

花粉直感对马家柚果品质的影响

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摘要:【目的】通过对马家柚配置不同授粉组合, 探究花粉直感效应对马家柚果品质的影响。【方法】以江西省上饶市地方优良品种马家柚为杂交母本, 以信木柚、四倍体葡萄柚为杂交父本, 通过人工授粉进行杂交, 比较不同处理下马家柚果品质差异。【结果】信木柚与四倍体葡萄柚花粉活力分别为94.34%和93.75%, 经过异花授粉能显著提高马家柚坐果率, 四倍体葡萄柚高于信木柚。在常规品质方面, 信木柚授粉能提高果实平均单果质量、横径、纵径、种子质量、果皮质量和固酸比; 四倍体葡萄柚授粉能提高果实平均可食率, 降低果实平均单果质量、果皮厚度、种子质量和果皮质量, 且授粉后种子呈瘪籽状。在代谢物方面, 果肉中主要的初生代谢物为氨基酸类、有机酸类、糖类和醇类, 不同授粉品种之间初生代谢物含量有明显差异, 但与亲本之间没有明显规律。另外在授粉后的果实与亲本果实中共统计到85种挥发性物质, 其中醛类11种, 脂类28种, 酯类16种, 醇类14种, 酮类14种, 烷烃类化合物5种和7种酚、羧酸类化合物, 不同果实中均以柠檬烯含量最高, 含量占比在87.48%~92.57%之间, 不同授粉品种的挥发性物质含量存在差异, 且信木柚授粉组合中有21种物质表现出明显的花粉直感效应。【结论】异花授粉可以提高马家柚坐果率, 可以通过花粉直感效应在一定程度上快速改善马家柚的综合品质, 为马家柚实际生产提供理论依据和调控技术支撑。

关键词:马家柚; 花粉直感; 果品质; 香气组分; 异花授粉

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Effect of xenia on fruit quality of Majiayou

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Abstract:【Objective】Pollination of Majiayou with a local variety Xinmuyou and a tetraploid grapefruit was used to investigate xenia effect on the fruit quality of Majiayou. It was expected to improve the fruit quality of Majiayou by selecting pollen parent. 【Methods】Mature 9-10-year-old Majiayou trees were used as the seed parent. Xinmuyou and a tetraploid grapefruit were used as the pollen parents (pollination A group, Majiayou × Xinmuyou; pollination B group, Majiayou × tetraploid grapefruit), and natural open pollination was used as the control. After the fruit ripened, a fruits from different pollination groups were analyzed for fruit quality, primary metabolites in the pulp, and volatile substances in the pericarp. 【Results】Pollen viability of Xinmuyou and the tetraploid grapefruit was 94.34% and 93.75%, respectively. Cross-pollination significantly increased the fruit set rate of Majiayou, and the effect of the tetraploid grapefruit was more significant compared to that of Xinmuyou. The average single fruit weight was 1109.09 g in pollination A group, which was higher than pollination with the tetra-

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ploid grapefruit (pollination B group) and the control. Single fruit weight in pollination B was the lowest. Fruit diameter, pericarp weight and pericarp thickness (2.06 cm) in pollination B were significantly lower than the other groups. Pollination A significantly increased seed weight. Seed weight in pollination B group was the lowest, and most of the seeds were shrunken. The flesh recovery was highest in pollination B group, followed in descending order by the control and pollination A group. The difference between pollination B and pollination A was significant. In the control, total soluble solids (TSS) content and titratable acidity (TA) was higher than the other two pollination groups. However, TSS/TA ratio was 13.48 in the control, significantly lower than in pollination A and B groups. The primary metabolites included amino acids, organic acids, sugars, and alcohols. There were significant differences in the content of primary metabolites between different pollination groups, but there was no clear pattern in the contents of primary metabolites in fruits among pollen parents. Pollination B resulted in the highest citric acid content ($2.35 \text{ mg} \cdot \text{g}^{-1}$) and sucrose content ($39.19 \text{ mg} \cdot \text{g}^{-1}$), which were significantly higher than the control and pollination A. Glucose content in fruit of pollination A group was $43.52 \text{ mg} \cdot \text{g}^{-1}$, which was significantly higher than that of the other groups. In pollination A and B, the main amino acid in the fruit was proline, whose concentration was $0.32 \text{ mg} \cdot \text{g}^{-1}$ in group B, which was significantly higher than the other two groups. A total of 85 volatile compounds were identified in fruits from different pollination groups and fruits from open pollination of the parents. They included 11 aldehydes, 28 terpenes, 16 esters, 14 alcohols, 14 ketones, 5 aliphatic hydrocarbons, 7 phenols, and 7 carboxylic acid compounds. 41 volatile compounds were detected in the fruit from open pollination, with limonene being the most abundant, accounting for 87.48% of the total content. In fruit from pollination A group, 36 volatile substances were found, with limonene accounting for 92.57% of the total content. In the fruit of Xinmuyou, 47 volatile substances were detected, with limonene making up 91.07% of the total content. In fruit from pollination B, 38 volatile substances were detected, with limonene representing 88.52% of the total content. In the fruit of the tetraploid grapefruit, 49 volatile substances were detected, with limonene constituting 88.65% of the total content. 21 volatile substances exhibited a significant xenia effect, including most of the terpene substances. Limonene content in fruit from open pollination was $25.822.76 \mu\text{g} \cdot \text{g}^{-1}$, while it was $154.583.28 \mu\text{g} \cdot \text{g}^{-1}$ in Xinmuyou fruit. However, in fruit from pollination with Xinmuyou, limonene content reached $84.271.06 \mu\text{g} \cdot \text{g}^{-1}$, which was more than three times higher than that under open pollination. This indicates that pollination with Xinmuyou pollen substantially increased the limonene content in the Majiayou fruit. 【Conclusion】 In conclusion, cross-pollination can increase the fruit set of Majiayou, and Majiayou fruit quality can be directly improved through the xenia effect. This research provides a theoretical basis and technical support for the practical production of Majiayou.

Key words: Majiayou; Pollen xenia; Fruit quality; Aroma components; Cross-pollination

马家柚 [*Citrus grandis* (L.) Osbeck] 是江西省上饶市广丰区的一个特色地方优良品种, 在 20 世纪 80 年代由当地机构对大量柑橘资源进行广泛调查和收集, 并经过多年筛选而获得的地方优良柚资源^[1]。马家柚果实较大, 果皮金黄色, 果肉粉红且多汁, 口感清香独特, 具有耐贮藏等优良特性, 已成为当地的主栽柑橘品种和重要经济来源^[2]。截至 2019 年, 上饶市马家柚栽培面积超 $2.53 \text{ 万 hm}^{2[3]}$, 其产业规模已

经基本成形。在遗传特性方面, 马家柚无单性结实能力, 自花结实率较低, 在生产上往往通过种植授粉树和放蜂来辅助马家柚进行异花授粉, 从而提高果实的产量^[4], 但目前在马家柚实际生产上还没有统一的授粉树品种, 在园区常见的授粉树多为粗皮马家柚和当地的土柚品种, 其授粉后果实个体差异大、品质不稳定, 且通过放蜂来提高马家柚异花授粉的效果受自然环境的影响较大, 所以导致近年来马家

柚果实时产量逐年下降,果实品质也呈现下降趋势。为此,通过试验探索出优异的马家柚授粉组合,实现稳定并改善马家柚果实品质是马家柚产区急需实现的目标。

花粉直感指通过不同父本花粉进行授粉后,受精形成的果实或种子受花粉的影响,在当代的表型性状和组成成分即表现出差异的现象^[5]。花粉直感现象最早在1876年有报道^[6],研究者根据所影响的部位不同,将花粉直感分为花粉种子直感和花粉果实直感。随着不断研究与发展,自然界很多植物当中都发现了花粉直感现象,如板栗^[7]、玉米^[8]、棉花^[9]、大白菜^[10]等,这都表明花粉直感对植物的生长起着重要的作用。

花粉直感现象在果树上也广泛存在,如柑橘^[11]、梨^[12]、猕猴桃^[13]、荔枝^[14]、苹果^[15]等。相关研究表明,花粉直感的存在能影响种子的形状和大小^[16-17];缩短果实的成熟期^[18];影响果实形状和大小^[19-20]、增强果皮光合能力^[21]、改善果实糖酸^[22-23]及内在物质含量^[24]等,但花粉直感带来的变异并不都是朝着有利于亲本性状的方向进行,花粉直感具体的机制目前还未明确定论。

笔者在本研究中利用地方品种信木柚和四倍体葡萄柚与马家柚进行异花授粉来探究花粉直感对马家柚果实时产量与品质的影响。结果显示异花授粉可以提高马家柚坐果率,改善果实品质,其中四倍体葡萄柚授粉可以显著降低果实种子质量,信木柚授粉能显著增加马家柚果皮香气。以上结果验证了花粉直感对马家柚的影响,可为生产上杂交组合的配置与品质快速改良提供理论依据,同时利用四倍体葡萄柚授粉有望快速解决马家柚果实种子多的问题。

1 材料和方法

1.1 试验材料

于2022年在江西省上饶市广丰区枧底镇马家柚科技中心果园(以下称枧底园)进行,选择树龄为9~10 a(年)树势生长一致的马家柚作为授粉母本,父本花粉选用信木柚和四倍体葡萄柚,其中信木柚来自于上饶市玉山县,其果皮具有香气,是当地的一个地方品种,四倍体葡萄柚来自于华中农业大学国家柑橘资源圃。共配置组合A(马家柚×信木柚)、组合B(马家柚×四倍体葡萄柚)和马家柚自然授粉的对照组。其他材料还包括两种父本的果实,其中信

木柚果实来源于上饶市玉山县信木农业公司种植园,四倍体葡萄柚果实来源于华中农业大学国家柑橘资源圃。

1.2 花粉收集与活力检测

选择含苞待放状的花进行采摘,再用镊子轻轻将其花药剥离,而后将花药置于28 °C恒温烘箱进行避光培养,培养2~3 d其花粉便散出,将花粉装入避光收集管中,放入-20 °C进行保存备用。利用醋酸洋红染色法对花粉活力进行检测,在干净的载玻片上滴一滴1%醋酸洋红染液,用毛笔或小刷子蘸取花粉轻轻撒于醋酸洋红染液中,盖上盖玻片,静置染色1~2 min,在显微镜下观察花粉染色情况,每种花粉重复染色3次,每次选取5个视野,统计并记录每个视野下花粉活力情况,花粉活力%=(深红色花粉数/观察花粉总数)×100。

1.3 授粉与果实品质测定

每个授粉组合选择5株树势均匀的马家柚,在树体不同方位选择结果枝进行标记,标记120朵花左右,每个结果枝选择5~6朵花进行人工授粉,对照组则只进行疏花处理。于第二次生理落果后统计不同组合的坐果率。待果实成熟后在每株授粉树不同方位选择5个果实进行常规品质测定:通过游标卡尺测量果实横纵径,并计算果形指数;电子天平测定果实单果质量、果皮质量、果渣质量、种子质量等指标,并计算可食率;用手持糖酸仪测定可溶性固形物含量和可滴定酸含量,计算果实固酸比等。最后通过IBM SPSS Statistics 20软件用于差异显著性分析。

1.4 果肉初生代谢物测定

提取和测定方法参考前人所述^[25],将果肉组织在液氮冷冻下磨成细粉,称取0.3 g粉末组织,加入2700 μL -20 °C预冷的甲醇,摇匀后加入150 μL的核糖醇内标(4 mg·mL⁻¹),充分震荡至呈匀浆;将样品置于超声清洗仪中4 °C超声处理30 min;70 °C水浴解育15 min,置于-20°C使溶剂冷凝1 h;4 °C,5000 r·min⁻¹离心15 min;取100 μL上清液于1.5 mL离心管中,30 °C真空浓缩制干后进行衍生化,衍生化之后在GC-MS仪器中进行上样检测。通过数据库比对鉴定代谢物,通过代谢物和内标核糖醇峰面积比值进行相对定量,计算公式为:代谢物的相对含量=(物质峰面积/核糖醇峰面积)×核糖醇质量/样品质量,数据整理利用Excel 2010、SPSS 26和Origin 2022等软件进行分析与作图。

1.5 果皮挥发性物质测定

提取与测定方法参考前人研究并略有修改^[26], 将果皮黄皮层放于液氮下冷冻磨成细粉, 称取0.1 g置于2 mL离心管中, 加入500 μL超纯水后涡旋混匀, 再加入500 μL含有壬酸甲酯(1:20)的MTBE提取液, 涡旋混匀, 将混合液4 °C超声萃取40 min, 然后在4 °C离心机12 000 r·min⁻¹离心10 min, 用1 mL注射器吸取上清液用0.22 μm滤膜过滤进2 mL进样瓶中, 做好标记后在GC-MS仪器中进行上样检测。挥发性物质相对含量计算: 通过内标壬酸甲酯来计算, 计算公式为: 挥发性组分的相对含量=(挥发性物质峰面积/壬酸甲酯峰面积)×壬酸甲酯质量/样品质量, 数据整理利用Excel 2010、SPSS 26和Origin 2022等软件进行分析与作图。

2 结果与分析

2.1 不同父本花粉活力与坐果率统计

如表1所示, 采用醋酸洋红染色法对父本花粉进行检测, 统计到信木柚与四倍体葡萄柚的花粉活力分别为94.34%和93.75%, 对不同授粉处理的坐果率进行统计, 发现异花授粉能显著提高马家柚坐果率, 且四倍体葡萄柚花粉>信木柚花粉。

表1 不同父本花粉活力与坐果率统计

Table 1 Statistics of pollen viability and fruit set in treatments with different male parents

花粉来源 Pollen source	花粉活力 Pollen vitality/%	坐果率 Fruit set/%
四倍体葡萄柚 Tetraploid Grapefruit	93.75	33.33±2.14 a
信木柚 Xinmuyou	94.34	29.17±3.32 a
自然授粉 Natural pollination	/	16.11±1.17 b

注: 不同小写字母表示差异显著($p<0.05$)。“/”表示该处理下无法测定其花粉活力。下同。

Note: Different small letters indicate significant difference ($p<0.05$). “/” indicates that the pollen vitality cannot be determined under this treatment. The same below.

2.2 不同授粉品种对马家柚果实品质的影响

通过测定不同品种授粉后的果实品质, 探究花粉直感对马家柚果实品质的影响, 由表2可知, 信木柚授粉后的平均单果质量为1 109.09 g, 高于四倍体葡萄柚和自然授粉, 其中四倍体葡萄柚授粉位于三者中最低; 不同授粉品种的果实果形指数和囊瓣数无显著性差异; 四倍体葡萄柚授粉的果实横径和果皮质量显著低于信木柚与自然授粉; 四倍体葡萄柚

授粉后的果实平均果皮厚度为2.06 cm, 低于信木柚(2.31 cm)与自然授粉(2.51 cm); 信木柚授粉能显著增加果实平均种子质量, 四倍体葡萄柚授粉后果实平均种子质量位于三者中最低, 且经过四倍体葡萄柚授粉后果实种子大多为瘪籽(图1); 不同授粉品种间果实可食率自高到低依次为四倍体葡萄柚、自然授粉和信木柚, 其中四倍体葡萄柚授粉的可食率显著高于信木柚; 自然授粉下果实的可溶性固形物含量高于四倍体葡萄柚和信木柚, 可滴定酸含量显著高于四倍体葡萄柚与信木柚, 但自然授粉下果实的平均固酸比为13.48, 显著低于信木柚与四倍体葡萄柚授粉果实, 综合固酸比自高到低依次为信木柚授粉、四倍体葡萄柚授粉和自然授粉。

2.3 不同授粉品种对果肉初生代谢物的影响

分析不同品种授粉果实与父本果实的初生代谢物, 其主要初生代谢物种类与含量如表3所示, 主要为氨基酸类: 包括脯氨酸、DL-焦谷氨酸和天冬氨酸; 有机酸类: 乳酸、苹果酸、柠檬酸、奎宁酸、棕榈酸和硬脂酸; 糖类: 果糖、葡萄糖和蔗糖; 醇类: 丙三醇和肌醇。其中以糖类物质为主, 且不同授粉品种之间柠檬酸、果糖和葡萄糖含量有显著差异, 表明不同父本花粉会影响授粉果实的初生代谢物含量, 但经过授粉的果实初生代谢物含量与父本果实之间没有明显规律。

进一步分析不同授粉品种授粉后的果实初生代谢物含量, 如图2所示, 四倍体葡萄柚授粉后的果实酸类物质中柠檬酸平均含量最高, 为2.35 mg·g⁻¹, 显著高于自然授粉与信木柚授粉; 糖类物质中蔗糖平均含量最高, 为39.19 mg·g⁻¹, 显著高于自然授粉与信木柚授粉。信木柚授粉果实的糖类物质中d-葡萄糖平均含量最高, 为43.52 mg·g⁻¹, 显著高于自然授粉与四倍体葡萄柚授粉。四倍体葡萄柚与信木柚授粉的果实氨基酸类物质中以脯氨酸为主, 其中四倍体葡萄柚授粉的脯氨酸平均含量为0.32 mg·g⁻¹, 高于信木柚与自然授粉。

2.4 不同授粉品种对果皮挥发性物质的影响

分析不同品种授粉果实与亲本果实的挥发性物质, 对不同果实的挥发性物质组分与含量进行PCA分析, 如图3所示, 可知不同样品间重复性良好。在不同授粉品种与亲本的果皮中累计统计到85种挥发性物质, 如表4所示, 其中醛类11种, 蒽烯类28种, 酯类16种, 醇类14种, 酮类14种, 还有5种烷烃类化合

表2 不同授粉处理的果实品质
Table 2 Fruit quality in different pollination treatments

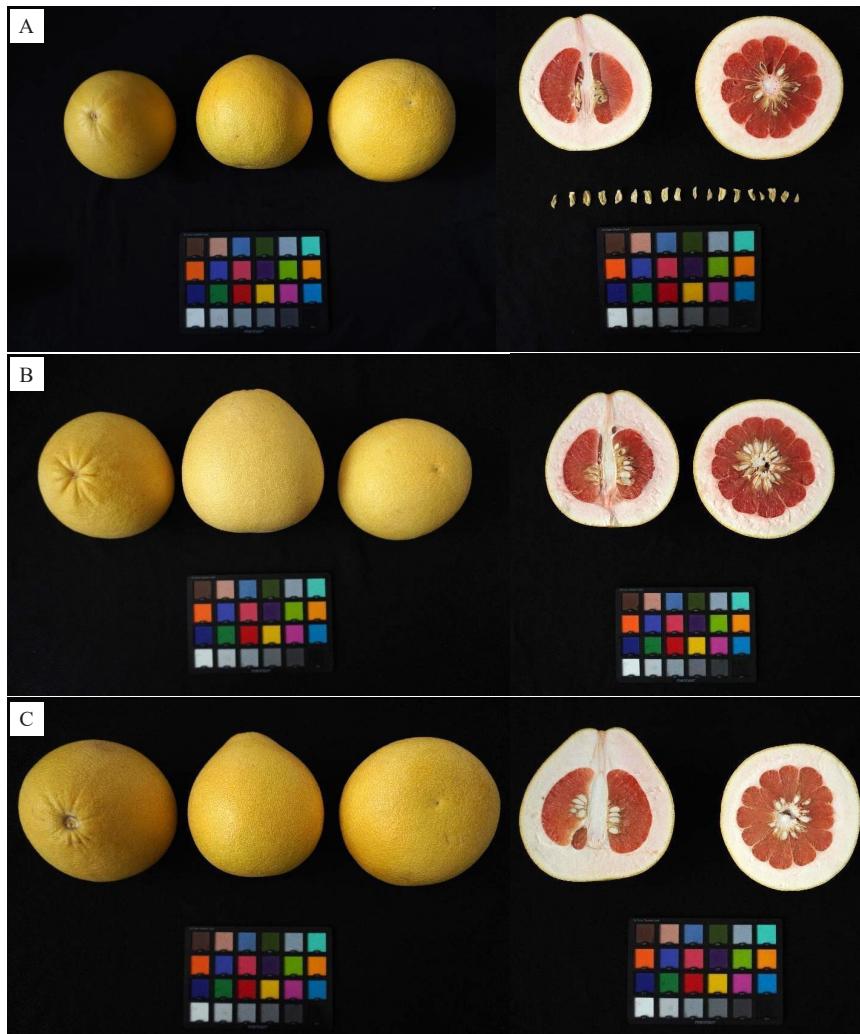
花粉来源 Pollen source	单果质量 Single fruit mass/ g	横径 Cross diameter/ cm	纵径 Longitudinal diameter/cm	果形指数 Fruit type index	果皮厚度 Peel thickness/ cm	囊瓣数 Number of capsule valves	种子质量 Seed mass/g	果皮质量 Peel mass/g	w(可溶性 固形物) Soluble solids content/%			可食率 Edible rate/%
									w(可溶性 定酸) Titratable acid content/ %			
4x葡萄柚授粉 4x Grapefruit pollination	894.41±36.09 b	14.30±0.18 b	14.83±0.26 a	1.04±0.01 a	2.06±0.07 b	12.29±0.22 a	21.02±5.57 b	346.86±15.49 b	45.00±0.69 a	15.35±0.31 ab	0.90±0.03 b	17.15±0.47 a
信木柚授粉 Xinnuyou pollination	1 109.09±75.98 a	15.46±0.37 a	15.72±0.29 a	1.02±0.02 a	2.31±0.12 ab	12.27±0.19 a	65.02±4.15 a	446.81±30.78 a	39.98±1.36 b	15.03±0.51 b	0.88±0.04 b	17.36±0.70 a
自然授粉 Natural pollination	986.50±54.45 ab	15.22±0.28 a	15.28±0.42 a	1.00±0.02 a	2.51±0.11 a	13.00±0.30 a	39.33±12.46 b	417.20±19.80 a	41.91±1.83 ab	16.37±0.41 a	1.23±0.04 a	13.48±0.50 b

物和7种酚、羧酸类化合物。在85种挥发性物质中,自然授粉的果实中检测出41种,含量最高为柠檬烯($25\ 822.76\ \mu\text{g}\cdot\text{g}^{-1}$),占总量的87.48%;信木柚授粉检测出36种,含量最高为柠檬烯($84\ 271.06\ \mu\text{g}\cdot\text{g}^{-1}$),占总量的92.57%;信木柚的果实中检测出47种,含量最高为柠檬烯($154\ 583.28\ \mu\text{g}\cdot\text{g}^{-1}$),占总量的91.07%;四倍体葡萄柚授粉检测出38种,含量最高为柠檬烯($11\ 157.49\ \mu\text{g}\cdot\text{g}^{-1}$),占总量的88.52%;葡萄柚的果实中检测出49种,含量最高为柠檬烯($194\ 799.03\ \mu\text{g}\cdot\text{g}^{-1}$),其含量占总量的88.65%。通过分析不同授粉品种的果实与亲本果实之间的关系,发现在信木柚授粉组合中有21种挥发性物质,表现出明显的花粉直感效应,包括大部分萜烯类物质,以柠檬烯为例,自然授粉下果实的柠檬烯含量为 $25\ 822.76\ \mu\text{g}\cdot\text{g}^{-1}$,父本信木柚的柠檬烯含量为 $154\ 583.28\ \mu\text{g}\cdot\text{g}^{-1}$,而经过信木柚授粉后的果实柠檬烯含量达到 $84\ 271.06\ \mu\text{g}\cdot\text{g}^{-1}$,比自然授粉提高了3倍之余。表明通过信木柚给马家柚配置授粉组合可以显著提高马家柚果实的香气。

3 讨 论

马家柚作为江西省上饶市的地方优良品种,经过近几年的快速发展已成为当地主栽的柑橘品种,且马家柚产业也已基本成型。但近年来马家柚品质不稳定问题较突出,一方面与频繁变化的极端天气有关,另一方面与不同农户不同管理措施有关。如何规范管理、稳定品质、形成标准化果实,成为当前迫切需要解决的问题。前期研究发现,马家柚无单性结实能力,且自花结实率低。基于此问题,本研究通过使用不同授粉品种对马家柚进行异花授粉试验来探究其对果实品质的影响,期望为马家柚的实际生产与品质改良提供理论依据。

通过试验发现:异花授粉能显著提高马家柚坐果率,这与陈杰忠^[27]、焦嘉乐等^[28]研究一致,而不同授粉品种对坐果率提高程度不同可能与花粉的遗传特性以及外在环境的影响有关;在常规品质方面,花粉直感能影响马家柚的内在品质与外在品质,这与在苹果^[15]、梨^[12]、猕猴桃^[13]、荔枝^[14]等果树上的研究结果相似;在本研究中,花粉直感能显著影响单果质量、横径、果皮厚度、种子质量、果皮质量、可溶性固形物含量、可滴定酸含量和固酸比等理化指标,其中四倍体葡萄柚授粉能显著降低果实单果



A. 四倍体葡萄柚授粉果实; B. 信木柚授粉果实; C. 自然授粉果实。

A. Fruit from pollination with tetraploid grapefruit pollen; B. Fruit from pollination with Xinmuyou pollen; C. Open pollination fruit.

图 1 不同授粉组合果实外形与种子情况

Fig. 1 Fruit shape and seed condition in different pollination treatments

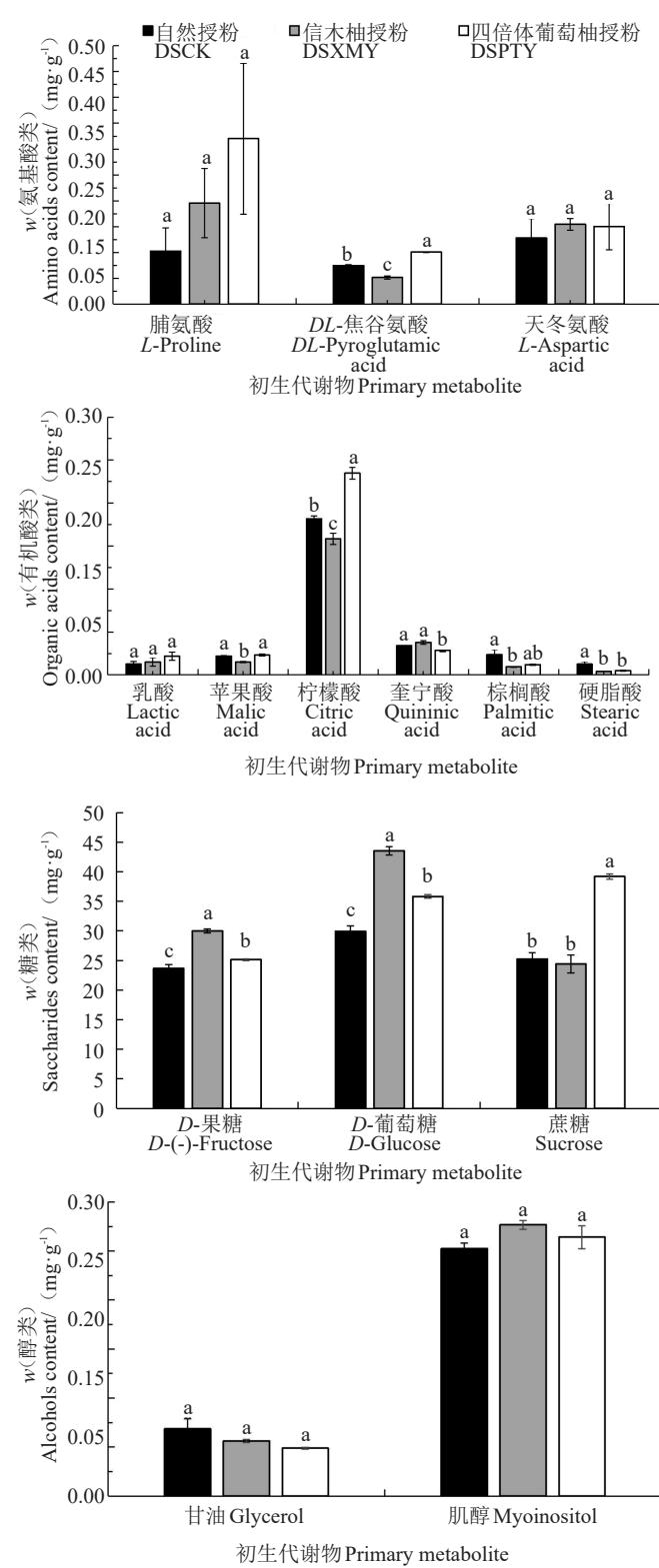
质量、果皮厚度和果皮质量,推测可能因父本葡萄柚的果型较小而使授粉后果实单果质量受到影响,这与贺熙勇等^[19]、李艳民等^[20]关于花粉直感对果型影响的研究一致,而经过四倍体葡萄柚授粉后果实种子为瘪籽,原因可能是四倍体与二倍体进行授粉后其种子内胚乳发育不良,使其成为瘪籽状,从而降低种子质量,增加马家柚整体口感;而信木柚授粉后果实种子质量增加表明人工授粉提高了马家柚授粉受精效率,从而产生更多的种子,这与彭建平等^[29]、谢明权等^[30]关于异花授粉可以提高授粉受精进而增加果实种子数的研究结果相同。另外果肉中初生代谢物主要以糖类和有机酸类为主,不同授粉处理之间初生代谢物含量有所差异,其中四倍体葡萄柚授粉后果实中柠檬酸含量显著高于其余两个处理,

但在测定果实可滴定酸时,四倍体葡萄柚授粉果实的可滴定酸含量却要低于自然授粉下果实可滴定酸含量,原因可能与样品取样的部位有关,且同一处理下不同果实个体间也可能存在差异,导致测定的可滴定酸与柠檬酸含量在整体趋势下产生较小的偏差。

影响柑橘果实风味的挥发性物质主要有单萜、倍半萜、醇类、醛类、酮类等,其中以单萜类物质含量最丰富,特别是柠檬烯^[26],笔者在本研究中测定到85种挥发性物质,其中醛类11种,萜烯类28种,酯类16种,醇类14种,酮类14种,5种烷烃类化合物和7种酚、羧酸类化合物,在不同果实中均以柠檬烯含量最高,表明影响马家柚果实风味的主要物质为柠檬烯,与前人结论一致。在信木柚授粉组合中有21种

表3 不同授粉品种与亲本果肉中初生代谢物含量
Table 3 Content of primary metabolites in flesh of the fruits from different pollination treatments and male parents

花粉来源 Pollen source	氨基酸类 Amino acids		有机酸类 Organic acids						糖类 Saccharides			醇类 Alcohols		
	DL-焦谷氨酸 DL-Pyroglutamic acid	L-脯氨酸 L-Proline	乳酸 Lactic acid	苹果酸 Malic acid	柠檬酸 Citric acid	奎宁酸 Quininic acid	棕榈酸 Palmitic acid	硬脂酸 Stearic acid	D-果糖 D-Fructose	D-葡萄糖 D-Glucose	蔗糖 Sucrose	甘油 Glycerol	肌醇 Myoinositol	
自然授粉 Natural pollination	0.10±0.05 b	0.07±0.00 b	0.13±0.04 b	0.13±0.03 a	0.22±0.00 c	1.82±0.03 c	0.34±0.00 a	0.24±0.06 a	0.13±0.03 a	23.66±1.02 c	29.95±0.87 c	25.26±1.02 c	0.69±0.11 a	2.52±0.06 a
信木柚授粉 Xinnuyou pollination	0.20±0.07 b	0.05±0.00 c	0.15±0.01 b	0.15±0.05 a	0.15±0.01 d	1.58±0.07 d	0.38±0.02 a	0.09±0.01 b	0.04±0.00 b	29.98±0.33 a	43.52±0.68 a	24.40±1.55 c	0.56±0.02 a	2.77±0.04 a
信木柚 Xinnuyou	0.35±0.12 ab	0.09±0.01 a	0.41±0.02 a	0.13±0.04 a	0.88±0.02 a	0.67±0.05 e	0.13±0.01 d	0.10±0.02 b	0.05±0.01 b	8.34±0.39 d	10.26±0.48 e	51.38±2.41 a	0.65±0.07 a	1.98±0.13 b
4x葡萄柚授粉 4x Grapefruit pollination	0.32±0.15 ab	0.10±0.00 a	0.15±0.04 b	0.22±0.05 a	0.23±0.01 bc	2.35±0.07 b	0.28±0.01 b	0.12±0.01 b	0.05±0.01 b	25.13±0.15 b	35.83±0.29 b	39.19±0.47 b	0.49±0.01 a	2.64±0.12 a
4x葡萄柚 4x Grapefruit	0.58±0.01 a	0.05±0.00 c	0.06±0.00 b	0.13±0.03 a	0.26±0.01 b	2.58±0.03 a	0.22±0.00 c	0.11±0.01 b	0.06±0.01 b	25.52±0.37 b	26.30±0.45 d	19.38±0.48 d	0.61±0.03 a	2.56±0.03 a



不同小写字母表示差异显著($p<0.05$)。
Different small letters indicate significant difference ($p<0.05$).

图2 信木柚和四倍体葡萄柚授粉对马家柚果肉初生代谢物含量的影响
Fig. 2 Differences in the content of primary metabolites in the fruit flesh of Majiayou pollinated with Xinmuyou and a tetraploid grapefruit

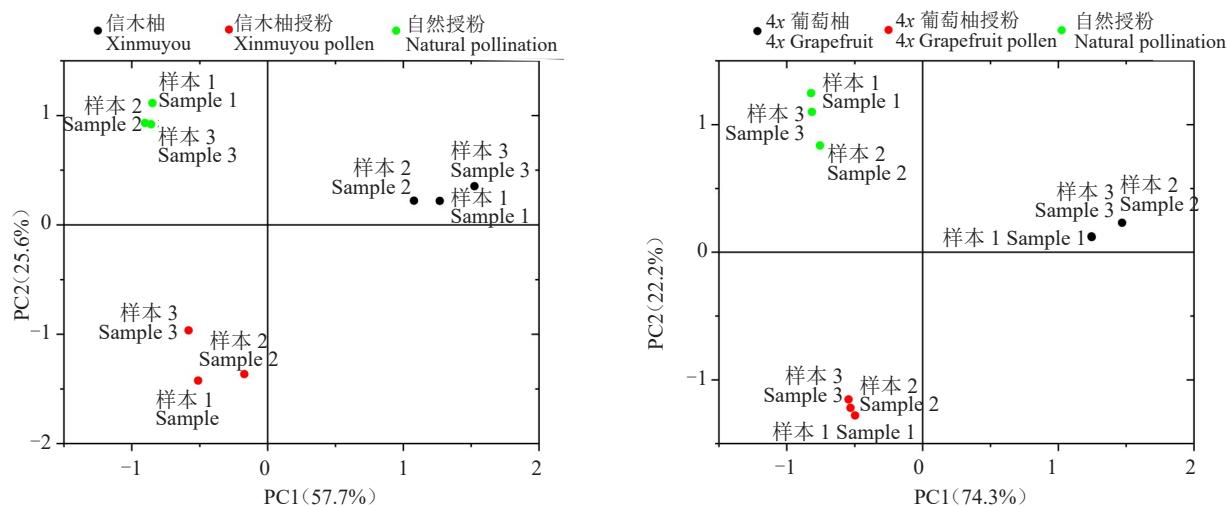


图 3 两个授粉组合挥发性物质主成分分析

Fig. 3 Principal component analysis of volatile substances in two pollination groups

表 4 不同授粉组合果皮与亲本果皮挥发性物质含量比较

Table 4 Comparison of volatile substance content in pericarp of the fruits from different pollination treatments and parental pericarp

 $(\mu\text{g}\cdot\text{g}^{-1})$

挥发性物质 Primary metabolite	自然授粉 Natural pollination	信木柚授粉 Xinmuyou pollen	信木柚 Xinmuyou	4x 葡萄柚授粉 4x Grapefruit pollen	4x 葡萄柚 4x Grapefruit
醛类 Aldehyde					
3-己烯醛 3-Hexanal	6.21±0.30	8.39±1.92	18.88±1.02	15.64±0.53	45.24±3.29
正己醛 Hexenal	11.66±1.08	18.62±5.07	10.78±0.18	16.47±0.14	10.33±0.57
反式-2-己烯醛 <i>Trans</i> -2-hexenal	20.02±0.50	5.94±0.85	5.19±0.22	8.62±0.59	10.72±0.29
(-)香茅醛(-)-Citronellal	-	-	34.11±2.19	-	182.56±10.53
正辛醛 Octanal	-	-	-	-	1 215.74±73.39
正癸醛 Decanal	-	-	-	-	565.11±30.08
柠檬醛 Citral	-	-	-	-	286.65±16.71
紫苏醛 Dl-Perillaldehyde	-	-	-	-	112.31±6.59
月桂醛 Lauryl aldehyde	-	-	-	-	97.94±4.79
甜橙醛 Sinensal	-	-	-	-	201.58±10.36
壬醛 Nonanal	-	-	-	-	79.48±4.81
萜烯类 Terpenes					
3-蒈烯 3-Carene	167.08±6.94	885.07±222.07	2 101.08±147.31	68.42±7.39	118.88±6.03
桧烯 Sabinene	40.64±1.65	211.97±56.65	691.96±54.28	16.45±1.67	4 323.57±280.84
左旋-β-蒎烯(1S)-(1)-β-pinene	464.69±15.26	2 489.26±693.85	5 865.18±418.14	142.50±14.73	8 334.90±536.66
柠檬烯 Limonene	25 822.76±951.39	84 271.06±14 187.77	154 583.28±6 566.76	11 157.49±864.50	194 799.03±10 751.78
(+)-(E)-氧化柠檬烯 (+)-(E)-Limonene oxide	11.87±0.49	43.84±9.89	15.12±0.79	8.97±0.65	61.98±2.89
β-伞形烯 β-Umbelliferone	65.42±4.01	324.77±103.05	683.72±50.28	-	146.42±8.65
(-)罗汉柏烯(-)-Thujopsene	7.64±0.36	-	-	-	-
α-马榄烯 α-Maaliene	9.54±0.45	17.78±3.96	15.93±0.38	12.38±1.17	-
氧化石竹烯 Caryophyllene oxide	12.06±0.80	13.78±1.49	-	8.20±0.84	35.29±2.19
水芹烯 α-Phellandrene	-	47.08±16.10	137.74±10.12	-	-
罗勒烯 β-Ocimene	-	552.59±86.96	1 775.88±76.47	-	-
异松油烯 Terpinolene	-	6.83±2.22	15.77±1.50	-	21.11±1.08
β-榄香烯 β-Elemene	-	9.87±2.62	22.5±1.31	5.27±0.48	56.35±2.79

注: 表中“-”表示该样品中未检测出该种物质。

Note: “-” in the table indicates that the substance was not detected in the sample.

表4(续) Table 4 (Continued)

(μg·g⁻¹)

挥发性物质 Primary metabolite	自然授粉 Natural pollination	信木柚授粉 Xinmuyou pollen	信木柚 Xinmuyou	4x 葡萄柚授粉 4x Grapefruit pollen	4x 葡萄柚 4x Grapefruit
β-石竹烯 β-Caryophyllene	—	70.17±13.78	205.80±12.05	—	—
(-)莰烯 (-)-Camphene	—	—	17.08±1.06	—	23.07±1.99
2,6-二甲基-2,4,6-辛三烯 2,6-Dimethyl-2,4,6-octatriene	—	—	22.76±1.51	—	—
α-蒎烯 α-Pinene	—	—	46.75±2.16	—	3 534.90±235.87
α-石竹烯 α-Caryophyllene	—	—	18.46±1.20	—	—
巴伦西亚橘烯 Valencene	—	—	41.05±1.37	—	226.45±14.25
(Z)-三十五碳-17-烯 17-Pentatriacontene	11.25±1.46	—	87.58±36.58	—	—
紫苏烯 Perillen	—	—	—	2.81±0.17	—
雪松烯 Cedrene	—	—	—	1.68±0.02	—
(-)反式石竹烯 Trans-Caryophyllene	—	—	—	7.70±0.76	165.70±11.47
荜澄茄烯 Cadinene	—	—	—	8.22±1.01	148.66±9.28
水合桧烯 4-Thujanol	—	—	—	—	62.92±2.72
萜品油烯 Terpinolene	—	—	—	—	68.01±3.87
(+)-环苜蓿烯 Cyclosativene	—	—	—	—	12.55±0.55
(E)-β-金合欢烯 (E)-β-Farnesene	—	—	—	—	56.64±2.86
酯类 Esters					
磷酸三乙酯 Triethyl phosphate	40.64±3.92	52.15±19.52	36.15±10.96	44.66±4.81	36.64±0.65
2-甲基-辛酸甲酯	10.33±0.24	—	10.89±0.60	9.81±0.38	13.53±0.32
2-Methyl octanoate methyl ester					
2-甲基-5-(2-丙烯基)-2-环己烯-1-醇乙酸酯 Carvyl acetate	14.15±0.56	37.52±15.76	10.03±0.34	8.29±0.86	—
乙酸橙花酯 Nerylacetate	30.40±1.41	148.75±13.35	64.50±9.01	5.54±0.55	—
己酸己酯 Hexyl hexanoate	10.49±0.37	16.79±6.36	—	7.96±1.01	—
辛酸己酯 Hexyl octanoate	10.88±0.48	—	—	3.58±0.44	—
抗坏血酸二棕榈酸酯 L-Ascorbyl dipalmitate	233.17±37.55	244.34±39.81	236.80±37.29	43.17±5.82	395.48±7.05
L-抗坏血酸 6-硬脂酸酯 M-L-Ascorbic acid 6-stearate	94.27±11.02	86.17±13.33	134.00±14.65	—	125.06±4.26
丁酸香茅酯 Citronellyl Butyrate	—	—	39.82±1.45	—	—
乙酸香叶酯 Acetic acid geranyl ester	—	—	95.42±5.73	—	—
(E)-2-甲基-2-丁烯酸己酯 2-Butenoic acid,2-methyl-, hexyl ester,(E)-	—	—	—	5.14±0.68	—
甲酸辛酯 Formic acid, octylester	—	—	—	—	15.14±0.45
甲酸特丁酯 Terbutyl formate	—	—	—	—	258.05±14.86
3,7-二甲基-6-辛烯醇丁酸酯 3,7-Dimethyl-6-octenol butyrate	—	—	—	—	35.07±1.55
香叶酸甲酯 Methyl geranate	—	—	—	—	13.29±0.62
(-)二氯乙酸香芹酯 (-)Lavandulyl acetate	—	—	—	—	4.71±0.30
醇类 Alcohols					
3-己烯-1-醇 3-Hexen-1-ol	13.58±0.56	—	—	13.89±0.74	—
(-)顺式-异戊烯醇 (-)-Cis isopentenol	3.09±0.27	—	—	—	—
香芹醇 Carveol	11.40±0.94	26.25±4.17	7.95±0.82	6.05±0.50	—
反式-橙花叔醇(±)-Trans-Nerolidol	31.05±1.57	53.95±4.99	170.21±12.83	11.37±1.13	—
马榄醇 Maaliol	98.90±6.66	55.83±25.24	103.06±6.40	49.55±5.02	—
金合欢醇 Farnesol	476.27±31.40	209.99±70.31	136.67±9.43	204.00±19.50	—
2-[(Z)-十八碳-9-烯氧基]乙醇 2-[(Z)-9-Octadecenoxy]ethanol	176.08±7.23	132.34±21.54	—	—	—
A-菖蒲醇 α-Acorenol	—	7.25±1.62	5.77±0.90	3.67±0.39	8.87±0.68

表4(续) Table 4 (Continued)

(μg·g⁻¹)

挥发性物质 Primary metabolite	自然授粉 Natural pollination	信木柚授粉 Xinmuyou pollen	信木柚 Xinmuyou	4x 葡萄柚授粉 4x Grapefruit pollen	4x 葡萄柚 4x Grapefruit
芳樟醇 Linalool	-	-	45.66±2.73	-	2 069.24±115.33
橙花醇 Nerol	-	-	23.49±1.90	-	14.39±0.91
香叶醇 Geraniol	-	-	15.22±1.13	-	-
马鞭草烯醇(<i>E</i>)-Verbenol	-	-	5.06±0.33	-	218.67±12.45
正己醇 Hexanol	-	-	-	5.46±0.32	-
4-萜烯醇 Terpinine-4-ol	-	-	-	-	16.73±0.61
酮类 Ketones					
右旋香芹酮(+)-Carvone	8.54±0.56	32.51±10.94	5.25±0.33	6.62±0.41	25.52±1.24
α-香附酮 α-Cyperone	14.49±1.94	-	13.23±0.68	-	-
(+)-香柏酮(+)-Nootkatone	1 198.64±87.56	631.79±216.03	1 663.03±104.00	548.12±54.76	30.10±1.66
8-羟基-4-蒈澄茄烯-3-酮 8-Hydroxy-4-cadinene-3-one	28.52±6.50	13.58±4.29	38.56±3.33	-	-
烷烃类 Alkanes					
1-亚甲基-4-(1-甲基乙烯基)环己烷 Cyclohexane,1-methylene-4-(1-methyl-ethenyl)-	6.07±1.04	6.42±1.37	-	-	20.55±1.77
4-异丙基甲苯 P-cymene	3.88±0.08	8.69±2.51	-	2.76±0.06	-
3-乙基-5-(2-乙基丁基)十八烷 Octadecane,3-ethyl-5-(2-ethylbutyl)-	4.36±0.73	-	-	-	-
1-甲基-4-(1-甲基乙烯基)苯 Benzene,1-methyl-4-(1-methylethyl)-	2.38±0.04	-	-	-	-
2,6,10-三甲基十四烷 Tetradecane,2,6,10-trimethyl-	5.18±1.22	8.42±2.57	9.19±0.24	3.86±0.89	-
其他 Others					
4-氨基-1,5-戊二烯二元酸 4-Amino-1,5-pentandioic acid	2.58±0.06	-	-	-	-
2,4-二叔丁基苯酚 2,4-Di-t-butylphenol	7.30±1.00	11.35±4.21	8.38±1.30	4.53±0.45	-
6-十八烯酸 6-Octadecenoic acid	222.09±33.75	271.71±0.40	302.89±41.11	32.29±11.02	-
2,2'-亚甲基双-(4-甲基-6-叔丁基苯酚) Phenol,2,2'-methylenebis[6-(1,1-di-methylethyl)-4-methyl-	109.48±27.71	-	140.93±30.73	92.93±22.39	164.56±16.69
10,12-二十八二炔 10,12-octadecadiynoic acid	-	-	-	10.94±1.08	-
9(<i>E</i>),11(<i>E</i>)-十八碳二烯酸 9(<i>E</i>),11(<i>E</i>)-9,11-Octadecadienoic acid	-	-	-	-	634.79±22.03
α-亚麻酸 α-Linolenic acid	-	-	-	-	641.02±15.45

物质表现出明显的花粉直感效应,其中柠檬烯含量在经过授粉后提高3倍之余,说明花粉直感在挥发性物质方面表现更加突出。

花粉直感在众多果树上均有体现,虽然花粉直感的机制还尚未明晰,但利用花粉直感效应却可以为实际生产提供科学的理论依据。笔者在本研究中通过对马家柚异花授粉来探究花粉直感对马家柚果实品质的影响,旨在为马家柚授粉组合的选配和快速改良马家柚综合品质提供理论依据。

4 结 论

对马家柚配置不同授粉组合,进而分析不同授

粉组合间果实坐果率与果实品质,发现与自然授粉处理相比,异花授粉可以提高马家柚坐果率,同时对马家柚常规品质有不同程度的改善,其中四倍体葡萄柚授粉可以有效解决马家柚种子较多的问题,信木柚授粉可以增加马家柚果皮香气。通过以上研究可对马家柚实际生产上授粉组合的选配与马家柚果实品质的快速改良提供理论依据和调控技术支撑。

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