

## 不同果实发育期干旱胁迫对温州蜜柑 果品质形成的影响

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**摘要:**【目的】研究不同时期干旱胁迫对果品质的影响,为提升果品质及节水灌溉提供理论依据。【方法】以‘山下红’温州蜜柑(*Citrus unshiu* Marc.)为材料,分析了果实发育过程中细胞分裂期、果实膨大期及较长时期连续干旱后果实外在和内在品质的变化。【结果】与对照相比,不同果实发育阶段干旱胁迫后果实体积均呈下降趋势,细胞分裂期、果实膨大期、连续干旱期果实体积分别下降22.5%、49.6%、65.7%。对各处理成熟果实分析显示,连续干旱期处理总酸较对照升高86%,总糖升高6.5%,细胞分裂期干旱总酸较对照升高37.3%,总糖下降6%,果实膨大期干旱总酸较对照升高31.8%,总糖升高26.1%。发育过程中果实分析显示,细胞分裂期、果实膨大期和连续干旱严重阻碍了果实中柠檬酸降解,使果实中柠檬酸含量显著升高。【结论】综合不同果实发育阶段干旱胁迫后果实外在与内在品质的响应特点,不同时期干旱胁迫均导致温州蜜柑果实柠檬酸含量升高,细胞分裂期干旱导致果品质发生高酸低糖的不可逆劣变,果实膨大期干旱对果实体积、糖和酸含量均有巨大影响。

**关键词:**温州蜜柑;干旱胁迫;糖;酸

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## Effect of drought stress at different development stages on fruit quality formation in Satsuma Mandarin

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**Abstract:**【Objective】Moderate drought is an important means to regulate fruit quality. Citrus grows in southern China, where abundant rainfall happens during cell division but less rain during fruit enlargement, which is sensitive to drought. The impact of drought on fruit quality during different periods remains unclear. In this regard, the effect of drought on fruit quality at different fruit development stages was examined in order to provide strategy for improving citrus fruit quality with water-saving irrigation.【Methods】The experiments were carried out in National Centre for Citrus Improvement, Changsha, China. Five-year-old Satsuma Mandarin (*Citrus unshiu* Marc. ‘Yamasitaka’) trees grafted on trifoliate

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iate orange [*Poncirus trifoliata* (L.) Raf.] were transplanted into plastic pots with a volume of 27 L. The cultivation medium was  $V_{\text{sawdust}}: V_{\text{river sand}}: V_{\text{peat}} = 2:1:0.5$ . A TDR300 portable soil moisture analyzer (Spectrum Technologies, USA) was used to measure water content in the substrate. Water content below 40% (relative to maximum water holding capacity of the substrate) was considered as drought stress. Drought treatment was applied at fruit cell division stage (June-July), fruit enlargement stage (August-September) and throughout the whole fruit development stage (June-September) in this study. Meanwhile, normal irrigation (approximate 70% of the maximum water holding capacity in the substrate) was treated as the control. The control group and each of the treatment groups had 10 trees. Nine fruit were collected at each time of sample collection, and the appearance indexes were determined immediately after fruit collection. The fruit were divided into two parts, half of which were stored in the refrigerator at  $-20^{\circ}\text{C}$ , while the other half was quickly peeled and frozen in liquid nitrogen and stored at  $-80^{\circ}\text{C}$ . High performance liquid chromatography (HPLC) and direct measurement were performed to analyze the changes in external and internal quality indexes during fruit development. 【Results】The results showed that fruit volume decreased after drought stress during different fruit development periods. Fruits under persistent drought showed a smallest fruit size, which was 65.7% lower than that of control. Besides, fruit size under drought at fruit enlargement stage and cell division stage was 49.6% and 22.5% smaller than that of the control, respectively. The results indicated that drought during fruit enlargement had a greater impact on fruit development, and was the key period affecting fruit size and yield. Analysis of the mature fruit showed that total acid and sugar increased by 86% and 6.5% under continuous drought stress, respectively. Total acid increased by 37.3% and total sugar decreased by 6% in the group with drought applied during cell division compared with the control. Meanwhile, total acid and total sugar increased by 31.8% and 26.1% in drought treatment applied during fruit enlargement, respectively. Furthermore, restoring irrigation after drought stress during cell division exhibited no obvious effect on sugar decrease and acid increase, suggesting that drought during cell division had irreversible negative effects on fruit quality. The sugar-acid ratio in mature fruit in drought stress at different fruit development periods was the highest in the control and in the drought treatment during fruit enlargement, followed by the group with drought during cell division, and the continuous drought group was the lowest, indicating that drought during fruit enlargement had a great effect on sugar and acid metabolism and thus on fruit quality formation. In addition, all drought treatments resulted in increased in organic acids in fruit. Citric acid is the major acid, accounting for over 75% of total acids. The degradation of citric acid in fruit under drought treatments was seriously hindered, leading to increased organic acid content in fruit. 【Conclusion】Drought stress at different periods of fruit development may intensify citric acid synthesis and suppress its degradation. Drought during cell division causes an irreversible deterioration of fruit quality with high acid and low sugar contents. Drought during fruit enlargement has a great impact on fruit volume as well as sugar and acid contents.

**Key words:** Satsuma Mandarins; Drought stress; Sugar; Acid

水是植物体中各种物质转运的载体,直接参与细胞分裂、糖分转化等生理生化过程<sup>[1]</sup>。当柑橘受到干旱胁迫时,树体中脱落酸(ABA)、脯氨酸和可溶性糖等含量增加,降低水势并保持一定的膨压促进气孔关闭,通过主动渗透调节增强自身的抗旱性,

使其在低渗透势下仍能从环境中吸收水分和养分<sup>[2-4]</sup>;相应的,干旱胁迫也会引起果实中可溶性固形物和有机酸含量上升、降低渗透势,提高水分和溶质向果实流入,从而实现了果实品质的调控<sup>[5-6]</sup>。

果树对不同程度干旱胁迫的反应特点表现不

一。适度的干旱胁迫对果树的果实产量和品质均有调控效果。Huang等<sup>[7]</sup>的研究表明,在柑橘果实汁囊膨胀的早期阶段施加轻度干旱胁迫,干旱胁迫抑制了果实生长,果实体积减小,果汁中可溶性固形物和果皮中可溶性糖含量增加,果实内部生长潜力增强,在恢复灌水后,可加速果实的生长发育。邓胜兴<sup>[8]</sup>的研究表明,土壤含水量维持在65%时,果实纵横径、单果质量略有下降,果实生长受到一定抑制,但果实中有机酸、维生素C、可溶性糖等含量显著增加,对提高果实品质最为理想。重度干旱胁迫下,果实中总糖、蔗糖、还原糖、维生素C等含量出现不同程度下降,柑橘果实品质变差。肖玉明等<sup>[9]</sup>的研究表明,土壤含水量为40%的干旱胁迫下,温州蜜柑成熟时果实体积变小,单果质量、果皮质量、横径与纵径分别较对照减小59.0%、61.7%、25.2%、21.7%,果实中可溶性固形物、可溶性糖、有机酸含量显著增加,蔗糖、葡萄糖、果糖、总糖、有机酸和柠檬酸含量分别较对照增加33.3%、72.3%、65.0%、48.9%、60.4%和66.3%。Aguado等<sup>[10]</sup>的研究表明,在奈维林娜脐橙成熟期适度干旱,增加了果实中可溶性固形物和可滴定酸,而果实大小和果汁含量未受影响。类似的García-Tejero等<sup>[11]</sup>的研究结果表明,在脐橙果实成熟期,较严重的干旱胁迫显著增加可溶性固形物,可滴定酸含量,而对产量,横纵径、单果质量及汁重的影响较小。

果树不同时期的水分丰亏影响果实代谢活动和品质形成。García-Tejero等<sup>[11]</sup>的研究结果表明,细胞分裂期干旱胁迫加剧奈维林娜脐橙果实落果,减少了果实数量,降低产量,果实膨大期与果实成熟期干旱促使可溶性固形物和可滴定酸的含量升高,改善了果实品质,但果实膨大期干旱胁迫显著减小了果实体积。在伦晚脐橙果实细胞分裂期和果实成熟期进行干旱控水,研究结果表明,细胞分裂期干旱加剧了果实脱落,减少了果实数量和产量,而果实成熟期干旱显著提高了可溶性固形物和可滴定酸含量,且果实大小未受影响<sup>[12]</sup>。Hutton等<sup>[13]</sup>的研究表明,在伏令夏橙果实膨大期延长灌溉间隔,土壤水分亏缺加剧,导致果实体积减小,但随干旱胁迫时间延长及胁迫程度的增加,果实中可滴定酸和可溶性固形物含量显著升高,改善了果实品质。Zhang等<sup>[14]</sup>的研究表明,在椪柑果实生长发育不同阶段进行干旱胁迫,椪柑果实中有机酸含量均显著升高,其柠檬酸含量

升高最为明显,果实品质发生改变,这种变化与柠檬酸代谢相关基因表达量发生变动有关,CitACO1、CitGAD4的下调和Citcs1、Citcs2的下调可能是促进果实柠檬酸积累的原因之一。因此,果树不同时期干旱对果实品质形成影响不同,通常果实膨大期干旱胁迫将降低产量,果实品质有不同程度改变。

综上,通过适度干旱调控果实品质形成是调控果实品质的重要手段。柑橘生长在我国南方,通常在细胞分裂期雨水较多,果实膨大期少雨干旱。不同时期干旱对果实品质有怎样的影响,哪个时期干旱对果实品质影响较大,这些问题尚不明确。因此,本研究以温州蜜柑为材料,通过不同果实发育阶段干旱研究干旱时期对柑橘果实品质形成的影响,研究结果为柑橘果实品质提升及节水灌溉供理论依据。

## 1 材料和方法

### 1.1 材料

本试验在国家柑橘改良中心长沙分中心温室大棚进行。以5 a(年)生枳砧‘山下红’温州蜜柑(*Citrus unshiu* Marc.)为材料,将供试材料移栽于体积27 L的塑料盆中,栽培基质为V<sub>锯木屑</sub>:V<sub>河沙</sub>:V<sub>草炭</sub>=2:1:0.5。

### 1.2 方法

1.2.1 试验设计 在盆栽基质完全浇透水后,使用TDR300便携式土壤水分测定仪(spectrum technologies,美国)测得盆栽基质的最大持水量,以相对于基质最大持水量30%~40%的含水量为干旱胁迫处理。依据果实生长发育规律,分别设计果实细胞分裂期(6—7月)干旱、果实膨大期(8—9月)干旱和果实发育期连续(6—9月)干旱3种不同时期干旱处理,以正常浇水(基质含水量为最大持水量70%左右)处理为对照(表1)。干旱处理时,先将处理组材料浇透水,待含水量降至设定后每天使用TDR300便携式土壤水分测定仪监测。对照和各处理均10株重复。处理开始后每27 d取果实样品,样品采集时每处理每次各采集9个果实,果实采集后立即进行外观指标测定,后置于-20 ℃冰箱保存,用于果实主要外观品质及内在品质的测定。以上各测定均3次生物学重复。

1.2.2 果实主要外观品质测定 使用游标卡尺测量果实横纵径以及果皮厚度,百分之一电子天平测量

表1 温州蜜柑果实发育过程中不同干旱时期设计

Table 1 Drought treatments design at different fruit development stages of Satsuma mandarin

处理 Treatment	日期 Date				
	06-05—07-02	07-03—07-29	07-30—08-26	08-27—09-23	09-24—10-20
细胞分裂期干旱 Cell division stage	★	★	☆	☆	☆
果实膨大期干旱 Fruit enlargement	☆	☆	★	★	☆
连续干旱 Continuous drought	★	★	★	★	☆
对照 Control	☆	☆	☆	☆	☆

注:☆表示正常管理,★表示干旱处理。

Note: Black star means drought treatment and white means normal management.

单果质量、果皮质量,并计算得出果实纵横比以及可食率。每个测定指标9个单果重复。

1.2.3 果实主要糖酸含量测定 运用高效液相色谱法(HPLC)测定果肉中可溶性糖、有机酸含量。测定方法按照本实验室已发表的测定方法进行<sup>[15]</sup>。

1.2.4 数据处理 试验数据运用Excel 2013和SigmaPlot 10.0软件进行整理分析与绘图,运用SPSS 17.0软件进行统计分析。

## 2 结果与分析

### 2.1 不同时期干旱胁迫对成熟期果实外在品质的影响

如表2所示,温州蜜柑果实不同生长发育阶段

受到干旱胁迫均影响其外在品质。对照组的果实横纵径分别为59.13、50.01 mm,皮厚1.93 mm,单果质量为103.44 g,表现为果大皮薄,可食率高。连续干旱胁迫下果实外在品质受到影响最大,横纵径分别为40.38、33.66 mm,单果质量为35.39 g,较对照下降65.7%。同时,连续干旱胁迫使果皮显著增厚,为对照的1.7倍,表现为果小皮厚,可食率显著下降,表明长期的连续干旱严重影响果实正常生长发育。果实膨大期干旱胁迫下果实横纵径显著减小,分别为46.01、36.71 mm,单果质量较对照下降了49.6%。细胞分裂期干旱胁迫对外在品质的影响则较轻,单果质量较对照减轻了22.9%,其他指标较对照无显著性差异。

表2 不同果实发育期干旱胁迫后成熟果实外在品质情况

Table 2 Changes in fruit appearance under different drought treatments

类别 Category	对照 Control	细胞分裂期 Cell division stage	果实膨大期 Fruit enlargement	连续干旱 Persistent drought
单果质量 Fruit mass/g	103.44±13.54 a	79.70±30.83 b	52.10±16.05 c	35.59±4.12 c
果皮质量 Peel mass/g	20.74±2.45 a	21.09±2.84 a	11.74±4.79 b	14.19±1.96 b
横径 Transverse diameter/mm	59.13±2.01 a	55.55±1.66 a	46.01±5.89 b	40.38±3.09 b
纵径 Longitudinal diameter/mm	50.01±2.05 a	43.03±3.03 a	35.71±4.67 b	33.66±0.74 b
果皮厚 Peel thickness/mm	1.93±0.01 b	2.11±0.11 b	1.72±0.36 b	3.27±0.20 a
可食率 Edible rate/%	79.90±1.20 a	73.60±3.30 b	77.80±2.90 a	60.00±1.00 c
纵横比 (LD/TD)	0.85±0.01 a	0.78±0.08 a	0.78±0.02 a	0.84±0.09 a

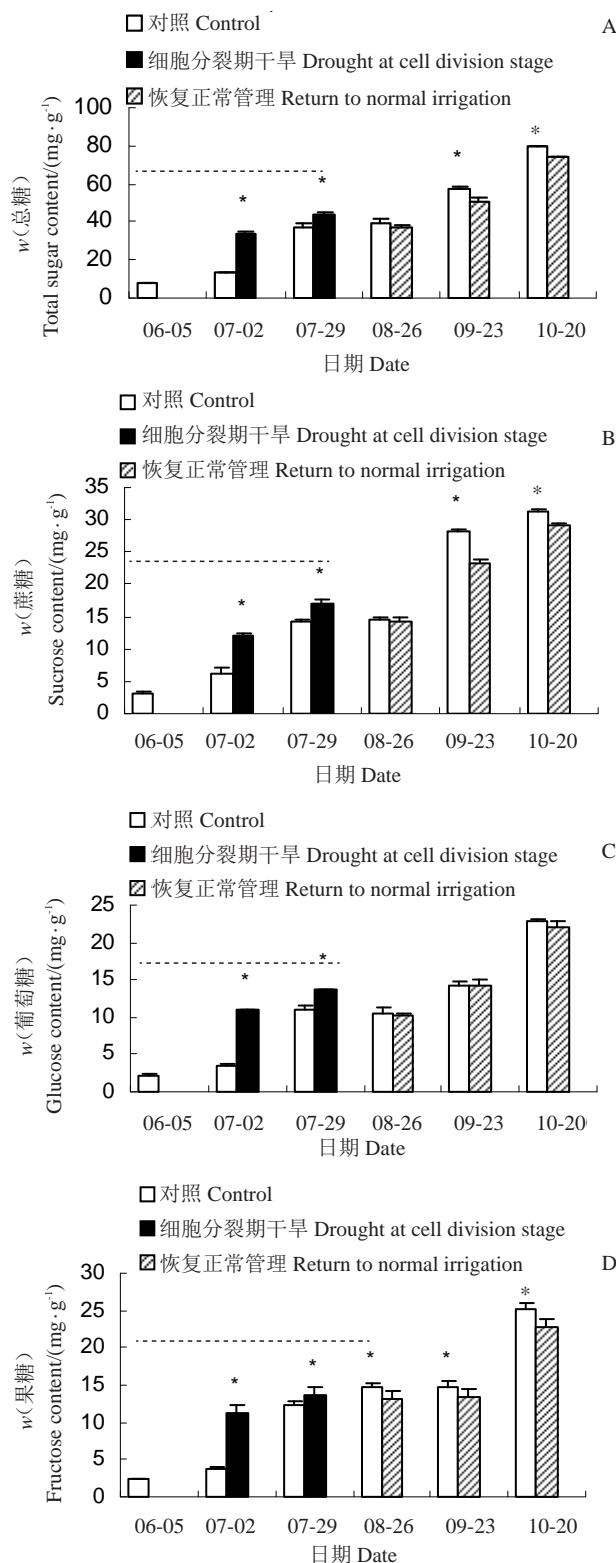
注:同一行数据的不同字母表示在  $p < 0.05$  水平下差异显著。

Note: The different letters in the same row indicate significant difference at  $p < 0.05$  level.

### 2.2 细胞分裂期干旱胁迫对果实内在品质的影响

细胞分裂期干旱处理后果实中糖积累出现显著低于对照的趋势。在7月份干旱胁迫过程中,果实中蔗糖、葡萄糖、果糖含量均显著高于对照,恢复浇水管理后果实中糖虽继续持续积累但显著低于对照。果实成熟后(10月20日),果实中总糖、蔗糖和果糖分别较对照减少了6.77%、6.88%和9.64%(图1),细胞分裂期干旱显著减少了成熟果实中糖含量。

随温州蜜柑果实发育,果实中总酸含量呈现发育前期迅速升高后持续下降的趋势,细胞分裂期干旱处理后果实中酸含量下降显著减缓,持续高于对照。柠檬酸是总酸主要的贡献组分,细胞分裂期干旱后其后期下降显著减缓,果实成熟时总酸和柠檬酸均高出对照约37%以上(图2-A, B)。苹果酸和奎宁酸在总酸中占有较小的比例,细胞分裂期干旱处理后其降解也显著减缓,均高于对照(图2-C, D)。



\*表示同一时期处理与对照在  $p < 0.05$  水平差异显著, --- 表示干旱处理时间。下同。

Asterisk indicates significant difference in the same sample date at  $p < 0.05$ , dashed line indicates the period of drought treatment. The same below.

图 1 细胞分裂期干旱对果实总糖(A)、蔗糖(B)、葡萄糖(C)、果糖(D)含量的影响

Fig. 1 Effect of drought at cell division stage on total sugars (A), sucrose (B), glucose (C) and fructose (D) contents in fruit

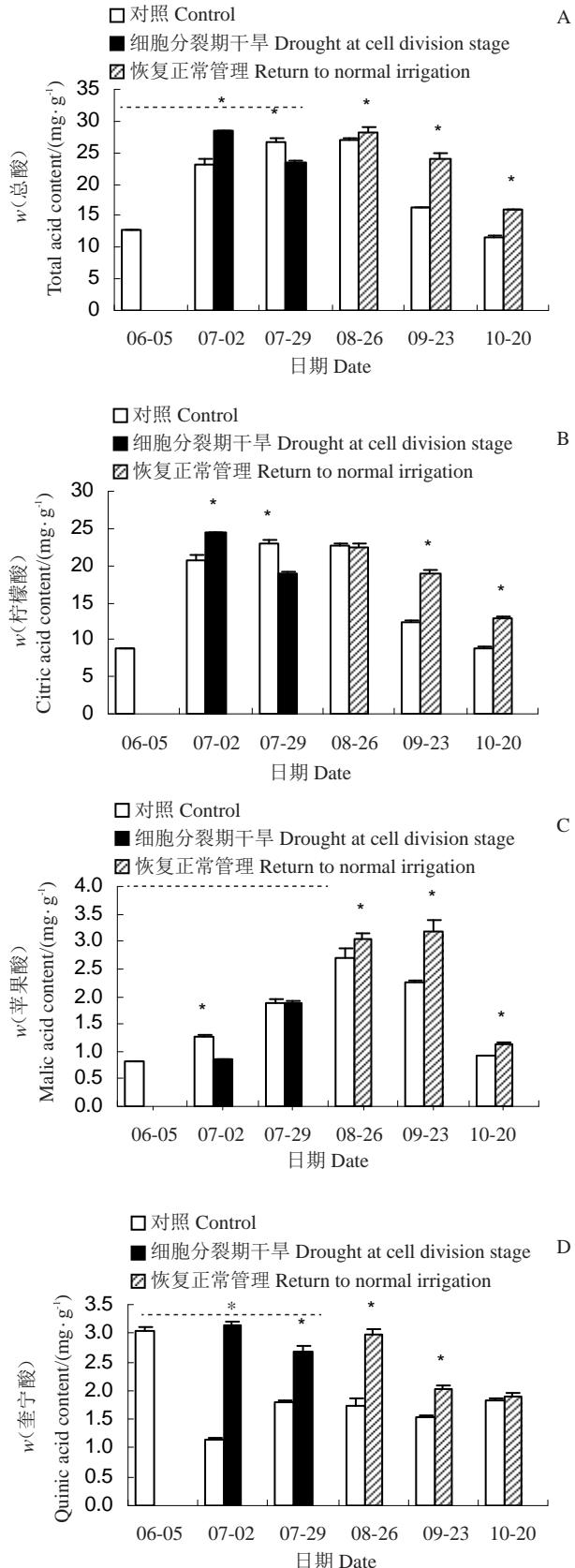


图 2 细胞分裂期干旱对果实总酸(A)、柠檬酸(B)、苹果酸(C)、奎宁酸(D)含量的影响

Fig. 2 Effect of drought at cell division stage on total acid (A), citric acid (B), malic acid (C) and quinic acid (D) contents in fruit

温州蜜柑细胞分裂期干旱后,果实柠檬酸降解显著减缓是品质变化的主要特征之一。

### 2.3 果实膨大期干旱胁迫对果实内在品质的影响

果实膨大期干旱胁迫处理果实中糖酸含量均表现出显著高于对照的趋势。在8月份干旱胁迫过程

中,果实中蔗糖、葡萄糖、果糖含量显著高于对照,恢复浇灌管理后果实中糖积累持续升高,显著高于对照。果实成熟时,果实中总糖、蔗糖、葡萄糖、果糖含量分别较对照增加了26%、28.81%、22.2%、12%,显著高于对照(图3),果实膨大期干旱处理显著增加

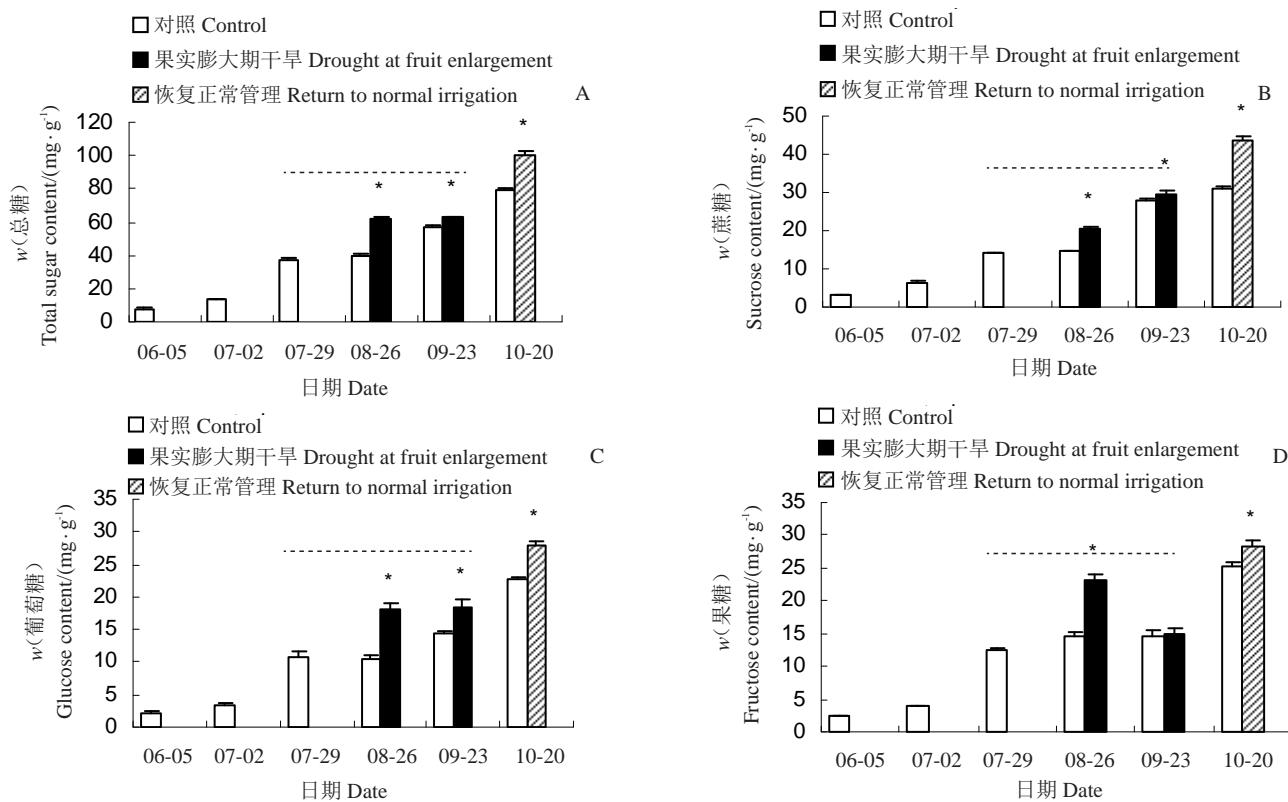


图3 果实膨大期干旱对果实总糖(A)、蔗糖(B)、葡萄糖(C)、果糖(D)含量的影响

Fig. 3 Effect of drought at fruit enlargement on total sugar (A), sucrose (B), glucose (C) and fructose (D) contents in fruit

了果实糖含量。

果实膨大期干旱处理后果实中总酸含量下降显著减缓,柠檬酸含量下降也显著减缓,果实成熟时总酸和柠檬酸均高出对照约30%(图4-A, B)。果实膨大期干旱处理后苹果酸和奎宁酸降解也显著减缓,果实成熟时分别较对照增加了51.1%和30%,均显著高于对照(图4-C, D)。温州蜜柑果实膨大期干旱后,果实柠檬酸降解显著减缓是品质变化的主要特征之一。

### 2.4 连续干旱对果实内在品质的影响

连续干旱处理后果实中糖酸含量均呈现高于对照的趋势。在7—9月的干旱胁迫过程中,果实中蔗糖、葡萄糖、果糖含量显著高于对照,恢复浇灌管理后,糖积累持续增加,果实成熟期总糖与蔗糖含量分别高于对照6.35%、14.9%,葡萄糖和果糖与对照无差异(图5)。

随温州蜜柑果实发育,果实中总酸含量呈现发育前期迅速升高后持续下降的趋势,连续干旱处理后果实中酸含量下降显著减缓,持续高于对照;果实成熟时,总酸含量高出对照86%(图6-A)。柠檬酸作为总酸主要的贡献组分,在连续干旱后下降显著减缓,果实成熟时柠檬酸高出对照83%(图6-B)。连续干旱处理后苹果酸和奎宁酸的降解也显著减缓,果实成熟时分别升高107%和88.5%,均显著高于对照(图6-C, D)。温州蜜柑连续干旱后,果实糖含量增加和柠檬酸降解减缓显著,表现出与果实膨大期干旱类似的品质变化趋势。

## 3 讨 论

水分是果实品质形成的关键因素之一,与果实品质的形成密切相关,水分亏缺会导致果实外在及内在品质等一系列变化<sup>[16]</sup>。

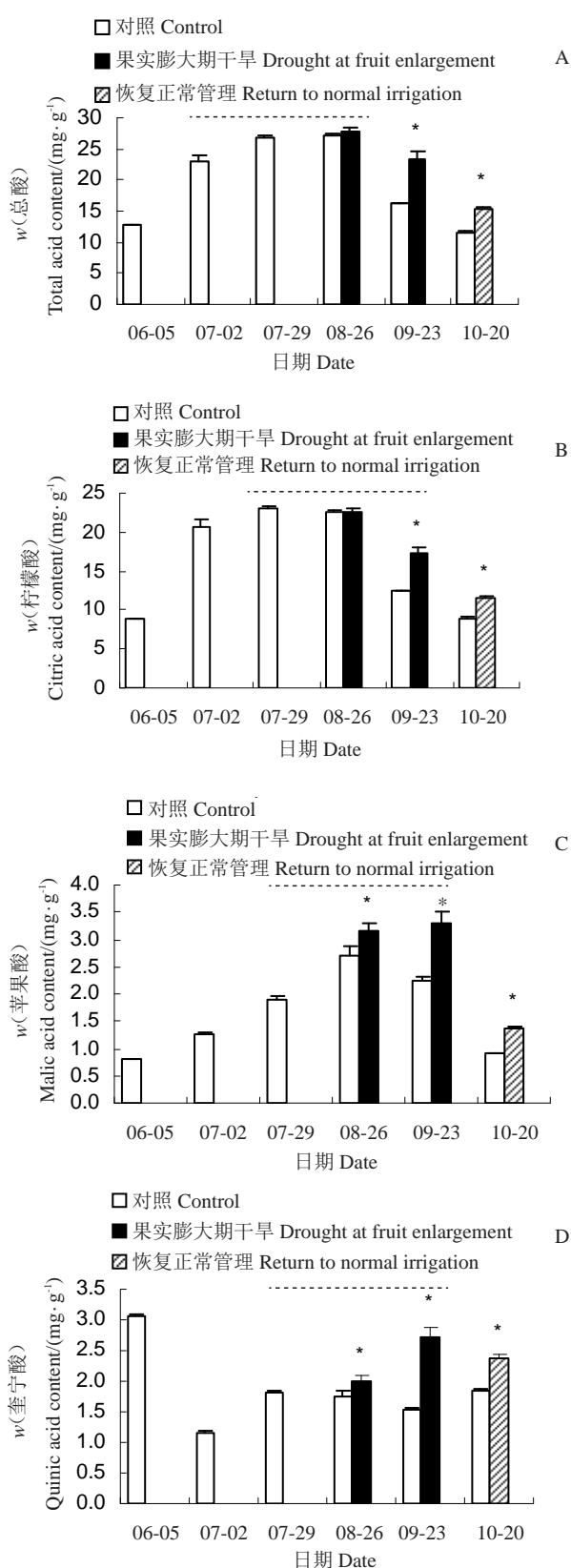


图4 果实膨大期干旱对果实总酸(A)、柠檬酸(B)、苹果酸(C)、奎宁酸(D)含量的影响

Fig. 4 Effect of drought at fruit enlargement on total acid (A), citric acid (B), malic acid (C) and quinic acid (D) contents in fruit

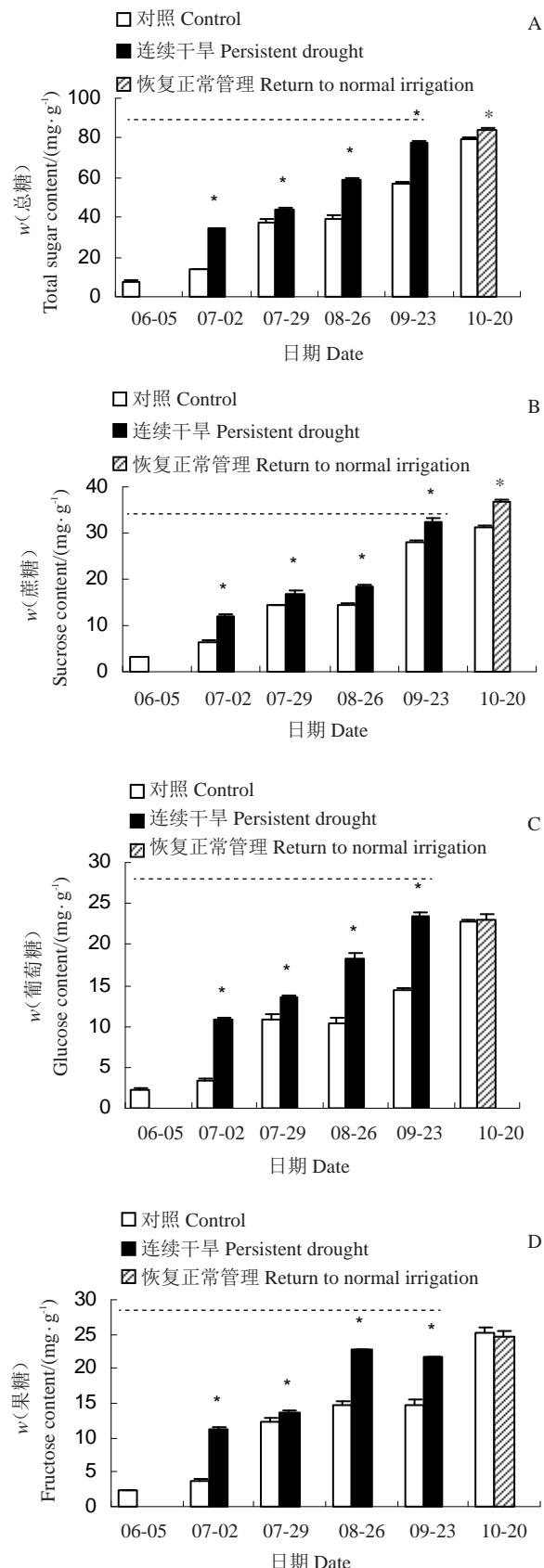


图5 连续干旱对果实总糖(A)、蔗糖(B)、葡萄糖(C)、果糖(D)含量的影响

Fig. 5 Effect of continuous drought on total sugar (A), sucrose (B), glucose (C), and fructose (D) contents in fruit

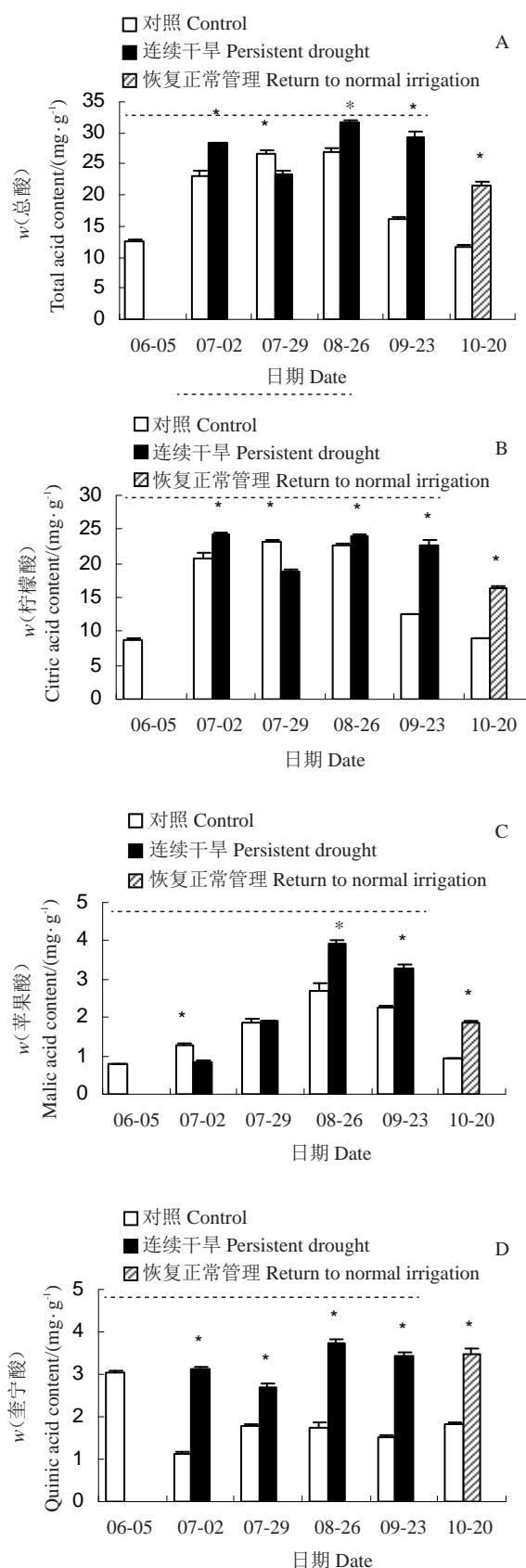


图 6 连续干旱对果实总酸(A)、柠檬酸(B)、苹果酸(C)、奎宁酸(D)含量的影响

Fig. 6 Effect of continuous drought on total acid (A), citric acid (B), malic acid (C), and quinic acid (D) contents in fruit

果实在不同生育阶段承受干旱胁迫的反应特点表现不一,果实细胞分裂对水分胁迫具有很强的忍受能力,但果实细胞膨大的速率受水分胁迫的影响极大<sup>[17]</sup>。在‘克里曼丁’红橘果实细胞分裂期干旱胁迫研究结果表明,细胞分裂期干旱减少果实数量,果实体积影响较小,单果质量较对照减小10%<sup>[18]</sup>。在‘克里曼丁’果实膨大期(7—9月)进行干旱胁迫,干旱显著减小果实体积而降低产量,果实体积与干旱程度、发育时间呈负相关<sup>[18]</sup>。Gonzálezalzozano等<sup>[19]</sup>的研究表明,在柑橘果实成熟时,适度的干旱胁迫不会影响果实外在品质。本研究结果显示温州蜜柑连续干旱期胁迫下果实体积较对照降低65.7%,果实膨大期较对照下降了49%,细胞分裂期较对照下降22.9%,结果表明细胞分裂期遭受干旱胁迫后,果实体积在发育后期可随胁迫解除而恢复生长,干旱胁迫对果实膨大期果实体积的损伤则难以修复,与前人研究结果一致。表明柑橘果实发育过程中果实膨大期干旱对果实影响较大,是影响果实大小和产量的核心时期。

不同阶段的干旱胁迫对柑橘果实内在品质影响不一<sup>[20]</sup>。在柑橘果实成熟期,适当的干旱胁迫可促进柑橘果实中可溶性糖与可滴定酸含量的积累,改善果实品质,已成为国内外公认的事实<sup>[6,19,21]</sup>。在‘克里曼丁’果实膨大期,干旱胁迫会减少果实体积,但可增加果实可溶性固形物与可滴定酸<sup>[22]</sup>。陈瑛等<sup>[23]</sup>的研究表明脐橙果实膨大期适度的干旱,可增加果实中糖的积累。本研究中,果实膨大期,总糖与总酸含量显著增加,不同果实发育期干旱胁迫后成熟果实中糖酸比表现为对照和果实膨大期干旱>细胞分裂期干旱>连续干旱期干旱,表明果实膨大期干旱对果实糖和酸代谢均有较大影响,与前人研究结果相似,表明果实膨大期干旱对温州蜜柑果实内在品质的形成有巨大影响。细胞分裂期干旱对果实品质影响的研究尚不全面<sup>[11-12]</sup>。本研究结果显示温州蜜柑果实细胞分裂期干旱后糖含量显著降低、酸升高,果实膨大期干旱后糖酸含量显著升高,连续干旱后糖酸显著升高。细胞分裂期干旱胁迫后再恢复浇水管理不能改变其糖含量降低、酸含量升高的趋势,表明该时期干旱对果实品质有不可逆的负面影响。

#### 4 结 论

综合温州蜜柑不同果实发育阶段干旱胁迫后果

实外观与内在品质的响应特点,不同时期干旱胁迫均导致果实柠檬酸合成加剧与降解减缓,细胞分裂期干旱导致果实品质发生高酸低糖的不可逆劣变,果实膨大期干旱对果实体积、糖和酸含量均有巨大影响。

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