

甜樱桃果实品质研究进展

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摘要:果实品质是良种选择和果品选优的重要依据,然而在甜樱桃生产中仍存在果实品质不佳等问题。为科学提升甜樱桃果实品质和产量,本文首先重点阐述了果实外观品质(形状、大小、果皮颜色等)和内在品质(质地、甜酸度、风味、激素等)形成过程中的生理生化变化机制;分析了内部因素(品种、砧木等)和外界因素(温度、光照、水分、养分等)对果实品质形成的影响;其次总结了提高甜樱桃果实品质的不同措施及其研究进展;最后对未来提高甜樱桃果实品质的研究内容和方向进行了展望。

关键词:甜樱桃;果实品质;可溶性糖;有机酸;矿质营养

中图分类号:S662.5

文献标志码:A

文章编号:1009-9980(2025)10-2430-10

Research advance in fruit quality of sweet cherry

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Abstract: Fruit quality is an important basis for breeding and selection of high-quality fruits. However, there are problems such as insufficient fruit quality in the production of sweet cherries. In order to scientifically improve the quality and yield of sweet cherry fruits, this article focuses on the appearance quality parameters such as fruit shape, size, and skin color, as well as a series of physiological and biochemical changes such as texture, sweetness and sourness, flavor, hormones, and other internal quality formation. The influence of internal and external factors are also analyzed, such as variety and rootstock, temperature, light, water, and nutrients, on the formation of fruit quality; Secondly, the research progress in different measures to improve the quality of sweet cherry fruits is summarized; Finally, prospects are proposed for the research content and direction of improving cherry fruit quality. Sweet cherry fruit is a stone fruit, and its texture characteristics include hardness, brittleness, and juiciness, which directly determine consumers' choices, and the storage and transportation properties of the fruit. The sweetness is soluble solids content (SSC), the acidity is titratable acidity (TA), and the optimal SSC/TA ratio is between 1.5 and 2.0. Cherry fruits belong to the sugar accumulation type, with glucose and fructose as the main sugar components. The sucrose content is low and the fruit does not accumulate starch and sorbitol. The flavor substances in cherries mainly include aldehydes, alcohols, ketones, acids, esters, and terpene compounds. Sweet cherries are rich in dietary phenolic compounds. It is mainly composed of phenolic acid (hydroxy cinnamic acid) and flavonoids (xanthone alcohol, flavonoids, flavanone, flavan-3-ol, flavones and anthocyanins). The total phenolic content in the flesh and peel of sweet cherries accounts for 3.99% to 39.01% and 61.99% to 76.02% of the total phenolic contents in the entire fruit, respectively. They are rich in minerals such as calcium ($14 \text{ mg} \cdot 100 \text{ g}^{-1}$), magnesium ($10 \text{ mg} \cdot 100 \text{ g}^{-1}$), phosphorus ($20 \text{ mg} \cdot 100 \text{ g}^{-1}$), and potassium ($200 \text{ mg} \cdot 100 \text{ g}^{-1}$). Cherry fruits are nonclimacteric and the ripening process is mainly controlled by the plant hormone abscisic acid (ABA). Their content rapidly increases during the color transition period and reaches the highest level 4 days before harvest. The fac-

收稿日期:2025-05-07

接受日期:2025-05-31

基金项目:国家桃产业技术体系樱桃熊岳综合试验站(CARS-30-ZY-25)

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tors that affect the quality of sweet cherry fruit vary greatly among cherry varieties in terms of fruit hardness. The interaction between scions and rootstocks affects the water relationship, leaf air exchange, mineral element absorption, plant size, flowering, fruit setting time, fruit quality, and yield efficiency of the grafted tree. Low temperature is beneficial for the accumulation of sugars, starch, and other substances in plants. In areas with large temperature differences between day and night, fruits accumulate more dry matter, and have larger sizes with high sugar content. Adequate light can promote the rapid accumulation of secondary metabolites during fruit development. Drought stress leads to severe physiological fruit drop and yellowing of sweet cherries, which affects fruit yield. The impact of precipitation on fruit quality is mainly manifested in the inhibition of root growth, absorption, and transportation activities before fruit maturity, resulting in inhibition of above ground growth. Mechanical damage to sweet cherry skin is isotropic, and its mechanics mainly depend on the epidermis and subcutaneous tissue, rather than the stratum corneum. The measures to improve the quality of sweet cherry fruit include cultivation management mode, surface coverage, reasonable fertilization, exogenous hormones, and storage methods. Drip irrigation and summer pruning will increase fructose levels and total phenolic content. The position of trees in the orchard and the position of fruits on the trees affect fruit weight and quality, and fruit size and sweetness decrease with increasing plant density. Grass covering cultivation can significantly increase the yield of sweet cherries and improve the quality of their fruits. Long term film covering can lead to certain enhancement of photosynthetic characteristics in the leaves and improve the coloring of cherry fruits, but there is no difference in the size of cherry fruits produced with or without film covering. Increasing the dosage of N has a positive impact on the required fruit quality attributes (such as fruit color and flesh hardness), while excessive potassium application has no positive impact on fruit quality, and may even have a negative impact. The most suitable potassium application amount is 400 g K_2O per plant, and a high dosage of 600 g leads to a decrease in other nutrients, as well as FF, SS, and TA. Boron fertilizer has no effect on the vitality and yield of sweet cherry trees, and B fertilizer has no effect on the average fruit weight, titratable acidity and fruit cracking sensitivity. In addition, foliar calcium spraying before fruit ripening can significantly increase the content of Ca, Mg, K, Na, and Fe mineral elements during fruit storage. The application of growth regulators can improve the storage, increase the red color and fruit size, and reduce cracks. The application of cytokinin at the early stage of fruit development, or the application of synthetic auxin at the time of stone hardening stage can stimulate the growth of sweet cherries, thus stimulating their final fruit size. In addition, auxin has also been proved to play an important role in calcium transport and absorption of fruits during development in plants. Several types of polysaccharide coatings have been used for sweet cherry preservation, such as sodium alginate, chitosan, whey protein isolate, almond gum, acacia senegal and aloe gel, guar gum (GG) and ginseng extract.

Key words: Sweet cherry; Fruit quality; Soluble sugar; Organic acid; Mineral nutrition

甜樱桃 (*Prunus avium* L.) 原产于亚洲西部和欧洲东南部, 现集中分布在北纬 25° 至南纬 55° 之间的欧洲、亚洲和北美洲温带冷凉地区^[1], 是果实成熟最早的落叶果树之一。甜樱桃果实营养丰富, 除鲜食外, 还可以加工成酒、果汁、罐头、果脯等多种副产品。甜樱桃果实由子房发育而成, 发育期短, 从授粉到果实完全成熟需 50~70 d。甜樱桃果实成熟过程

表现出特征鲜明的双相生长模式, 属于非呼吸跃变型^[2], 采后果实质地迅速软化是导致甜樱桃不耐贮藏的主要原因之一。

品质评价是对果实大小、形状、颜色等所有外观品质和质地、硬度、风味、甜酸度和功能营养成分等内在品质的综合评价, 是良种选择和果品选优的重要依据。樱桃果实品质形成过程涉及色素积累、果

实软化、香气和风味物质形成等系列生理生化变化。可溶性糖、有机酸及挥发性物质三者的组分及含量决定果实的品质和风味。樱桃呈酸甜或甜酸风味,其甜味由果糖、葡萄糖、蔗糖和山梨醇构成,酸味主要是由于有机酸(如苹果酸、柠檬酸、琥珀酸、乳酸和草酸)的存在^[3]。果实中的糖和有机酸是合成维生素和氨基酸等营养成分的基础物质,在果实的呼吸作用、光合作用以及酯类、酚类和氨基酸的合成中发挥重要作用^[4]。果实中的多糖(如果胶)、多酚与抗氧化剂有关。可溶性糖、花青素和激素含量在果实转色期发生显著变化,樱桃果实成熟与糖、维生素和有机酸含量的变化有关。

光照、温度、降水等气候条件影响树体的生长发育和果实的品质形成。充足的光照能促进果实发育过程中次生代谢物质迅速积累;昼夜温差直接影响果实的形态建成和干物质积累^[5];充分的降水量有利于果实膨大,直接影响到果实的单果质量和果形,雨后裂果影响果实品质。矿物质含量是评价果实营养价值的重要指标之一,氮、磷、钾是甜樱桃生长发育中必需的大量元素,还需要钙、铁、锌、硼等元素。矿质元素不仅是构成酶和维生素的活性因子,还参与合成某些激素并影响核酸代谢^[6]。此外,科学的栽培管理措施也能有效提高果实品质。

1 果实外观品质

1.1 果实形状

甜樱桃果实为核果,由外果皮、中果皮(果肉)、木质内果皮(果核)三部分构成。受精后的单个子房发育成具有肉质子房壁的果实,子房壁最内层的内果皮木质化,形成坚硬的核,核内含单粒种仁。优质甜樱桃果实果粒完整,有光泽,果柄完整新鲜,果实无机械损伤,无病虫害,大小整齐一致,无畸形果。根据欧洲参考品种Burlat的成熟度,樱桃品种可分为早熟、中熟和晚熟类型^[7]。果实形状和大小受细胞分裂(细胞数量)、分布和膨大(细胞大小)的控制。果实梗洼的相对深度和果实的高宽比是甜樱桃果实形状的两大决定因素^[8]。甜樱桃品种的果形等级评定中,分为五个标准果形类别(FSC),分别为FSC1(肾形)、FSC2(扁圆形)、FSC3(圆形)、FSC4(椭圆形)和FSC5(心形)^[8]。果顶形状以凹居多,其次是平、凸和尖^[9]。

1.2 果实大小

果实质量由果肉质量决定,与果肉质量的大小和变化幅度相近。樱桃果实水分含量均超过80%^[9],收获前一周可增加25%的果实质量。甜樱桃单果质量12~15 g,可食率93%以上。樱桃果实生长发育分为三个阶段,S1阶段中果皮细胞分裂和伸长,呈指数型生长;S2阶段以细胞壁的增厚和硬化为主,内果皮开始木质化,果实生长缓慢,这一过程与内果皮硬化和胚胎发育相一致,S2阶段的中期之后细胞分裂停止^[10];S3阶段的特征为中果皮的迅速膨大和果实质量的增加。

单果质量的变化规律与果肉细胞的变化规律一致,细胞数量不受环境影响,具有较高的遗传力,该性状相对容易从育种选择中获得。野生甜樱桃NewYork54中果皮细胞数是28层细胞,从幼果到果实成熟没有增加;早期选育中果型樱桃品种EmperorFrancis中果皮细胞数为41层;而大果型Bing和Regina的细胞层数分别为48层和44层;经过两代大果选育的超大果型的品种Selah细胞层数量显著增加到78层。中果皮细胞数量增加是甜樱桃果实增大的遗传潜力,与驯化和现代育种有关。此外,中果皮细胞数量非常稳定,不受生长位置、决定果实大小的生理因素或环境条件的影响。而细胞长度受环境影响较大,不同品种之间也差异显著,使中果皮细胞最大化的栽培管理可提高栽培品种果实的果个和单果质量。果肉细胞数量和细胞体积决定了不同品种果实大小的差异性,果肉细胞数量与果实质量的相关性高于果实细胞体积,是决定不同品种间樱桃果实大小的主要因素;而果肉细胞体积可以通过栽培环境进行调节^[11]。

1.3 果皮颜色

甜樱桃果实生长过程中颜色从绿色转变为淡黄色、稻草黄色、粉红色和红色。以红色调为主,从深粉红色到深红黑色,也有黄色品种。大多数红肉甜樱桃具有暗红色的果肉、汁液和表皮,而黄肉甜樱桃品种可能具有黄色的果肉和表皮。果实颜色与果实成熟过程有关,受花青素种类、无色酚类物质的浓度和分布及pH的共同作用,并伴随着硬度、甜度、酸度和香气的变化^[11]。着色过程始于叶绿素含量下降和类胡萝卜素的积累,导致果实颜色变黄。成熟初期甜樱桃粉红色的着色和糖含量的增加与脱落酸(ABA)的积累有关。红色主要由花青素含量决定,果皮中的花青素含量高于果肉^[12]。随着果实颜色的加深,可溶性固

形物含量显著增加,总酚和总黄酮含量增加,抗氧化活性最高。颜色较深的果实含有较高的可溶性固形物、糖类和花青素含量,深色品种的抗氧化活性高于浅色品种,且不同颜色果实内糖类、有机酸、槲皮素和山奈酚等物质组分含量不同。

甜樱桃富含膳食酚类化合物,主要由酚酸(羟基肉桂酸)和黄酮类化合物(黄酮醇、黄酮、黄烷酮、黄烷-3-醇、异黄酮和花青素)组成。花青素和黄酮醇模式可用于确定樱桃的品种分类^[13]。甜樱桃果肉和果皮中总酚含量分别占整个果实总酚含量的3.99%~39.01%和61.99%~76.02%,说明总酚主要存在于樱桃的表皮及邻近组织。果实呈现蓝色、紫色和红色等颜色归因于水溶性花青素(类黄酮化合物)的积累^[14]。花青素是甜樱桃中主要的酚类物质(占总酚类物质的58.44%~65.33%)^[15],樱桃果实中花色苷以花色苷-3-*O*-芸香苷为主,含量最高。早熟品种的酚酸类物质、黄酮类化合物和黄烷-3-醇类化合物的积累主要集中在转黄色阶段,而中熟品种主要集中在绿色阶段,表明次生代谢产物的积累具有品种特异性^[15]。非花青素多酚含量随着果实成熟而降低,花青素含量随着果实成熟而增加^[12]。

2 果实内部品质

2.1 质地

果实质地特征(硬度、脆度、多汁性等)直接决定果实的贮藏性和运输性等,主要取决于果实的细胞形态、膨压、细胞壁强度和胞间结构等^[16]。甜樱桃绿果期细胞小且排列整齐,细胞壁结构完整;转色期细胞壁和胞间层降解,细胞体积增大,细胞间隙增大;果实成熟后期,果实的细胞壁完整性被破坏,同时伴随着胞间层的降解和质壁分离。早熟品种细胞壁降解比中晚熟品种严重,细胞间的连接已经完全消失。早熟品种果肉通常较软^[17],晚熟品种果肉坚实,细胞致密。果实成熟过程中硬度的变化包括多糖的溶解、解聚、结合和重排,半纤维素-纤维素糖是甜樱桃幼果细胞壁的主要成分^[18],半纤维素的降解会引起细胞壁结构的松散,其含量从幼果期就不断下降并维持在较低水平^[19]。胞间结构与果胶含量密切相关,胞间层由果胶多聚物构成,硬肉樱桃的细胞壁化合物聚合度更高。樱桃果实发育初期的果胶为原果胶,此时果肉硬度大、细胞壁结构基本完整。软肉品种成熟时比硬肉品种具有较低的总细胞壁含量和较

高的水溶性果胶含量^[16]。

2.2 甜酸度

甜度可表示为可溶性固形物含量(SSC),酸度表示为可滴定酸(TA)含量,最佳的固酸比(SSC/TA)在1.5~2.0之间,可溶性固形物含量(*w*,后同)在17%~19%之间,果汁的最佳pH为3.8^[16]。总可溶性固形物(TSS)和可滴定酸含量与樱桃风味密切相关,随着总可溶性固形物和可滴定酸含量的升高,消费者的接受度不断增加。可滴定酸含量还依赖于樱桃品种,其含量范围在0.4%~1.5%之间^[20]。甜樱桃果实pH随着品种的不同而发生显著变化,甜心品种的最小和最大pH分别为3.56和3.80。樱桃属于已糖积累型果实,糖组分主要为葡萄糖和果糖,蔗糖含量较低,不积累淀粉和山梨醇。成熟期甜樱桃果实葡萄糖浓度在56.35(D.diCesena)~82.78(Van)g·kg⁻¹之间,其次是果糖,果糖主要来自叶片的光合产物,浓度在44.30(D.diCesena)~61.92(Van)g·kg⁻¹之间,蔗糖是第三丰富的糖类,其浓度在4.16(Vista)~6.92(Belge)g·kg⁻¹之间。樱桃中的核糖醇浓度较低(0.58~1.46 g·kg⁻¹),山梨醇含量占总糖醇含量的90%以上^[21]。有机酸的总含量在28.60(Dalbasti)~54.11(Bing)g·kg⁻¹之间,主要包括苹果酸、柠檬酸、琥珀酸、草酸、酒石酸、富马酸和乙酸等7种有机酸。苹果酸占总有机酸含量的65%~80%,为典型的苹果酸型水果,Bing(42.78 g·kg⁻¹)和Sweetheart(40.53 g·kg⁻¹)的苹果酸含量高于其他品种。第二主酸为柠檬酸,其含量在0.59~6.17 g·kg⁻¹之间^[21],这两种酸也是西班牙、土耳其和斯洛文尼亚地区甜樱桃的主要成分^[3,10]。

2.3 风味

樱桃中的风味物质主要包括醛类、醇类、酮类、酸类、酯类以及萜烯类化合物。主要挥发性物质1-己醇、(*E*)-2-己烯-1-醇、苜醇、己烯醛、(*E*)-2-己烯醛、苯甲醛、乙酸乙酯、丁酸乙酯、己酸乙酯、*L*-柠檬烯、芳樟醇、己酸、乙醇、2-丙酮、乙醛、己醛、苯甲醛、苯甲醇等是甜樱桃果实的特征香气成分^[22],其中(*E*)-2-己烯醛、2-己烯醛、己醛、(*E*)-2-己烯-1-醇是最关键的香气成分^[23]。香气成分在果实着色阶段开始迅速积累,随着果实成熟而不断增加。挥发性物质中含量最丰富的化学基团是醛类,主要为C6醛(己醛)和芳香醛,对水果香气和风味有重要贡献,主要通过脂氧合酶(LOX)途径由脂肪酸生成。红灯果实转色期

C6醛含量迅速上升至84.16%，然后随着果实成熟进程逐渐下降，商品期和成熟期分别下降至59.20%和55.58%。苯甲醛由苦杏仁苷水解产生，给甜樱桃带来甜杏仁般的香味，其含量随着果实成熟度的增加而升高，在成熟期达到最大值^[24]。甜樱桃果实的醇类化合物包括C6醇和芳香醇，其含量最大值出现在商业采收期，乙醇则出现在成熟阶段。智利生产的Regina樱桃品种在上市时会产生草本味道，发病果园中己醛和(E)-2-己烯醛的含量比其他果园低，表明甜樱桃的C6醛类含量与该产区Regina草本异味的形成相关^[25]。

2.4 激素水平

樱桃果实发育早期，果实和种子之间有持续的交流，胚乳或种皮中产生生长素和赤霉素，这种交流的中断是导致生理落果的诱因之一^[2]。ABA在红色和紫色果实着色过程中起核心作用，可提高花青素和糖含量，其含量在转色期迅速增加，并在采收前4天达到最高水平，同时降低果实硬度和酸度^[26]。早熟品种Glenred果实ABA和花青素含量同时增加，ABA积累和粉红色着色两个过程同时发生；而中熟品种lapins果实则先积累ABA（稻草黄色阶段），数日后出现花青素积累和粉红色着色^[13]。外源乙烯处理对非跃变型甜樱桃果实的呼吸速率及果实软化没有显著影响，在果实发育和成熟过程中未观察到乙烯产生和呼吸的爆发^[2]。赤霉素(GAs)存在于甜樱桃果实成熟初期，在S3阶段种仁GAs含量达到峰值，而果皮中的GAs含量峰值几天后出现。GA₃与GA₄变化模式不同，GA₃在转色期表现最为活跃，促进果实膨大，降低果实着色、硬度及可溶性固形物、酚类物质、总花色苷含量和总抗氧化能力。GA₄含量随果实发育而降低，与花青素、可溶性固形物含量和果实生物量呈极显著相关。GAs处理可以降低樱桃果实的呼吸速率、抑制乙烯释放、延缓果实软化和色素变化，使果实保持较高的硬度和有机酸含量，从而改善果实质地及品质^[27]。

3 影响甜樱桃果实品质的因素

3.1 品种和砧木

不同樱桃品种间果实硬度存在基因型差异，遗传背景决定了果实的结构和化学特征。花色苷和无色酚类化合物的组成依赖于品种，Lapins和DuronedellaMarca中最具代表的酚类物质分别是花青素和

黄烷-3-醇^[12]。希腊22个樱桃品种中，Vasilidi和TraganaEdessisNaousis以及育种系TxAg33富含生物活性化合物，总酚含量较高^[28]。西班牙阿利坎特地区的7个甜樱桃主栽品种中具有最高抗氧化活性的是Burlat和Brooks^[29]。不同品种对失水导致的果皮皱缩(橘皮)病的敏感性不同，德国的DönissensGelbe和GilPeck品种抗性较强，易感病品种是Adriana、Regina和Hedelfinger^[30]。Bakirtzeika品种采后贮藏时间较长，是贮藏时间最长的希腊品种，其果梗去除的阻力较大，延缓了水分流失^[19]。土耳其主栽的12个甜樱桃品种中，Belge和Dalbasti的质地和风味高于其他品种，其中Belge品种总酚和花青素含量最高^[21]。

接穗与砧木的相互作用影响嫁接树水分、叶气交换、矿质元素吸收、植株大小、开花、坐果时间、果实品质和产量效率^[31]。研究Adara、Gisela5、Gisela6、Mariana2624、MaxMa14、Mayor、Pikú1、Pikü3、Pikó4和Saint-LucieGF64等10个砧木对Newstar品种树势、产量和果实品质的影响，发现MaxMa14砧木表现为果实最小，但着色好；Gisela5的树势弱，产量和果实品质差；Mariana2624、Mayor和Adara产量最高，果实品质好，农艺性能最好；Pikü3的产量较低，在果实大小、可溶性固形物含量和果实硬度等方面最高^[32]。选择合适的砧穗组合可提高果实硬度、果实质量及糖、维生素和酚类化合物含量，从而提高果实抗氧化活性。

3.2 环境因素

3.2.1 温度 避雨栽培下甜樱桃开花和坐果期间温度的升高，促进S1阶段细胞分裂，果实质量和产量高于露地。昼夜温差直接影响果实的形态建成和干物质积累，低温下有利于植物体内糖类、淀粉类等物质的积累，昼夜温差大的地区果实干物质积累多，果型较大，糖含量高^[5]。甜樱桃果实发育的最佳温度为24℃，临界温度为35℃，高温会严重抑制花青素在果皮中的积累，延缓果实着色进程。常温处理(24℃白天/14℃黑夜)和高温处理(HT,34℃白天/24℃黑夜)4d后，果皮中总花青素含量分别提高了45.50%和84.00%，总可溶性糖含量分别提高了29.49%和16.81%。高温抑制了甜樱桃皮中葡萄糖、果糖、山梨醇和半乳糖的积累，但不抑制蔗糖的积累^[33]。延迟冷却会导致果实快速变质、果实皱缩和茎部褐变，从而缩短采后寿命。在采收后4~6h内将

其冷却至0℃,以减少果实变质并最大限度延长采收后的寿命,但0~5℃之间处理的果实比>10℃处理的果实遭受更多的损伤,冲击碰伤发生率较高,内部和外部擦伤损伤均随着温度的升高而减少^[34]。

3.2.2 光照 光照是调控果实品质形成的环境信号,充足的光照能促进果实发育过程中次生代谢物质迅速积累。光质在树体生长和果实品质形成中也起着不可替代的作用,红光有利于促进碳水化合物的形成和着色,紫外光有利于增加红色果皮着色面积,蓝光有利于增大果实,提高糖含量。高光强度可提高果实中抗坏血酸含量^[15],低光环境可能会影响果实生长的微环境,导致糖和有机酸含量的变化。避雨棚栽培下的果实总可溶性固形物(TSS)、可溶性糖(SSs)、抗坏血酸(AsA)和花青素含量也有不同程度的升高,但可滴定酸含量降低。此外,避雨棚栽培可以显著促进总光合积累和果实产量提高^[35]。避雨棚栽培下甜樱桃维生素C含量显著低于露地栽培。连栋避雨栽培显著降低了裂果率(13.6%)和烂果率(4.6%),果实中糖(蔗糖、葡萄糖、果糖和山梨醇)和有机酸(柠檬酸、苹果酸、莽草酸和富马酸)含量与露地栽培相比差异不明显,酚类和花青素的含量也无显著差异,对甜樱桃果实质量无显著影响,对果实品质无负面影响^[36]。30%遮阴胁迫显著降低了红灯甜樱桃果实质量,通过直接影响叶片的生长发育来减少果实中营养物质的积累,显著降低了成熟时果实质量、糖含量和维生素C含量,显著提高了酸含量^[37]。

3.2.3 水分 干旱胁迫导致细胞分裂和细胞伸长受到影响,抑制了果实横径的增大,从而影响果实大小和形态。90%控水处理的果实可溶性固形物含量比不控水对照(CK)高,颜色比CK深,而产量不变。适当的干旱胁迫有助于增加甜度,随着干旱胁迫的加重,可溶性固形物含量降低,果面亮度降低、颜色加深、饱和度降低,甜樱桃果实总糖含量、总酸含量均随着干旱胁迫加重而升高^[38]。降水量对果实品质的影响主要表现在果实成熟之前,淹水会抑制根系生长、吸收和运输等,使地上部分生长受到抑制,严重时会导致果实脱落。降雨量和高海拔显著影响果实异味的发生,建议采用促进果实成熟但避免早熟的采收措施,以减少Regina草本风味的发生。橘皮问题的发生率与贮藏期间的相对湿度呈负相关(相对湿度较低时发生率更高),果肉和果皮的

渗透势均略有下降,果皮水分蒸腾到空气中,即使在100%相对湿度下也会发生果皮水分渗透脱水到果肉中的现象^[30]。

3.2.4 养分条件 甜樱桃果实富含多种矿物质,在生长发育阶段,7种矿质营养元素含量表现为前期含量较高而后期含量较低的变化趋势。果实中钾含量最高,显著高于其他元素。甜樱桃果实发育前期积累大量钙和钾元素,果实成熟后期,木质部功能丧失,果实中钙含量下降。钙元素含量在果实S2、S3阶段降至30%左右,钾含量降至55%左右^[28]。不同甜樱桃品种对土壤中养分含量的响应不同,主要影响氮和铁,其次是磷和钾。氮通过影响甜樱桃营养生长改变果实品质,高氮可以提高果实硬度,但降低甜度、酸度、风味强度、整体质地和多汁性等方面的品质^[39]。施钾可以改善甜樱桃果实品质,果实大小、硬度、可溶性固形物含量、可滴定酸含量均随施钾量的增加而升高,最适宜的施钾量为 K_2O 400 g·株⁻¹^[40]。钙可抑制果胶分解,提高细胞壁强度、果实硬度,促进可溶性固形物积累。适量的硒元素也可有效提高甜樱桃果实平均单果质量、维生素C含量及果实硬度,降低可滴定酸含量,改善果实品质^[28]。

4 提高甜樱桃果实品质的措施

4.1 栽培管理模式

果园管理如滴灌和夏季修剪,可提高果糖和总酚含量。果树在果园中的位置和果实着生位置是影响果实品质的重要因素,果实大小和甜度随着植物密度的增加而减小。树体栽植密度影响甜樱桃树体间透光与接收光的能力,4 m×4.5 m栽植密度下,拉宾斯品种的光合能力、产量和果实品质表现最优,4 m×5 m次之,3.5 m×4 m最差^[41]。对于吉塞拉5号和吉塞拉6号,丛枝形结构产生的果实最大,中心主干形结构产生的果实最小。在马扎德砧木上,Y字形的优质果率最高,丛枝形的最低。同一树形的单果质量、可溶性固形物含量、果肉硬度从树冠上层至下层逐渐降低,可滴定酸和石细胞含量逐渐增高。在果实快速发育的S3阶段对成熟叶片进行修剪可以提高甜樱桃果实品质。覆草栽培提高了6年生红灯/中国樱桃坐果率,较对照提高26.35%,平均单果质量和可食率分别高出0.71 g和0.85%,可溶性固形物含量增加了1.27%,花期滞后3~5 d。覆草栽培可以显著提高甜樱桃的产量,改善甜樱桃果实品质,在高寒

地区由于花期的延迟可有效地抵抗倒春寒^[42]。覆反光膜可改善樱桃果实的着色,但覆膜和未覆膜处理下的樱桃果实大小无显著差异^[43]。

4.2 合理施肥

影响甜樱桃果实品质的主要元素是氮和铁,其次是磷和钾。高氮($125\text{ g}\cdot\text{株}^{-1}$)处理果实颜色和硬度增加,甜度、酸度、风味强度、整体质地和多汁性品质降低^[38]。果实大小、硬度、可溶性固形物含量、可滴定酸含量均随着施钾量的增加而升高,缺钾果实小、色暗淡、酸无味。0900Ziraat 樱桃/吉塞拉6砧木连续2年施钾,果实大小、果实硬度(FF)、可溶性固形物含量、可滴定酸含量均随钾剂量增加而升高,pH、抗氧化活性和总酚含量均降低。最适宜的施钾量为每株 $400\text{ g K}_2\text{O}$,高剂量 600 g 导致其他营养元素含量减少,还导致果实硬度及可溶性固形物和可滴定酸含量降低^[38]。花前施 0.2% 硼酸可以提高坐果率,中果皮细胞增大(S2阶段),内源硼含量增加,各种糖(如果糖和葡萄糖)、醇(如肌醇和麦芽糖醇)、有机酸(如苹果酸和柠檬酸)、氨基酸(如缬氨酸和丝氨酸)在各个发育阶段(S1~S5阶段)因硼的施用而积累^[44]。硼肥对甜樱桃树的活力和产量没有影响,施硼果实中可溶性固形物和花青素含量均高于对照^[45]。由于钙在木质部中低流动性且不通过韧皮部运输,在果实成熟前叶面喷施钙肥能显著提高果实贮藏期间钙、镁、钾、钠、铁矿质元素的含量^[46]。

4.3 外源激素

应用外源植物激素和营养元素可改善樱桃果实品质。植物生长调节剂通过延缓果实成熟期,延长生长周期来提高单果质量。在果实发育早期施用细胞分裂素,或在果核硬化时施用合成生长素,可以改变其最终果实大小。6-BA能显著提高甜樱桃果实硬度, GA_3 处理的Van和Sunburst樱桃果实硬度和可溶性固形物含量均较高。生长素(1-萘乙酸,NAA)处理通过上调花青素生物合成和转运基因表达来提高甜樱桃的花青素含量^[47]。9DAFB施用 GA_3 和 $\text{GA}_{4/7}$ 均促进了果实径向膨大, GAs 处理通常会延缓果实成熟,表现为更高的硬度和更浅的外果皮颜色^[48]。赤霉素、类固醇激素和高油菜素内酯合用,可有效缓解赤霉素对花色苷和酚类物质及可溶性固形物含量的负面影响^[28]。氯吡脲和细胞分裂素花后30 d施用显著提高了果实质量,当施用质量浓度为 $200\text{ mg}\cdot\text{L}^{-1}$ 时单果质量提高 15% ^[49]。转色期外

源施用ABA促进了果实ABA的积累、花青素的生物合成和固酸比(SSC/TA)的增大,从而促进了果实成熟^[26]。坐果期外源施用ABA,成熟果实中结合态果胶和半纤维素含量较高,同时水溶性聚合物含量减少,细胞壁强度增加,有助于甜樱桃增大、增色和提高可溶性固形物含量,延缓果实软化。

5 展 望

5.1 目标性状基因标记育种

分析现有甜樱桃资源营养成分和性状,以及一些特定品种在酚类化合物积累模式方面的潜在优势,为改良营养品质育种工作提供宝贵资源。利用目标性状基因标记选育优质新品种,如抗软化基因XTH和PG基因家族的PavXTH14、PavXTH15、PavPG38等基因,通过降解果实细胞壁促进果实软化,为培育抗软化甜樱桃品种提供潜在靶点^[50-51]。制定包括单倍型辅助育种在内的育种计划,以拓宽遗传背景,培育适应当地环境条件的优质新品种。此外,应用生物技术,整合基因组、转录组、代谢组和表型分析,解析植物发育和果实成熟的分子机制,鉴定控制果实品质性状表达的转录因子、生物合成途径的关键基因和触发环境效应因子,从而提高优质品种的选育效率。

5.2 栽培技术改进

光合作用的生理特性取决于树冠和叶面积,其直接影响作物产量和果实硬度、色泽、含糖量等果实品质指标。以单株和单位面积群体作为对象的光合研究,为生产上调整栽培密度、优化群体结构、提高单位面积群体的光合利用率和实现高产优质提供理论基础。通过基因编辑或杂交育种可优化关键酶活性,提高叶片 CO_2 固定能力,改良品种。对于甜樱桃树体碳素同化物分配特点、糖由叶片向果实的运转机制、核糖形态转化的细节仍不清楚,还有待于深入研究。

5.3 单性结实

桃、樱桃等核果果实内种子的缺失有利于降低加工成本。种子的缺失会延长果实保质期。植物激素的外源应用已被证明可诱导单性结实果实的发育;遗传手段去除种子可能对樱桃产业具有潜在的变革性,基因工程和基因组编辑策略可以改变激素生物合成或信号转导以获得单性结实果实。CRISPR/Cas9基因组编辑技术已被用于生产单性结实番

茄植株,证明了这项技术调控种子发育的潜力。此外,已经在樱桃基因组数据库中鉴定了许多无核果基因的直系同源物^[52],表明基因组编辑是樱桃中无核/无籽果实生产的可行选择途径。

5.4 生物刺激剂

生物刺激剂可通过调节植物生理的多个方面(光合作用、激素代谢、养分吸收和转运、次生代谢等)来促进植物营养生长,提高果实产量、品质以及植物对非生物胁迫的耐受性。叶面喷施生物刺激剂(热带植物提取物)可显著提高果实产量,也能改善Kordia果实质量,钙含量提高26.2%,可溶性固形物含量提高11.8%,果肉硬度和果皮颜色分别提高6.7%和12.0%^[53]。在采收前2~4周施用海藻提取物可降低裂果率约10%,叶片喷施海藻提取物和钙肥可以提高甜樱桃品种Skeena和Sweetheart果实中的有机酸含量^[54]。生物刺激剂将是甜樱桃栽培中合成激素和营养元素的有效替代品。

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