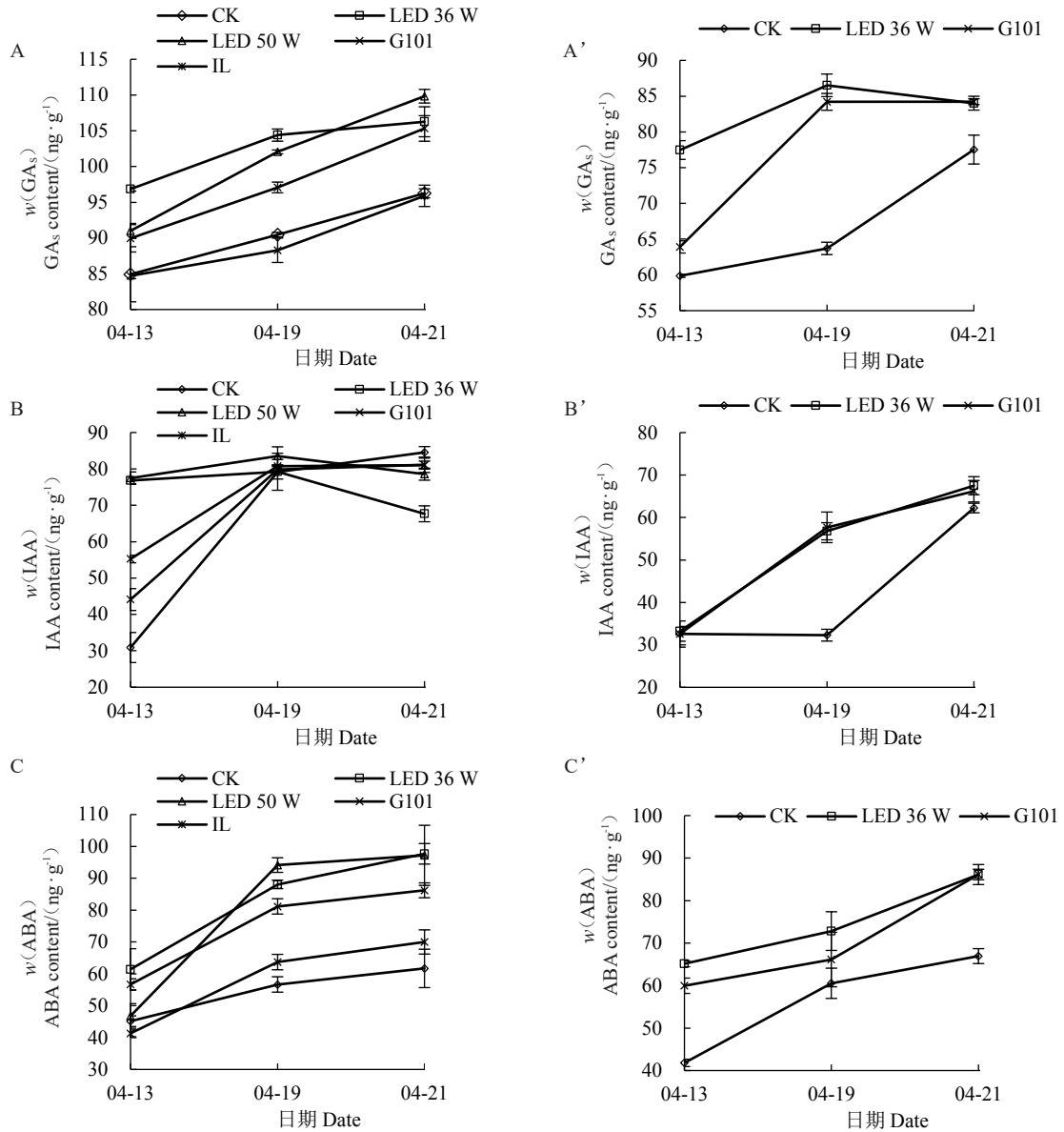
品种 Cultivar	处理 Treatment	日期 Date		
		04-13	04-19	04-21
诸暨短柄 Zhuji duanbing	CK	1.37±0.37 a	2.06±0.34 a	2.46±0.20 a
	LED 36 W	1.50±0.21 a	2.20±0.62 a	2.91±0.48 a
	LED 50 W	1.77±0.31 a	2.47±0.48 a	2.85±0.32 a
	G101	1.83±0.39 a	2.26±0.32 a	2.65±0.33 a
黑珍珠 Heizhenzhu	IL	1.68±0.47 a	2.12±0.39 a	2.59±0.50 a
	CK	0.88±0.13 a	1.62±0.45 a	2.01±0.18 a
Heizhenzhu	LED 36 W	0.68±0.15 a	1.38±0.28 a	2.48±0.38 a
	G101	0.73±0.09 a	1.34±0.28 a	2.16±0.28 a

注:CK. 不补光对照;LED 36 W. LED 灯(36 W);LED 50 W. LED 灯(50 W);G101. G101 型激光植物生长灯;IL. 白炽灯。同一品种不同处理进行差异性分析,不同小写字母表示差异显著($p < 0.05$)。下同。

Note: CK. No light supplement control; LED 36 W. LED lamp (36W); LED 50 W. LED lamp (50 W); G101. G101 laser plant growth lamp; IL. incandescent lamp. The significance of difference among different treatments of the same cultivar. The small letters indicate significant difference ($p < 0.05$). The same below.

处理的果实 IAA 含量上升在采收前 9 d 达到最高点,随后波动,比对照组和其他补光处理提前 6 d 左右。在黑珍珠果实中,LED 补光灯与 G101 型激光植物生长灯处理的 3 种内源激素含量上升也均提前于对照组,其中 GA_3 含量在采收前 3 d 达到高点并波动,比对照组早 3 d 以上。整体上,各补光处理使果实内源激素动态变化趋势提早于对照组,促进了两个品种的果实发育成熟进程,其中 LED 补光处理综合效果较好。

2.1.3 补光处理对樱桃成熟软化相关基因的影响
根据内源激素动态,选择促进果实成熟进程效果最明显、两个樱桃品种均具有的 LED 36 W 补光处理组,进行成熟软化相关基因检测,与对照组进行比较,发现 LED 36 W 补光处理在基因水平上促进了两个品种果实的成熟和软化(图 2)。采收期果实中 ABA 合成酶基因 *NCED1* 在 LED 36 W 补光处理后表达量显著高于自然光照对照组,在分子层面调控果实成熟相关的内源激素水平。而调控细胞壁降解



A~C. 诸暨短柄樱桃; A'~C'. 黑珍珠樱桃。

A-C. Zhujidianbing; A'-C'. Heizhenzhu.

图1 樱桃果实发育后期内源激素含量的动态变化

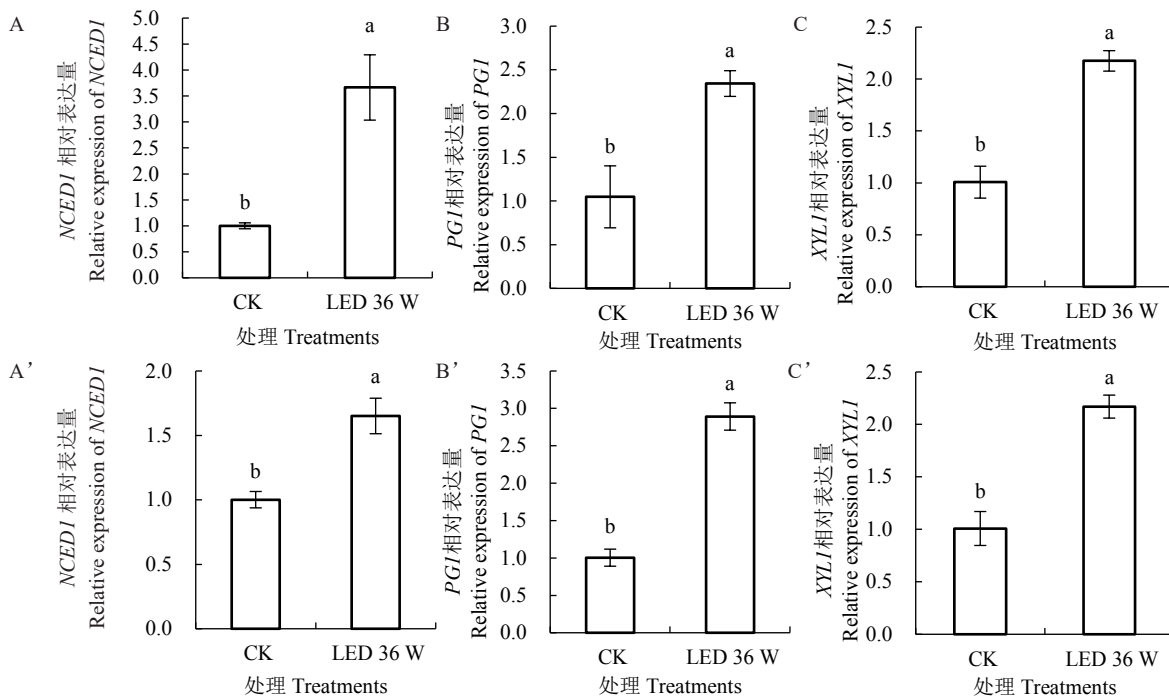
Fig. 1 Dynamic changes of endogenous hormones in cherry at late development stage

的多聚半乳糖醛酸酶基因 *PG1*、木聚糖酶基因 *XYL1* 在该处理下相对表达量也显著高于对照,表明补光处理能够通过正向调控细胞壁降解进程促进果实的软化。

2.1.4 补光处理对果皮花青素合成的影响 果皮着色也是樱桃果实成熟过程的重要指标,LED 36 W 补光灯处理对两种樱桃果皮花青素合成均具有明显促进效果,对果皮着色起积极影响(图3)。通过检测采收期果皮中花青素合成与转运途径基因 *PAL*、*CHS*、*DFR*、*ANS*、*UFGT*、*Riant* 与转录因子 *MYB10*,

发现在诸暨短柄果皮中,LED 36 W 补光处理使 *CHS*、*ANS*、*Riant* 与 *MYB10* 表达量显著高于对照组。而在黑珍珠果皮中,该处理使 *PAL*、*CHS*、*ANS*、*Riant* 与 *MYB10* 表达量均显著高于对照组。LED 36 W 补光处理通过在分子层面激活合成途径基因和转录因子的高水平表达,启动果皮中花青素的合成,进而促进樱桃果皮的着色。

2.1.5 补光处理对果实过氧化物酶活性的影响 过氧化物酶 *POD* 作为活性氧清除剂在果实成熟过程中发挥协调作用,与细胞内的活性氧生成之间保持



A~C. 诸暨短柄樱桃; A'~C'. 黑珍珠樱桃。不同小写字母代表差异显著($p < 0.05$)。下同。

A-C. Zhujidianbing; A'-C'. Heizhenzhu. Different small letters represent significant difference ($p < 0.05$). The same below.

图2 果实成熟软化相关基因的表达

Fig. 2 Relative gene expression related to fruit ripening and softening

着平衡,笔者在本研究中发现POD活性在两个品种樱桃果实发育后期呈现下降趋势,黑珍珠POD活性整体高于诸暨短柄(表3)。各补光处理下果实POD活性的下降不同程度地提早于对照组,两种功率LED补光灯处理的POD活性下降最早,在采收前9 d内持续低于同时期对照组。在诸暨短柄果实中,其他补光处理果实的POD活性下降到两种LED补光处理的水平在时间上滞后9 d左右,而在黑珍珠果实中,G101处理POD活性下降在前期比LED 36 W处理滞后6 d左右,在采收前3 d则加速下降,在采收期达到与LED 36 W处理相同的水平。这在酶活性动态变化层面体现出果实发育成熟的进程被补光处理所促进,其中两种功率LED补光处理的促进效果最明显。

2.2 补光处理对果实糖分积累的影响

2.2.1 补光处理对果实可溶性固形物(TSS)含量的影响

各补光处理不同程度地提高了两个品种樱桃果实采收期TSS含量,以红蓝光比例6:1的LED补光源效果最好(图4)。LED 50 W补光灯处理对诸暨短柄果实TSS含量的提高效果最明显,使果实采收期TSS含量达到17.63%,显著高于对照组的15.30%。而LED 36 W补光灯处理对黑珍珠果实

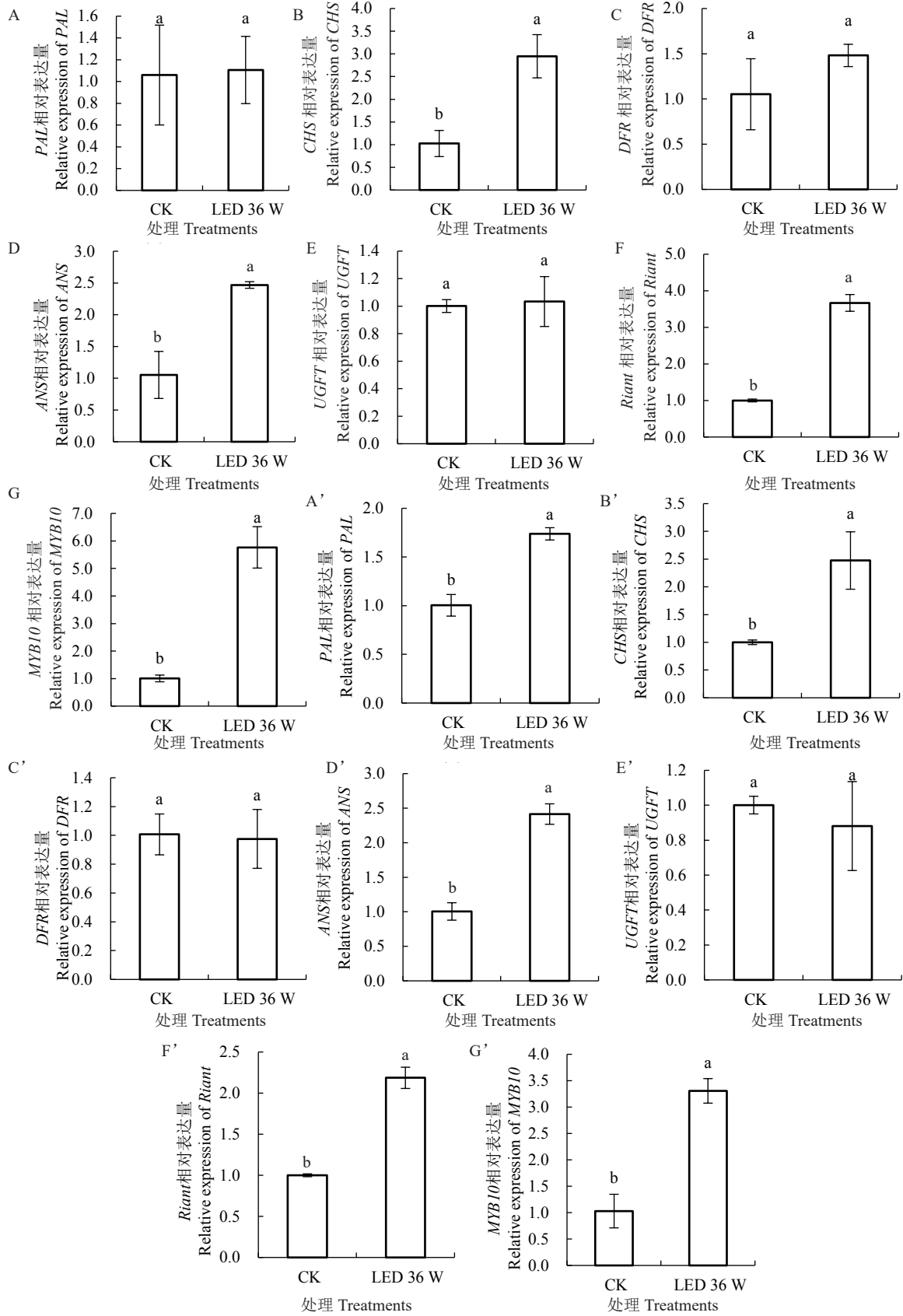
TSS含量的提高效果最明显,使果实采收期TSS含量达到14.67%,显著高于对照组的12.03%。

2.2.2 补光处理对蔗糖合成酶(SS)活性的影响

果实糖分合成与蔗糖合成相关酶密切相关,SS活性在樱桃果实发育后期上升,并在采收前到达高点。各补光处理组果实SS活性在采收前3 d内均显著高于同时期对照组,促进了果实糖分积累(表4)。其中LED补光处理的促进效果最明显,LED 36 W补光处理使诸暨短柄果实SS活性上升较早,在采收前9 d开始高于对照组与其他补光处理,并快速升高,在采收前3 d达到高点,比同时期对照组高69.17%。而LED 50 W补光处理SS活性达到高点较晚,在采收期SS活性最高,比同时期对照组高21.14%。黑珍珠果实发育后期SS活性整体水平稍高于诸暨短柄,但到达高点较晚,在采收前整体保持上升。LED 36 W补光处理使黑珍珠果实SS活性上升较快,在采收期比对照组提高18.75%。

2.2.3 补光处理对蔗糖磷酸合成酶(SPS)活性的影响

在两个樱桃品种果实发育后期,SPS活性均没有表现出明显的变化规律,黑珍珠SPS活性整体高于诸暨短柄(表5)。LED 36 W补光处理使黑珍珠果实SPS活性在采收前9 d内持续高于同时期对照组



A~G. 诸暨短柄樱桃; A'~G'. 黑珍珠樱桃。

A-G. Zhujidianbing; A'-G'. Heizhenzhu.

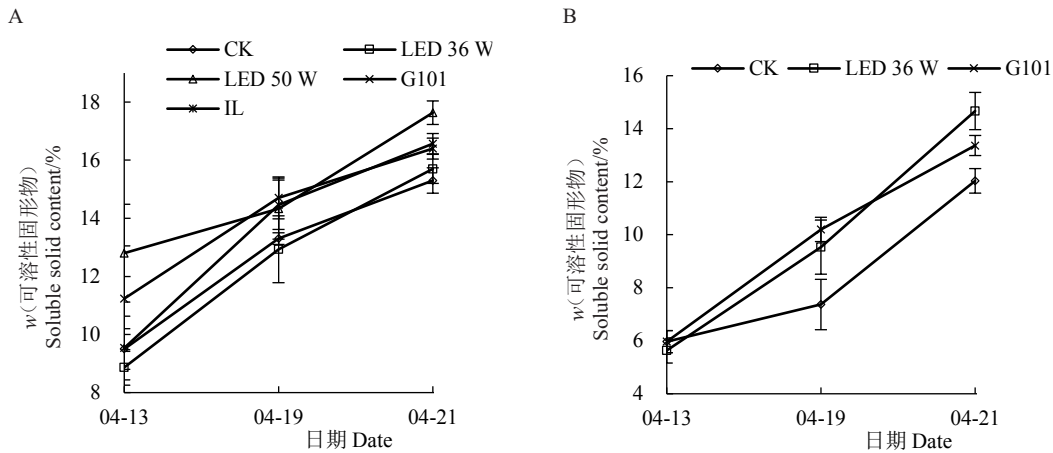
图3 果皮花青素合成相关基因的表达

Fig. 3 Relative gene expression related to anthocyanin synthesis in pericarp

表 3 樱桃果实过氧化物酶 POD 活性
Table 3 Activity of peroxidase (POD) in cherry

(U·g⁻¹)

品种 Cultivar	处理 Treatment	日期 Date		
		04-13	04-19	04-21
诸暨短柄 Zhujidianbing	CK	1 343.38±25.05 a	1 219.74±7.13 a	1 203.10±32.16 a
	LED 36 W	1 079.46±10.90 d	865.47±4.12 c	827.43±62.18 c
	LED 50 W	993.86±10.90 e	810.78±17.95 d	760.85±70.37 c
	G101	1 146.04±4.12 c	1 096.10±4.12 b	977.22±71.33 b
黑珍珠 Heizhenzhu	IL	1 248.28±12.35 b	1 131.77±32.95 b	981.98±14.85 b
	CK	1 975.84±14.27 a	1 761.85±12.35 a	1 362.40±12.35 a
Heizhenzhu	LED 36 W	1 495.55±14.85 c	1 203.10±39.29 c	943.93±14.85 b
	G101	1 616.81±22.93 b	1 552.62±10.90 b	979.60±35.90 b



A. 诸暨短柄樱桃; B. 黑珍珠樱桃。
A. Zhujidianbing; B. Heizhenzhu.

图 4 补光处理对果实 TSS 含量的影响

Fig. 4 Effect of supplementary light treatment on TSS content

表 4 樱桃果实蔗糖合成酶 SS 活性

Table 4 Activity of sucrose synthase (SS) in cherry

(U·g⁻¹)

品种 Cultivar	处理 Treatment	日期 Date		
		04-13	04-19	04-21
诸暨短柄	CK	323.42±0.80 c	478.59±0.55 e	658.84 ±1.16 e
Zhujidianbing	LED 36 W	374.76±0.17 a	809.65±0.22 a	729.36±4.06 c
	LED 50 W	362.19±0.65 b	654.24±0.55 d	798.14 ±0.75 a
	G101	306.75±0.65 d	715.20 ±0.38 c	686.15 ±4.26 d
	IL	324.34±0.97 c	723.51 ±0.69 b	772.14 ±1.35 b
黑珍珠	CK	370.65±0.25 b	684.65±0.44 c	777.79±2.86 c
Heizhenzhu	LED 36 W	346.48±0.59 c	831.93±0.44 a	923.63±2.96 a
	G101	421.89±0.30 a	707.75±0.51 b	826.08±0.72 b

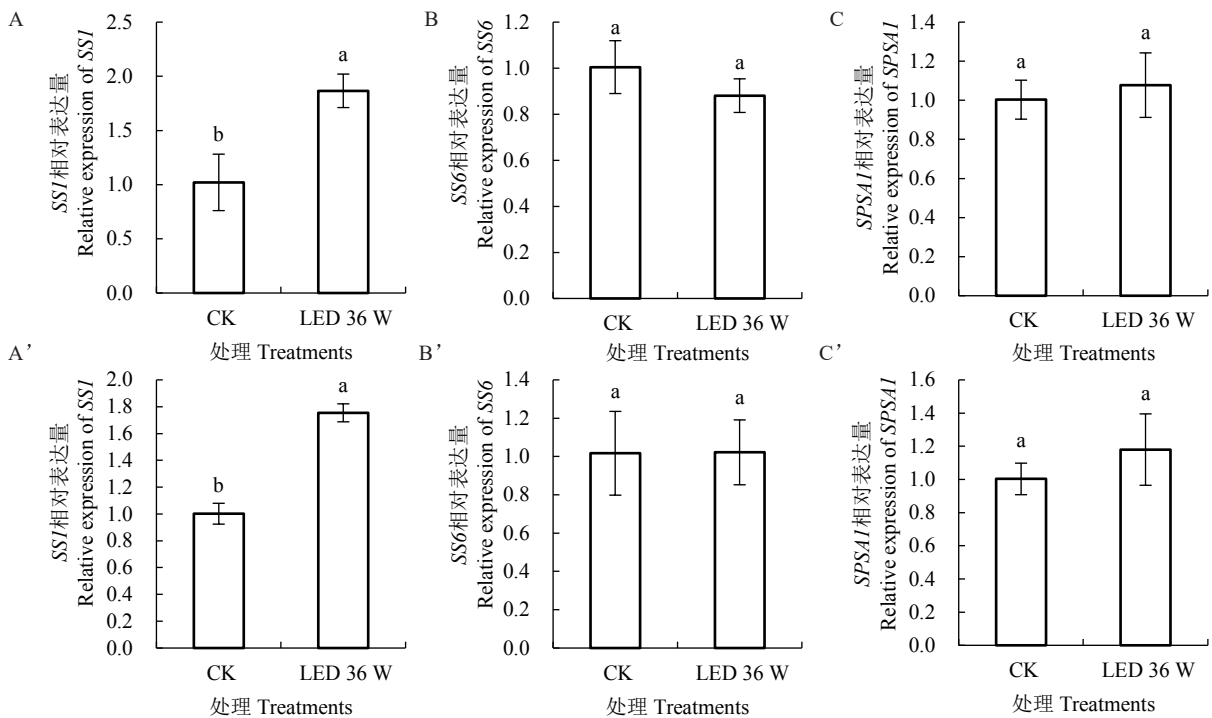
与其他补光处理,采收期 SPS 活性比对照组高 35.79%。而在诸暨短柄果实中,各处理组在果实发育后期 SPS 活性均普遍保持较低水平。

2.2.4 对蔗糖合成相关基因的影响 根据果实 TSS 与蔗糖合成相关酶活性,选择促进果实糖分积累效果最明显、两个樱桃品种均具有的 LED 36 W 补光

处理组,进行蔗糖合成相关基因检测,发现 LED 36 W 补光处理在基因水平上促进了两个品种的果实糖分积累(图 5)。分析采收期果实中与糖合成相关的蔗糖合成酶基因 *SSI*、*SS6* 与蔗糖磷酸合成酶基因 *SPSA1* 的相对表达量,结果表明,在两个品种中,LED 36 W 补光处理使果实中 *SSI* 基因表达量显著

表 5 樱桃果实蔗糖磷酸合成酶 SPS 活性
Table 5 Activity of sucrose phosphate synthase (SPS) in cherry

品种 Cultivar	处理 Treatment	日期 Date		
		04-13	04-19	04-21
诸暨短柄 Zhujidianbing	CK	192.99±1.26 d	183.57±0.50 e	214.97±2.57 a
	LED 36 W	178.42±0.66 e	220.48±0.63 c	199.45±2.19 b
	LED 50 W	199.09±0.25 c	226.43±0.13 b	191.69±0.75 c
	G101	210.84±0.76 b	212.58±0.38 d	170.73±1.24 e
黑珍珠 Heizhenzhu	IL	248.48±0.66 a	235.13±0.13 a	175.88±1.57 d
	CK	422.32±0.44 c	388.16±0.82 c	350.74±1.12 c
Heizhenzhu	LED 36 W	464.32±0.38 a	496.74±1.00 a	476.28±6.55 a
	G101	442.56±1.12 b	435.16±0.22 b	394.04±0.98 b



A~C. 诸暨短柄樱桃; A'~C'. 黑珍珠樱桃。
A-C. Zhujidianbing; A'-C'. Heizhenzhu.

图 5 蔗糖代谢相关基因表达

Fig. 5 Relative gene expression related to sucrose metabolism

高于对照组,而 SS6 与 SPSA1 表达量在不同处理之间无明显差异,表明 SS1 在响应补光处理这一过程中起主要作用。此结果与前文对 SS 与 SPS 的研究结果相符,即补光处理主要通过激活 SS1 的表达正向调控 SS 的合成,进而通过 SS 促进樱桃果实的糖分积累。

3 讨论

人工补光处理可以缩短园艺作物果实发育期,促进产品提早成熟上市,提高设施园艺生产经济效益^[20]。在影响果实的生长发育与成熟进程的诸多因

素中,内源激素起着重要的调控作用,赤霉素和生长素在果实品质形成过程中,促进了果肉细胞的生长和体积增大,脱落酸则对果实的成熟软化具有重要的调控作用。内源激素对果实发育的影响,在葡萄^[21]、梨^[22]等果树上已有研究,甜樱桃果实发育成熟过程中内源激素动态变化也有报道^[23-24]。笔者在本研究中发现,两种中国樱桃果实发育后期内源激素动态变化趋势与前人在甜樱桃中的研究成果基本一致,GA_s、IAA、ABA 含量总体呈现上升趋势,并在采收前达到高点。补光处理对两个品种樱桃的内源激素动态变化进程具有不同程度的促进作用,使激素

达到高点的时间提前于对照组,表明补光促进了樱桃果实成熟进程。在前人对补光调控果实内源激素的研究中,发现夜间补光在提高葡萄果实 IAA 和 GA₃ 含量的同时,还能降低 ABA 含量^[25]。而本研究中细化了内源激素测定时间点,以呈现激素水平的动态变化,在单一时间节点中补光处理对内源激素水平的影响与前人研究不完全一致。其原因可能包含了不同物种果实内源激素调控的差异以及取样测定时间节点不同等因素,有待进一步探究。

果实的成熟软化过程在基因层面受到分子网络的调控,研究主要围绕调控软化过程的植物激素 ABA 的合成途径基因,以及细胞壁降解相关酶类合成基因。*NCED* 是 ABA 合成途径中的限速酶,对于果实的成熟具有重要的作用^[26]。在番茄中沉默 *SINCE1* 会延缓果实成熟进程^[27],桃的 *NCED2/3* 基因也正向调控果实成熟^[28]。笔者在本研究中发现,两个中国樱桃品种采收期果实中 *NCED1* 相对表达量在 LED 36W 补光处理后均显著高于自然光照对照组,表明其在分子层面调控了果实内源激素水平,促进了果实成熟进程。多聚半乳糖醛酸酶基因 *PG* 是可合成分解果胶或果胶酶类基因中的一种,而木聚糖酶基因 *XYL* 是合成降解半纤维素的木聚糖酶的主要酶类,二者通过促进细胞壁的降解直接调控果实软化过程^[29]。在本研究中,两个品种中国樱桃果实采收期的 *PGI*、*XYL1* 相对表达量在 LED 36W 补光处理后均显著高于对照组,表明补光处理在基因调控层面还能通过调节细胞壁的降解促进樱桃果实的软化,与前人研究结果一致^[29]。

花青素的生物合成也会受到光照环境的影响,补光处理会显著提高苹果等多种果树果实果皮中的花青素含量^[30-31]。*PAL*、*CHS*、*DFR*、*ANS*、*UFGT* 与 *MYB10* 是果皮花青素合成途径的关键基因和转录因子^[32-34],调控谷胱甘肽 S-转移酶(*GST*)合成的 *Ri-ant* 基因则在花青素从内质网至液泡的转运过程发挥作用^[35]。笔者在本研究中发现,这些花青素合成与转运途径基因不同程度地被 LED 36 W 补光处理激活高水平表达,与前人研究成果基本一致。糖积累也在果实发育和品质形成过程中起着重要的作用,*SS* 与 *SPS* 是参与蔗糖合成的关键酶,在甜樱桃中也被证实参与糖分合成^[36]。在本研究中,LED 36 W 补光处理均显著地提高了果实 *SS* 活性和 *SPS* 活性。而对基因层面的研究则发现,调控 *SS* 合成的

SSI 基因在补光促进两种中国樱桃果实糖分积累这一过程中起主要作用,与在甜樱桃中对 *SS* 基因家族的研究结果基本一致。

笔者在本研究中发现,促进果实发育整体效果最好的处理是 LED 36 W 补光处理,该方法使樱桃果实成熟进程整体提早于对照组,并提高了果实糖分积累相关指标。同时,由于诸暨短柄果实成熟期稍早于黑珍珠,因而在内源激素和酶活性动态变化的过程中,同期两个品种存在差异,如何针对具体品种适配补光措施尚需进一步研究。

开发与设施栽培相配套的补光处理技术能够促进樱桃果实成熟与糖分积累,提升果实品质,值得进行深入研究并推广应用。

4 结 论

人工补光处理对设施栽培樱桃果实成熟与糖分积累具有促进作用。LED 补光灯(36 W, RB 6:1)处理能够促进果实内源激素变化进程,并在基因层面促进果实软化、果皮着色并提高果实糖分合成能力。该方案能够通过改善设施栽培中的光照环境有效提高果实综合品质,值得进行深入研究并推进其在浙江省樱桃产业中的应用。

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