

## 2个柑橘三倍体有性群体果实糖酸性状遗传评价

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**摘要:**【目的】探讨柑橘三倍体有性后代果实糖酸性状的遗传变异特点, 为倍性杂交科学选配亲本提供理论支持。【方法】以 W. 默科特橘橙(MCK)为母本, 异源四倍体细胞杂种诺瓦橘柚+埃及糖橙(NS)和埃及糖橙+丹西红橘(SD)为父本倍性杂交获得的 2 个三倍体有性群体的成熟果实为材料, 测定果实可溶性固形物(total soluble solid content, TSS)、可滴定酸(titratable acid, TA)及糖酸组分含量。【结果】三倍体有性后代果实 TSS 含量遗传偏向低糖亲本, TA 含量遗传趋向高酸亲本, 但偶有高糖低酸单株存在。蔗糖、果糖和葡萄糖是三倍体有性后代果实的主要糖组分, 且以积累蔗糖为主, 各糖组分含量均趋近正态分布, 总糖含量低于双亲的单株较多, 平均低低亲比率(ratio of lower than low parent, LL)为 70.56%。柠檬酸和苹果酸是三倍体后代果实的主要酸组分, 且以积累柠檬酸为主; 柠檬酸含量呈偏态分布, 果实总酸含量高于双亲的单株较多, 平均超高亲比率(ratio of higher than high parent, HH)为 76.00%。【结论】蔗糖、果糖和葡萄糖是由微效多基因控制的数量性状; 柠檬酸和苹果酸可能存在控制其含量的主效基因。倍性杂交产生的三倍体柑橘群体后代的果实糖酸含量趋向高酸低糖亲本, 且受父本影响较大。

**关键词:**柑橘; 三倍体; 可溶性糖; 有机酸; 遗传评价

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## Inheritance of sugar and acid contents in the fruits of triploid hybrids originated from two $2x \times 4x$ crosses with Nadorcott tangor as a female parent

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**Abstract:**【Objective】To uncover the inheritance of sugar and acid contents in the fruits of citrus triploid hybrids, we determined the components and contents of soluble sugars and organic acids in the fruit pulp of triploid hybrids and their parents from two citrus triploid hybrid populations by Gas Chromatography (GC). Citrus is one of the most important fruit crops worldwide. Seedlessness is an increasingly important trait in relation to citrus fruit quality. And the triploid breeding strategy has been proved to be an efficient way to create seedless citrus. In the past 20 years, Huazhong Agricultural University has produced a large number of citrus triploid hybrid populations based on the hybridization between diploid and tetraploid. However, less attention has been focused on the genetic trend of sugar and acid components in triploid citrus. Therefore, exploring the inheritance of sugar and acid contents in the fruit of citrus triploid hybrids is necessary to provide a basis for selecting parents in citrus triploid breeding.

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**【Methods】** Two triploid hybrid populations, previously obtained from interploidy crosses with diploid Nadorcott tangor as female parent and two allotetraploid somatic hybrids Nova tangor + Succari sweet orange (abbreviated as NS) and Succari sweet orange + Dancy red tangerine (abbreviated as SD) as male parents, were used as materials. And the two triploid hybrid populations were named as MNS and MSD, respectively. Fully ripening fruits were collected in 2018 and 2019 for fruit quality analysis. Twelve fruits from each tree were sampled and pooled for three technical replicates. One part of the fruit pulp was used for the determination of total soluble solid (TSS) and titratable acid (TA) contents and the other part was immediately frozen in liquid nitrogen and stored at -80 °C. The contents of TSS and TA in the fruit pulp of citrus triploid hybrids and their parents were measured using a refractometer. Additionally, the contents of sucrose, glucose, fructose, malic acid and citric acid of the fruits of two parents and their progenies were further determined by Gas Chromatography (GC). The genetic variation of fruit traits was evaluated by coefficient variation (*CV*), genetic transmitting ability (Ta) and transgression rate, and the normal distribution map was used to reflect the genetic tendency of the progeny. The data were processed by using Microsoft excel.

**【Results】** Sucrose, fructose and glucose were the major components of sugar, while citric acid and malic acid were the major components of organic acid in the fruit pulp of citrus triploid hybrids. The triploid hybrid populations exhibited a wide phenotypic variation in sucrose, fructose, glucose, total sugar, citric acid, malic acid and total acid contents, where the average coefficient of variation (*CV*) of sugar and acid contents was more than 15% and 30%, respectively, and the range of acid contents was higher than that of sugar contents, indicating that there was a bigger selecting potential for acid contents. Additionally, the genetic transmitting ability (Ta) of sucrose, fructose, glucose, total sugar, citric acid, malic acid and total acid contents was ranged from 65.50% to 184.85%, among which the highest was citric acid (with an average of 177.18% and 176.46% in the MNS and MSD triploid hybrid populations, respectively), indicating that the variations of these traits mainly resulted from inheritance. The total sugar contents of triploid hybrid populations inclined to low-sugar parent value, where the average ratio lower than low parent (LL) was more than 50%, showing a tendency of depression. However, the total organic acid contents were higher than those of the mid-parental value, where the average ratio higher than high parent (HH) was more than 70%, displaying obvious heterosis performance. The total sugar content was close to the normal distribution, indicating that it was a quantitative trait controlled by multiple genes. Nevertheless, the content of citric acid displayed a skewed distribution, implying that acid contents might be controlled by the major gene.

**【Conclusion】** Our observations indicated that interploidy hybridization between diploid and tetraploid did not change the contents of sugar and acid components in the fruit pulp of citrus, where sucrose, fructose and glucose were the main components of soluble sugars, while citric acid and malic acid were the major components of organic acids. The sugar content was normally distributed, and therefore likely to be controlled by multiple genes, whereas the organic acid content may be under the control of major gene for displaying a skewed distribution. The contents of sugar and acid in the fruit pulp of citrus triploid hybrids were closer to the parent with high-acid and low-sugar content, and were prone to be affected by the male parent.

**Key words:** *Citrus*; Triploid hybrid; Soluble sugar; Organic acid; Inheritance

柑橘是世界第一大类水果,也是我国南方最重要的果树<sup>[1]</sup>。我国柑橘主要用于鲜果市场,提升果实品质是柑橘品种改良的首要目标。可溶性糖和有机

酸是柑橘果实主要风味物质,其组分、含量及比例是影响柑橘果实食用品质的重要因素<sup>[2-3]</sup>。柑橘糖酸性状研究主要集中在果实发育过程中糖酸含量的变化,

而对其杂交群体遗传规律研究较少,原因可能是柑橘大部分品种存在珠心胚等杂交障碍,通过有性杂交难以获得一定数量的有性后代<sup>[4]</sup>。目前,糖酸性状遗传评价研究在苹果、葡萄、梨等果树上报道较多;前人通过对苹果、梨等有性群体果实糖酸组分评价,认为果实糖含量是由多基因控制的数量性状,不仅存在加性效应,还存在一定程度的非加性效应,且杂交后代糖含量多呈正态分布,平均值接近亲中值<sup>[5-7]</sup>;而果实有机酸含量推测是由一对主效基因和多个微效基因共同控制的,杂交后代酸含量多呈偏态分布<sup>[8-10]</sup>。

三倍体有性后代果实糖酸遗传评价研究对无核优质柑橘的培育具有理论指导意义。三倍体由于减数分裂异常,果实一般无核;且由于倍性增加,三倍体果实一般较大,具有风味浓郁、品质优良和营养丰富的特点,在鲜果市场具有较强的竞争力<sup>[11-12]</sup>。二倍体为母本与四倍体为父本倍性杂交是培育柑橘三倍体的经典途径,但胚珠在发育后期易败育,常规手段难以获得杂种后代,通常需要对幼嫩胚珠实施幼胚离体挽救培养,且柑橘三倍体再生难度大、耗时长,很难获得较大的三倍体遗传群体。因此,关于柑橘三倍体有性后代糖酸代谢特点以及亲本对三倍体后代糖酸积累的影响知之甚少。华中农业大学经过20 a(年)的积累,针对我国柑橘地方良种多数有核的问题,通过二倍体与四倍体倍性杂交获得了稳定开花结果的三倍体有性后代<sup>[13-16]</sup>,为柑橘三倍体有性后代糖酸性状遗传评价奠定了宝贵的材料基础。笔者拟以W.默科特橘橙为母本,异源四倍体体细胞杂种诺瓦橘柚+埃及糖橙、埃及糖橙+丹西红橘为父本倍性杂交创制且已连续多年开花结果的2个三倍体有性群体为材料,探讨柑橘三倍体有性群体果实糖酸的代谢和遗传特点,为未来柑橘三倍体育种亲本选配及无核新品种培育奠定理论基础。

## 1 材料和方法

### 1.1 试验材料

以W.默科特橘橙(*Citrus reticulata*×*C. sinensis*,MCK)、异源四倍体体细胞杂种诺瓦橘柚+埃及糖橙(*C. reticulata*×*C. paradisi*+*C. sinensis*,NS)、埃及糖橙+丹西红橘(*C. sinensis*+*C. reticulata*,SD)及其为亲本倍性杂交获得的2个三倍体有性群体(MCK×NS,MNS;MCK×SD,MSD)为研究材料<sup>[14]</sup>,分析柑橘三倍体有性群体果实糖酸的代谢特点及亲

本对三倍体后代糖酸积累的影响。以上材料均定植于云南省农业科学院热带亚热带经济作物研究所,行株距4.0 m×3.0 m。2018和2019年,MNS组合分别有17和26株,MSD组合分别有22和33株三倍体后代开花结果。采集各年份12月份成熟的果实,采摘时选择树冠外围不同方向大小一致、无病虫害的果实;4个果实为1个生物学重复,共3次重复。每个果实分为两半,一半用于可溶性固形物(total soluble solid content, TSS)和可滴定酸(titratable acid, TA)含量测定;另一半剥取果肉,液氮冷冻后保存于-80 ℃冰箱,用于可溶性糖和有机酸含量测定。

### 1.2 试验方法

1.2.1 果实TSS和TA含量测定 果实TSS和TA含量采用糖酸一体机(Atago,日本)测定。将4个果实(1个生物学重复)的果汁挤入同一个杯子混匀,糖酸一体机校准后,用移液器取100 μL果汁滴于糖酸一体机传感器上,按“Start”键测定样品TSS含量;随后用移液器吸取4.9 mL去离子水加至传感器上,将果汁稀释后测定样品的TA含量。每个生物学重复测定3次,共测定3个生物学重复,并记录数据。

1.2.2 果实可溶性糖和有机酸的提取及含量测定 柑橘果实糖酸提取和测定参照Shi等<sup>[17]</sup>的方法并适当修改。准确称取汁胞冻干样0.1 g,加入5 mL 80% (φ)甲醇并置于75 ℃水浴锅水浴30 min;待样品冷却至室温,用超声波萃取90 min。4000×g离心10 min后,收集上清液并将其转入10 mL容量瓶,加入0.2 mL的2.5% (φ)α-D-甲基葡萄糖甙(Sigma)内标液,用80% (φ)甲醇定容。摇匀后,取2 mL溶液于2 mL离心管,13 500 ×g离心15 min,取0.5 mL上清液至1.5 mL离心管并置于旋转蒸发仪60 ℃蒸发至无水状态。之后取干燥好的样品进行衍生化反应,首先加入0.8 mL的0.02 g·mL<sup>-1</sup>盐酸羟胺溶液,75 ℃反应1 h;冷却至室温后,迅速依次加六甲基二硅胺烷0.4 mL和三甲基氯硅烷0.2 mL,75 ℃反应2 h。冷却后,取0.5 mL上清液至2 mL的气相色谱进样瓶,用于气相色谱(GC)分析。GC工作条件如下:HP-5色谱柱(5%-Phenyl-methyl polysiloxane, 30 m×320 μm×0.25 μm),进样口温度270 ℃;检测器温度300 ℃;高纯氮作载气,流量45 mL·min<sup>-1</sup>,H<sub>2</sub>流量40 mL·min<sup>-1</sup>,空气流量450 mL·min<sup>-1</sup>,柱头压82.74 kPa,进样量1 μL,分流比30:1,分流流速60.1 mL·min<sup>-1</sup>,总流速64.6 mL·min<sup>-1</sup>。升温程序:初温130 ℃,以8 ℃·min<sup>-1</sup>

升至 $152\text{ }^{\circ}\text{C}$ , $12\text{ }^{\circ}\text{C}\cdot\text{min}^{-1}$ 升至 $176\text{ }^{\circ}\text{C}$ , $16\text{ }^{\circ}\text{C}\cdot\text{min}^{-1}$ 升至 $198\text{ }^{\circ}\text{C}$ , $20\text{ }^{\circ}\text{C}\cdot\text{min}^{-1}$ 升至 $238\text{ }^{\circ}\text{C}$ , $24\text{ }^{\circ}\text{C}\cdot\text{min}^{-1}$ 升至 $280\text{ }^{\circ}\text{C}$ ,最后在 $280\text{ }^{\circ}\text{C}$ 保温4 min。

**1.2.3 数据统计** 用Excel 2016对数据整理分析和绘图(Student's *t-test*,  $p < 0.05$ )。三倍体有性后代群体TSS、TA及糖酸各组分含量亲中值(median parental value,  $P$ )、杂交群体的平均值(population average value,  $F$ )、变异系数(variation of coefficient,  $CV$ )、遗传传递力(genetic transmitting ability,  $Ta$ )的计算参考崔艳波等<sup>[18]</sup>的方法。超高亲比率(ratio of higher than high parent,  $HH$ )、超中亲比率(ratio of higher than middle parent,  $HM$ )和低低亲比率(ratio of lower than low parent,  $LL$ )的计算参考刘有春等<sup>[19]</sup>的方法。

## 2 结果与分析

### 2.1 三倍体有性群体果实TSS和TA含量的分布

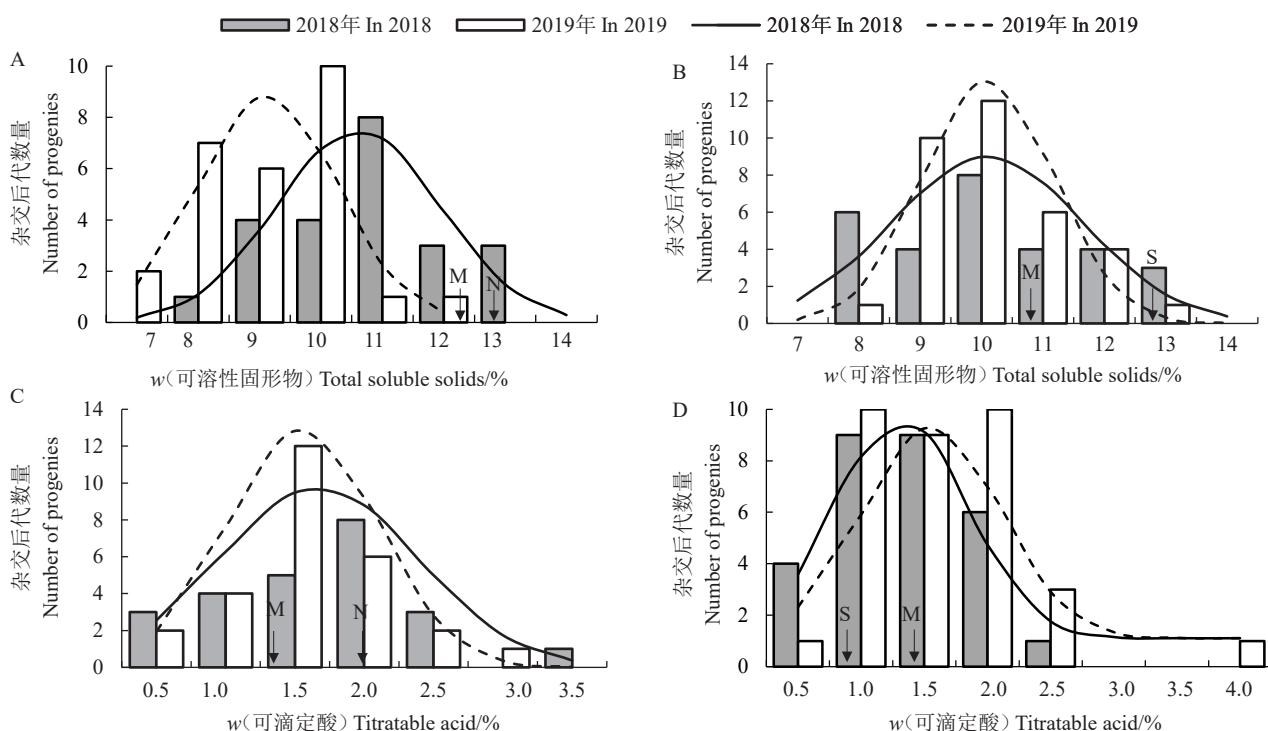
MNS和MSD 2个三倍体有性群体不同年份间果实TSS含量为连续变异且符合正态分布,表明柑橘TSS含量为多基因控制的数量性状;2个组合三

倍体后代果实TSS含量不同年份间相对稳定,大部分三倍体后代的TSS含量低于低值亲本(图1-A~B,表1),表明柑橘三倍体有性后代TSS含量的遗传偏向于低值亲本;但偶有高于高值亲本的单株存在,这为选育高糖柑橘品种提供了材料。

2个三倍体有性群体果实TA含量呈现不连续变异,频率分布呈偏态分布,且趋向于高值亲本,推测柑橘果实TA含量的遗传可能存在主效基因。2个组合三倍体后代TA含量在不同年份间相对稳定(图1-C~D,表1),且大部分三倍体后代TA含量高于高值亲本或介于双亲之间,出现较多高酸株系,表明柑橘三倍体有性后代TA含量存在超亲遗传现象;但也存在低于低酸亲本的单株,这为选育低酸三倍体品种提供了宝贵的育种材料。

### 2.2 三倍体有性群体果实可溶性糖组分频率分布及遗传特点

三倍体有性群体果实可溶性糖含量测定结果显示(图2),后代果实的可溶性糖成分与亲本一致,均以积累蔗糖为主,果糖和葡萄糖在成熟果实中含量相对较低。三倍体有性群体果实的蔗糖、果糖、葡萄



A 和 C 为 MNS 组合;B 和 D 为 MSD 组合。M 代表 MCK;N 代表 NS;S 代表 SD。

A and C represent the triploid hybrids from MNS; B and D represent the triploid hybrids from MSD; M represents MCK;

N represents NS; S represents SD.

图 1 三倍体有性群体果实 TSS 和 TA 含量分布

Fig. 1 The frequency distribution of TSS and TA contents in the fruits of two triploid hybrid populations.

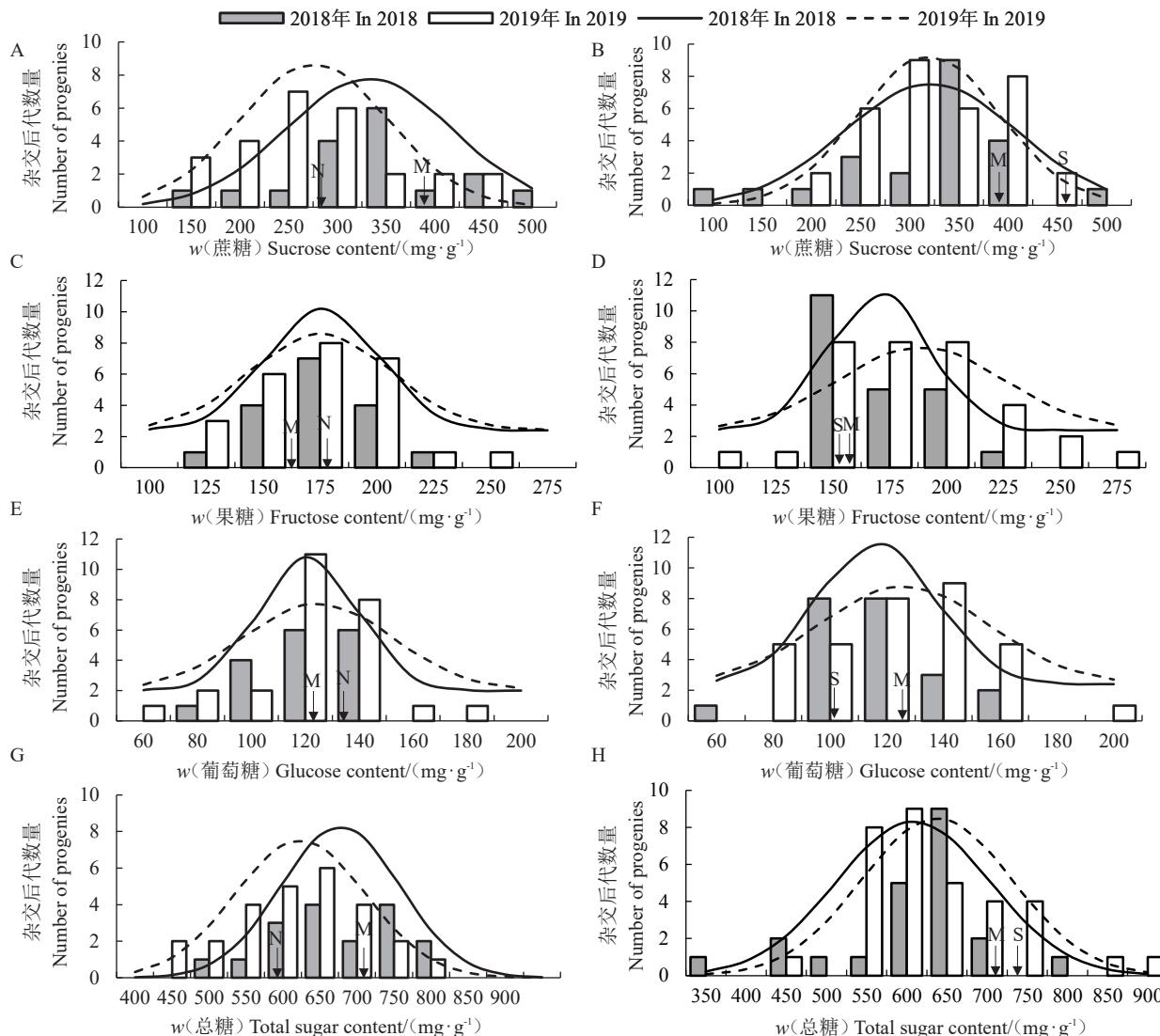
表1 三倍体有性群体果实TSS和TA含量的遗传变异

Table 1 Variation and inheritance of TSS and TA contents in the fruits of two triploid hybrid populations

指标 Index	组合 Crosses	年份 Year	后代株数 No. of progeny	$P_1/\%$	$P_2/\%$	$P/\%$	$F/\%$	标准差 $SD$	$CV/\%$	$Ta/\%$	$HH/\%$	$LL/\%$	$HM/\%$
可溶性固形物含量 Total soluble solids	MNS	2018	24	11.34	12.57	11.96	10.81	1.62	14.99	90.42	12.50	70.83	20.83
	MNS	2019	27	13.71	13.42	13.57	9.13	1.13	12.38	67.30	0.00	100.00	0.00
	MSD	2018	29	11.34	12.94	12.14	10.09	1.55	15.36	83.08	3.45	75.86	10.34
	MSD	2019	34	13.71	13.98	13.84	10.10	1.07	10.59	72.95	0.00	100.00	0.00
可滴定酸含量 Titratable acid	MNS	2018	24	1.26	2.08	1.67	1.67	0.72	43.11	100.17	20.83	29.17	54.17
	MNS	2019	27	1.39	1.93	1.66	1.55	0.54	34.84	93.40	25.93	44.44	33.33
	MSD	2018	29	1.26	0.95	1.10	1.32	0.52	39.39	119.58	55.17	37.93	55.17
	MSD	2019	34	1.39	1.08	1.23	1.63	0.67	41.10	132.16	52.94	23.53	70.59

注: $P_1$ 代表母本含量; $P_2$ 代表父本含量; $P$ 代表亲中值; $F$ 代表三倍体后代的平均值; $CV$ 代表变异系数; $Ta$ 代表遗传传递力; $HH$ 代表超高亲比率; $LL$ 代表低低亲比率; $HM$ 代表超中亲比率。下同。

Note:  $P_1$  represents the value in female parent;  $P_2$  represents the value in male parent;  $P$  represents the median parent value;  $F$  represents the average value of triploid hybrids;  $CV$  represents the variation of coefficient;  $Ta$  represents the genetic transmitting ability;  $HH$  represents the ratio of higher than high parent;  $LL$  represents the ratio of lower than low parent;  $HM$  represents the ratio of higher than mid-parent. The same below.



A、C、E、G为MNS组合;B、D、F、H为MSD组合。M代表MCK;N代表NS;S代表SD。

A, C, E and G represent the triploid hybrids from MNS; B, D, F and H represent the triploid hybrids from MSD; M represents MCK; N represents NS; S represents SD.

图2 三倍体有性群体果实蔗糖、果糖、葡萄糖和总糖含量分布

Fig. 2 The frequency distribution of the contents of sucrose, fructose, glucose and total sugar in the fruits of two triploid hybrid population

糖及总糖含量在不同年份间均呈现正态分布,具有典型的数量性状遗传特征,推测柑橘可溶性糖属微效多基因控制的数量性状,且三倍体后代果实的蔗糖及总糖含量大多趋向于低值亲本。

由图2可以看出,2个组合不同的三倍体有性后代果实的可溶性糖各组分含量差异明显。MSD组合2019年三倍体有性后代的蔗糖、果糖和葡萄糖含量(*w*,后同)变异范围分别为176.09~454.09、112.28~279.72和72.40~205.36 mg·g<sup>-1</sup>,对应的CV分别为26.99、25.86%和31.39%(表2),表明可溶性糖

各组分在三倍体有性后代表现出较广泛分离,且蔗糖含量变化范围大于葡萄糖和果糖,选择潜力较大。三倍体有性后代可溶性糖的Ta较强。MSD组合2019年三倍体有性后代的蔗糖、果糖和葡萄糖Ta值分别为65.50%、116.81%和107.52%,表明可溶性糖各组分的变异主要来自于遗传效应,由基因间的加性效应控制。2个三倍体有性群体中,果实可溶性糖各组分含量低于低值亲本的单株较多,特别是蔗糖和总糖含量。总糖含量平均LL为70.56%,表明三倍体有性群体可溶性糖各组分含

表2 三倍体有性群体果实蔗糖、果糖、葡萄糖和总糖含量的遗传变异

Table 2 Inheritance and variation of the contents of sucrose, fructose, glucose and total sugar in the fruits

of two triploid hybrid populations

糖组分 Sugar component	组合 Crosses	年份 Year	后代株数 No. of progeny	P <sub>1</sub> / (mg·g <sup>-1</sup> )	P <sub>2</sub> / (mg·g <sup>-1</sup> )	P/ (mg·g <sup>-1</sup> )	F/ (mg·g <sup>-1</sup> )	标准差 SD	CV/%	Ta/%	HH/%	LL/%	HM/%
蔗糖 Sucrose	MNS	2018	17	387.78	303.12	345.45	332.46	96.52	29.03	96.24	23.53	29.41	35.29
	MNS	2019	26	457.82	271.21	364.51	275.84	87.96	31.89	75.67	0.00	53.85	15.38
	MSD	2018	22	387.78	401.25	394.52	321.40	93.81	29.19	81.47	13.64	81.82	18.18
	MSD	2019	33	457.82	532.97	495.39	324.49	87.57	26.99	65.50	0.00	100.00	48.48
果糖 Fructose	MNS	2018	17	163.27	195.47	179.37	176.21	29.60	16.80	98.24	29.41	35.29	35.29
	MNS	2019	26	163.69	168.81	166.25	175.29	32.94	18.79	105.44	57.69	34.62	61.54
	MSD	2018	22	163.27	162.68	162.98	170.33	24.85	14.59	104.51	50.00	50.00	50.00
	MSD	2019	33	163.69	157.80	160.75	187.78	48.56	25.86	116.81	69.70	27.27	69.70
葡萄糖 Glucose	MNS	2018	17	120.57	142.45	131.51	121.27	21.96	18.11	92.21	11.76	47.06	35.29
	MNS	2019	26	131.27	129.37	130.32	122.17	27.44	22.46	93.74	34.62	57.69	38.46
	MSD	2018	22	120.57	107.80	114.18	116.34	24.64	21.18	101.89	36.36	40.91	54.55
	MSD	2019	33	131.27	101.75	116.51	125.26	39.32	31.39	107.52	45.45	27.27	63.64
总糖 Total sugar	MNS	2018	17	671.62	641.04	656.33	627.56	106.72	17.01	95.62	35.29	58.82	35.29
	MNS	2019	26	752.79	569.38	661.08	573.30	103.60	18.07	86.72	3.85	46.15	11.54
	MSD	2018	22	671.62	671.74	671.68	608.07	107.14	17.62	90.53	13.64	86.36	13.64
	MSD	2019	33	752.79	792.51	772.65	637.53	132.54	20.79	82.51	6.06	90.91	6.06

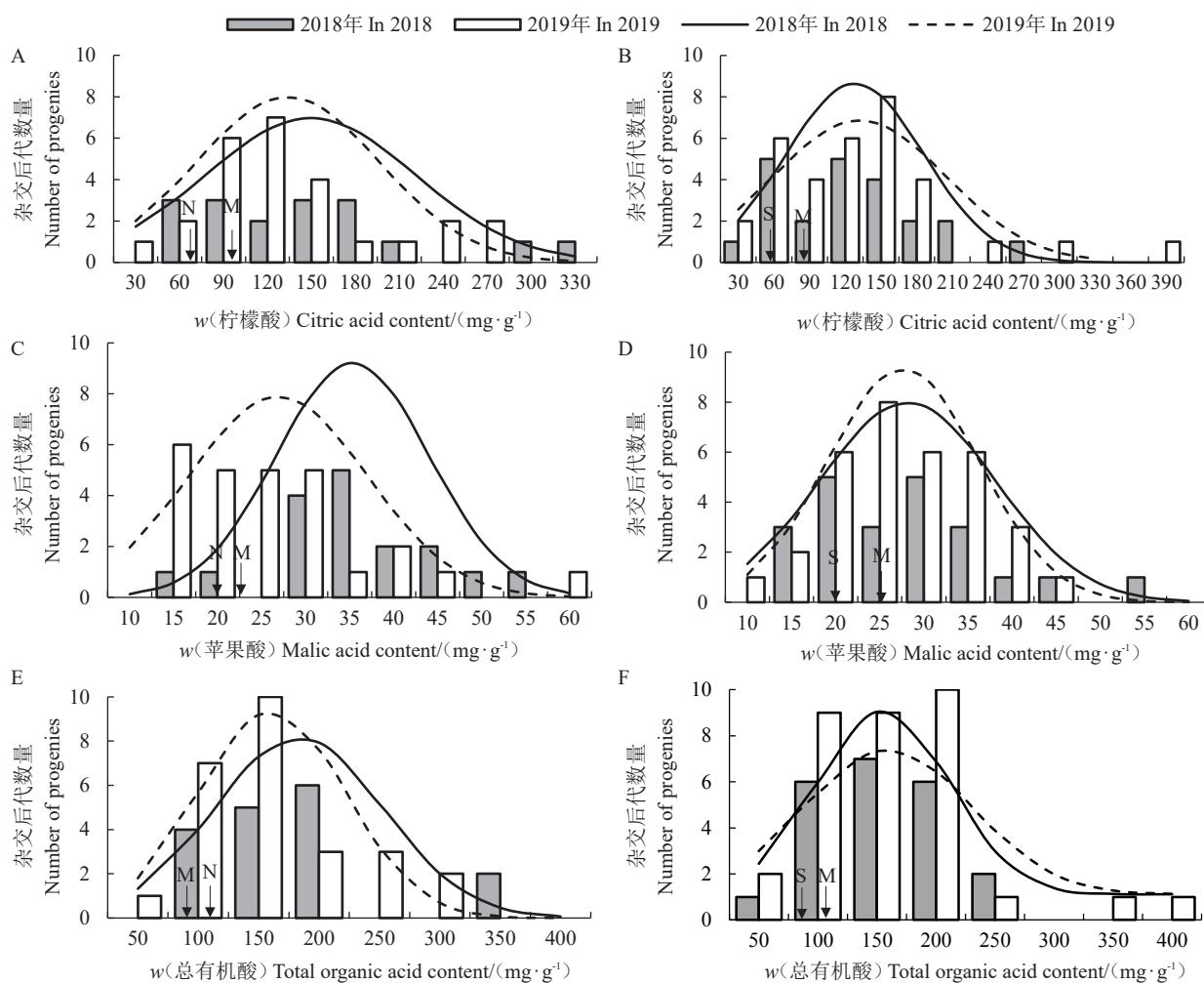
量整体呈现衰退变异。

### 2.3 三倍体有性群体果实有机酸组分频率分布及遗传特点

三倍体有性群体果实有机酸含量测定结果显示,后代果实的有机酸与亲本一致,均以积累柠檬酸为主,苹果酸次之,且2种有机酸在不同年份样品间的含量比较稳定。由图3可知,三倍体有性群体果实的柠檬酸、苹果酸及总酸含量大多呈现不连续变异,频率分布呈偏态分布,且趋向于高值亲本,推测柑橘有机酸的遗传可能存在主效基因。2个群体虽然多数三倍体后代总酸含量高于高值亲本,但均存在一定比例总酸含量低于双亲的三倍体,为选育低酸且无核的三倍体品种提供了宝贵

材料。

由图3可知,柠檬酸和苹果酸在2个群体不同三倍体后代果实的含量差异明显。MSD组合2019年三倍体有性后代果实的柠檬酸、苹果酸含量变异范围分别为35.25~391.98和9.94~44.95 mg·g<sup>-1</sup>,对应的CV分别为61.67%和36.23%(表3),表明三倍体有性后代果实的柠檬酸和苹果酸含量分离广泛。柠檬酸和苹果酸的Ta也较强。MSD组合2019年三倍体后代果实的柠檬酸、苹果酸Ta值分别为178.66%和112.93%,表明遗传效应在三倍体有性群体果实有机酸变异中起主导作用。2个三倍体有性群体中,果实总酸含量高于双亲的单株较多,平均HH为76.00%,表明柑橘三倍体有性群体果实有机酸的积



A、C、E 为 MNS 组合;B、D、F 为 MSD 组合。M 代表 MCK;N 代表 NS;S 代表 SD。

A, C and E represent the triploid hybrids from MNS; B, D and F represent the triploid hybrids from MSD; M represents MCK; N represents NS; S represents SD.

图 3 三倍体有性群体果实柠檬酸、苹果酸和总酸含量分布

Fig. 3 The frequency distribution of the contents of citric acid, malic acid and total organic acid in the fruits of two triploid hybrid populations

表 3 三倍体有性群体果实柠檬酸、苹果酸和总有机酸含量的遗传变异

Table 3 Inheritance and variation of the contents of citric acid, malic acid and total organic acid in two triploid hybrid populations

酸组分 Acid component	组合 Crosses	年份 Year	后代株数 No. of progeny	P <sub>1</sub> / (mg·g <sup>-1</sup> )	P <sub>2</sub> / (mg·g <sup>-1</sup> )	P/ (mg·g <sup>-1</sup> )	F/ (mg·g <sup>-1</sup> )	标准差 SD	CV/% CV%	Ta/% Ta%	HH/% HH%	LL/% LL%	HM/% HM%
柠檬酸含量 Citric acid	MNS	2018	17	89.03	72.78	80.90	149.54	75.93	50.77	184.85	82.35	17.65	82.35
	MNS	2019	26	89.34	68.73	79.04	133.97	67.85	50.65	169.50	73.08	11.54	88.46
	MSD	2018	22	89.03	57.97	73.50	128.07	59.85	46.73	174.26	63.64	9.09	72.73
	MSD	2019	33	89.34	58.48	73.91	132.05	81.43	61.67	178.66	69.70	15.15	78.79
苹果酸含量 Malic acid	MNS	2018	17	22.95	22.67	22.81	34.92	9.64	27.62	153.08	88.24	11.76	88.24
	MNS	2019	26	21.88	15.78	18.83	26.88	11.52	42.85	142.70	57.69	7.69	73.08
	MSD	2018	22	22.95	25.09	24.02	28.59	11.02	38.57	119.03	59.09	36.36	63.64
总酸含量 Total organic acid	MSD	2019	33	21.88	27.11	24.50	27.66	10.02	36.23	112.93	48.48	27.27	63.64
	MNS	2018	17	111.97	95.45	103.71	183.09	75.61	41.29	176.54	82.35	5.88	88.24
	MNS	2019	26	111.23	84.52	97.87	160.84	66.85	41.56	164.34	80.77	3.85	84.62
	MSD	2018	22	111.97	83.05	97.51	155.36	57.83	37.22	159.33	68.18	4.55	77.27
	MSD	2019	33	111.23	85.59	98.41	159.71	80.78	50.58	162.29	72.73	9.09	84.85

累存在超亲遗传,杂种优势明显。

### 3 讨 论

本研究结果表明,以W.默科特橘橙为母本倍性杂交获得的2个三倍体有性群体果实的可溶性糖均以积累蔗糖为主,其次为葡萄糖和果糖;有机酸以积累柠檬酸为主,苹果酸次之,该结果与柑橘二倍体的报道一致<sup>[3]</sup>。但与二倍体相比,三倍体果实中各糖酸组分含量出现广泛分离,含量变化较大,表明倍性增加对柑橘果实糖酸组分影响不大,主要影响糖酸各组分的含量变化。

本研究通过比较2个三倍体有性群体果实糖酸含量发现,四倍体父本对不同三倍体群体果实糖酸含量影响较大。当以总糖含量较高的SD为父本时,其三倍体群体果实总糖平均含量高于以NS为父本的三倍体群体。同理,以SD(2018和2019年果实的柠檬酸含量均低于NS)为父本杂交获得的三倍体有性群体柠檬酸含量平均值低于以NS为父本的三倍体群体,表明柑橘三倍体有性群体果实糖酸含量的高低可能与四倍体父本有关。父本对杂交后代性状影响较大的现象在其他果树中也有报道。Liang等<sup>[20]</sup>发现葡萄有性群体中,父本对子代果实花青苷含量的高低有重要影响。刘有春等<sup>[19]</sup>和徐豆等<sup>[21]</sup>分别测定越橘和欧洲李的正反交群体的果实有机酸含量,发现后代果实的有机酸含量趋向于父本,受父本影响较大。因此,未来柑橘倍性育种时,可有针对性地选择高糖低酸的四倍体为父本倍性杂交,以提高获得果实品质优良且无核的柑橘三倍体新品种的概率。

有性杂交时,亲本的非加性效应一般会解体,使得后代性状呈现广泛分离,劣变率较高;但同时也会出现超亲单株,使得杂交育种更有意义<sup>[22]</sup>。本研究中,2个三倍体有性群体的果实TSS和总糖平均含量均低于亲中值,总体呈现衰退变异,但也存在超亲遗传单株,符合有性杂交后代糖含量的遗传特点。前人在葡萄、杏等果树中也获得了相似结果<sup>[10,23-24]</sup>。究其原因,这可能是柑橘在长期育种过程中,育种家偏向于选择果实糖含量高的亲本进行有性杂交,而人工选择的亲本则存在一定程度的非加性效应,经过有性杂交会使非加性效应解体,引起杂交后代糖含量降低。与糖性状相反,2个三倍体有性群体的果实TA和总酸含量平均值均大于亲中值,且70%以

上的单株总酸含量高于高值亲本,表明即使非加性效应解体,有性杂交也会使果实酸含量产生杂种优势,表现出明显的超亲遗传效应。

前人对梨<sup>[18]</sup>、越橘<sup>[6,19]</sup>、苹果<sup>[9]</sup>、葡萄<sup>[10,24]</sup>等果树研究发现,果实糖含量一般为多基因控制的数量性状,加性效应在遗传效应中占比较大。本研究2个三倍体有性群体的果实TSS和总糖含量均呈正态分布的特点,表明柑橘三倍体有性群体果实TSS和总糖含量的遗传模式与已报道的其他果树相似,推测也属于由多基因控制的数量性状。与可溶性糖相比,前人发现有机酸在有性后代中的遗传规律较为复杂,一般呈偏态分布<sup>[9,25-26]</sup>,推断有机酸由1个或多个主效基因控制。在本研究中,2个三倍体有性群体果实总酸和柠檬酸含量均呈偏态分布,表明柑橘三倍体果实中可能存在控制有机酸含量的主效基因。本研究也发现,大部分三倍体后代果实的总酸及柠檬酸含量高于双亲,推测三倍体后代存在基因剂量效应,使得大部分三倍体后代果实有机酸含量高于二倍体亲本,这与前人研究结果一致<sup>[27]</sup>。

### 4 结 论

以W.默科特橘橙为母本进行倍性杂交获得的2个三倍体有性群体果实中,蔗糖、果糖和葡萄糖是主要糖组分,柠檬酸和苹果酸是主要酸组分。糖酸含量分布广泛,糖含量呈正态分布并趋向低值亲本,推测属于多基因控制的数量性状。酸含量呈偏态分布且趋向高值亲本,遗传上可能存在主效基因。研究表明杂交后代果实糖酸含量受父本糖酸含量影响较大,这为今后科学配置杂交组合、培育出无核且品质优良的三倍体柑橘提供理论依据。

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