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外源ALA对猕猴桃叶片生理特性与果实品质的影响

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摘 要:【目的】研究外源ALA对猕猴桃叶片生理特性与果实品质的影响。**【方法】**以3个猕猴桃品种和2个品系为试材,叶面喷施10 mg·L^{-1}外源ALA溶液,测定了叶片光合色素含量、可溶性糖(SS)含量、过氧化物酶(POD)活性、超氧化物酶(SOD)活性、丙二醛(MDA)含量以及果实可溶性固形物含量(SSC)等指标。**【结果】**外源ALA处理促进了楚红和丰硕两个猕猴桃品种的叶片光合色素含量显著增加,以楚红增幅最大,而丰悦的响应不显著。楚红叶片的可溶性糖含量显著高于对照,而丰悦和丰硕与对照差异不显著。3个品种叶片POD活性都高于对照,其中,丰悦和丰硕$p<0.01$,但楚红$p>0.01$。3个品种的叶片SOD活性与对照差异显著,MDA含量与对照差异极显著。丰硕对ALA处理的响应在POD和SOD活性以及MDA含量这3个指标上表现最为明显。各品种平均单果质量均有提高,除楚红外,其余品种均显著高于对照。除楚红外,各品种(系)果形指数均增加,但仅S1、S2品系与对照差异显著。各品种(系)果实SSC和干物质含量均显著提高,S2的增幅最大。**【结论】**外源ALA可有效调控猕猴桃叶片光合色素含量及主要耐热生理指标,提高耐热性和果实品质,并表现出能显著提高耐热性强的猕猴桃品种的耐热关键指标,增加大果型猕猴桃品种的单果质量,提高低糖类型猕猴桃品种的果实干物质含量等指标。

关键词:猕猴桃;5-氨基乙酰丙酸;光合色素含量;抗氧化酶活性;果实品质

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Effects of exogenous 5-aminolevulinic acid on leaf physiological characteristics and fruit quality of kiwifruit

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Abstract:【Objective】Areas with gentle terrain at medium-to-low altitude are more suitable for kiwifruit industrial development than mountainous regions. However, these areas often experience prolonged periods of high summer temperatures, resulting in high incidences of leaf shed and sunburned fruit, and thus a decrease in fruit quality. Fruit bagging and setting up shading nets above trees can reduce the incidences of leaf shed and sunburning caused by high temperature in summer. Exogenous 5-aminolevulinic acid (ALA) can improve the photosynthetic capacity, fruit quality, yield and stress resistance of plants. The present experiment was undertaken to explore the effects of exogenous ALA on leaf physiological characteristics and fruit quality of different kiwifruit cultivars.【Methods】The experiment was conducted in the Kiwi Resource Garden of Horticultural Research Institute of Hunan Academy of Agricultural Sciences at an altitude of 46 meters. The plants of three *Actinidia chinensis* cultivars (Chuhong, Fengyue, and Fengshuo) and two strains (S1, an *A. chinensis* selection from progeny of Cui-

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yu seedlings, and S2, an *A. deliciosa* selection from progeny of Miliang No. 1 seedlings) were used as experimental materials with the age of 6 a to 7 a. Exogenous ALA was sprayed 3 times from early June to early August at the concentration of 10 mg·L^{-1}, and clean water was sprayed as a control (CK). The leaves of Fengyue, Fengshuo and Chuhong with different treatments were picked on August 10, and the chlorophyll content and antioxidant enzyme activity were determined. The fruits of each cultivar were collected when the soluble solid content (SSC) was up to 7.5%, and individual fruit sizes and weights were measured. After ripening, the soluble solid content (SSC) and the dry matter content of fruits of all cultivars were determined.【Results】Exogenous ALA significantly increased the content of chlorophyll a, chlorophyll b and carotenoid in Chuhong and Fengshuo leaves. The three indicators in Chuhong leaves were increased by 55.98%, 53.57%, and 30.51% respectively, compared to the control. Those in Fengshuo leaves were increased by 20.61%, 17.38%, and 15.07%, respectively. While the difference between the treatment and the control of Fengyue was not significant, the soluble sugar content in leaves of Chuhong was significantly increased by 11.20%. Compared with the controls, the soluble sugar content in leaves of Fengyue and Fengshuo did not show significant differences. The POD activities in leaves of the three cultivars were higher than those of the controls, and the differences of Fengyue and Fengshuo were extremely significant ($p<0.01$) compared to the controls. In Chuhong, there was no significant difference in POD activity in leaves between the treament and the control. The SOD activities in the leaves of Chuhong, Fengyue, and Fengshuo were significantly different from those of the controls, with an increase by 8.52%, 8.26%, and 13.06%, respectively. And the MDA content in the leaves of all the cultivars was significantly reduced by ALA treatment compared to the controls, decreasing by 16.06%, 10.03%, and 24.24%, respectively. The heat tolerance of these three cultivars was in the order of Fengshuo＞Chuhong＞Fengyue. Additionally, the effects of ALA treatment on POD activity, SOD activity, and MDA content in Fengshuo leaves were the most significant. The results indicated that exogenous ALA had a more significant effect in improving the key indicators of heat resistance in cultivars with stronger heat tolerance compared to those with weaker heat tolerance. The average single fruit weight of the the cultivars was greater than that of the control with S1 showing the most significant increase at 15.16%. The fruit weight of the other four cultivars, which belong to the large-sized fruit type, differed significantly from that of the control. Chuhong, which belonged to the small-sized fruit type, showed no significant difference. The effect of exogenous ALA in increasing the average single fruit weight of the cultivars with bigger fruit was more significant than that with smaller fruit. The fruit shape index increased in all cultivars but Chuhong, which showed decreased fruit shape index by ALA treatment. The SSC of Chuhong fruit was above 17.0%, indicating a high-sugar cultivar, while the SSC of the other four cultivars Fengyue, Fengshuo, S1, and S2, ranged from 13.5% to 15.5%, classifying them as low-sugar cultivars. All the cultivars showed significant increases in SSC and dry matter content of the fruit, with S2 showing the largest rate of increase, with a 9.49% increase in SSC and a 14.68% increase in dry matter content under the treatment of ALA. The increase rate of SSC in Fengshuo fruit was 3.9%, lower than that of the others. The increase rate of dry matter content in Chuhong fruit was only 3.53%, lower than that in the others. The increase rate of SSC was in the order of S2＞S1＞Fengyue＞Chuhong＞Fengshuo, and the increase rate of dry matter content was in the order of S2＞Fengyue＞Fengshuo＞S1＞Chuhong. The results also showed that the effect of exogenous ALA on the dry matter content of cultivars with lower SSC was more significant than those with higher SSC.【Conclusion】Exogenous ALA can effectively regulate the physiological characteristics of kiwifruit leaves, enhance heat tolerance, and improve fruit quality.

Key words: Kiwifruit; 5-aminolevulinic acid; Photosynthetic pigment content; Antioxidant enzyme activity; Fruit quality

猕猴桃喜温暖湿润，在湖南主要分布于平均海拔600 m以上的湘西山地。随着猕猴桃产业不断发展，特别是新优品种如丰悦、翠玉[1]、丰硕[2]、楚红[3]等的培育和推广，越来越多的猕猴桃逐步由山区走向地势平缓、交通便利的中低海拔地区。然而，夏季极端性气候，包括绝对高温和长时间持续高温仍会给这些品种的生产带来严峻挑战，不仅导致严重落叶，果实综合品质也因夏季的极端高温而显著降低。这是中低海拔地区猕猴桃产业发展中急需解决的重大生产难题。前期研究发现，果实套袋或树体上方架设遮阳网可以在一定程度上降低夏季高温和强光照导致的猕猴桃落叶率和日灼果比例[4-5]。这对保护树体和确保果实品质具有重要意义。

5-氨基乙酰丙酸（5-aminolevulinic acid，ALA）是一种天然氨基酸，具有多种生物调节功能。它是叶绿素和亚铁血红素等卟啉化合物生物合成的关键前体，与植物光合作用、呼吸作用等具有密切关系[6]。在甜瓜[7]、西瓜[8-9]、草莓[10]、梨[11]、苹果[12-13]等植物上使用ALA后，可显著提高植物光合能力，改善果实品质，提高产量和植株抗逆性。在翠玉猕猴桃施用ALA后，果实可溶性固形物含量由13.64%提高到15.42%，增幅达13.0%[14]。为了探究外源ALA对不同品种猕猴桃的影响，笔者在本研究中以3个猕猴桃品种和2个品系为试材，在夏季高温来临前叶片喷施ALA溶液，观察其对叶片光合色素含量、主要耐热生理指标以及果实品质的效应，以期为ALA在猕猴桃生产中的应用提供理论依据。

1　材料和方法

1.1　材料

试验于2024年6—10月在湖南省农业科学院园艺研究所猕猴桃种质资源圃进行，试验地平均海拔46 m，属于低海拔地区。供试品种为丰悦、丰硕、楚红以及2个品系S1和S2。丰悦、丰硕、楚红和S1均属中华猕猴桃，S2属美味猕猴桃，S1和S2分别选自于翠玉和米良1号的实生后代。在长沙地区，上述品种花期为4月下旬至5月上旬，坐果期为5月上中旬，楚红正常采收期为9月上中旬，其他为9月中下旬。各供试植株树龄6~7 a，采用单主干双主蔓形，株行距为3.5 m×4.0 m，东西行向，正常管理。ALA试剂为南京禾稼春生物科技有限公司生产的金村秋牌水溶肥。

1.2　试验设计

试验设清水对照和10 mg·L^{-1} ALA处理。单株小区，3次重复，随机排列。不同小区植株分别于6月7日、7月6日和8月4日叶面喷施ALA溶液，共3次，用液量为60 L·666.7 m^{-2}，以叶片滴水为度。

1.3　指标测定

1.3.1　生理特性指标的测定　最后一次喷施后1周（8月10日，当时连续5日平均气温≥36 ℃），随机采摘不同处理丰悦、丰硕、楚红3个品种树冠外围健康叶片各10片，混合制样，用95%乙醇溶液萃取法测定光合色素含量[15]、磷酸缓冲液提取并测定丙二醛（MDA）含量[16]、蒽酮比色法测定可溶性糖（SS）含量[17]，采用北京索莱宝牌的酶活性检测试剂盒检测超氧化物歧化酶（SOD）和过氧化物酶（POD）活性。

1.3.2　果实品质的测定　于9月26日（楚红的SSC达8.0%，其余品种的SSC达7.5%）采收5个供试品种果实，每处理随机挑选30个，测定单果质量和纵径、横径。待果实后熟软化后，随机测定10个果实的可溶性固形物（SSC）和干物质含量。其中，用电子天平（精度0.01 g）测定单果质量，用数显游标卡尺（精度0.1 mm）测量果实纵、横径，计算果形指数，用“三良”牌数显糖度计（精度0.1%）测定可溶性固形物含量，用80 ℃恒温干燥法测定干物质含量。

1.4　数据分析

采用Microsoft Office Excel 2021进行数据整理和图表制作，数据结果以平均值和标准误表示，并对数据进行方差分析和差异显著性（$p<0.05$）测验。

2　结果与分析

2.1　喷施ALA对猕猴桃叶片生理特性的影响

2.1.1　喷施ALA对猕猴桃叶片光合色素含量的影响　从表1可以看出，ALA处理促进了楚红和丰硕叶片叶绿素a、叶绿素b和类胡萝卜素含量显著增加，其中楚红增幅最大，分别为55.00%、56.00%和31.03%。丰硕对ALA处理也有显著响应（$p<0.05$），三项指标的增幅分别为20.71%、16.67%和

表1 叶面喷施ALA对猕猴桃叶片光合色素含量的影响

Table 1 Effects of foliar spraying ALA on the photosynthetic pigment contents kiwifruit leaves

（g·kg^{-1}）

品种 Cultivar	处理 Treatment	w（叶绿素a） Chlorophyll a content	w（叶绿素b） Chlorophyll b content	w（类胡萝卜素） Content of carotenoids
楚红 Chuhong	对照 Control	1.00±0.02 b	0.25±0.00 b	0.29±0.01 b
	ALA	1.55±0.01 a	0.39±0.02 a	0.38±0.01 a
丰悦 Fengyue	对照 Control	1.54±0.06 a	0.36±0.01 a	0.43±0.01 a
	ALA	1.56±0.03 a	0.38±0.02 a	0.42±0.02 a
丰硕 Fengshuo	对照 Control	1.40±0.02 b	0.36±0.01 b	0.38±0.01 b
	ALA	1.69±0.04 a	0.42±0.01 a	0.43±0.01 a

注：同一品种内不同处理间不同小写字母表示在0.05水平差异显著。下同。

Note: The different small letters between treatments in a cultivar indicate significant difference at 0.05 level. The same below.

13.16%。但丰悦叶片的光合色素含量对ALA处理没有响应。这说明不同品种猕猴桃的叶片光合色素含量对ALA处理有不同的响应。

2.1.2 喷施ALA对猕猴桃叶片的主要抗逆生理指标的影响

从表2可以看出，ALA处理后，楚红叶片可溶性糖（SS）含量显著高于对照，增幅达11.05%，而丰悦和丰硕叶片的SS含量与对照差异不显著。这表明楚红叶片的SS含量对ALA处理的响应明显。楚红、丰悦和丰硕叶片的POD活性都高于对照，增幅分别为8.52%、93.99%和635.53%，其中，丰悦和丰硕与对照差异均达极显著水平（$p<0.01$），楚红因测定的试验误差较大而与对照无显著差异。这表明POD活性对ALA处理的响应与品种有关。

ALA处理后，楚红、丰悦和丰硕叶片的SOD活性分别比对照提高8.51%、8.25%和13.07%，达到差异显著水平。3个品种叶片MDA含量分别比对照降低15.59%、10.02%和24.23%，差异达极显著水平（$p<0.01$）。这表明，ALA处理对叶片SOD活性和MDA含量的响应在楚红、丰悦和丰硕上表现一致，品种间以丰硕的变化幅度最大。

表2 喷施ALA对不同品种猕猴桃叶片主要生理指标的影响

Table 2 Effects of foliar spraying ALA on the main physiological indicators of kiwifruit leaves

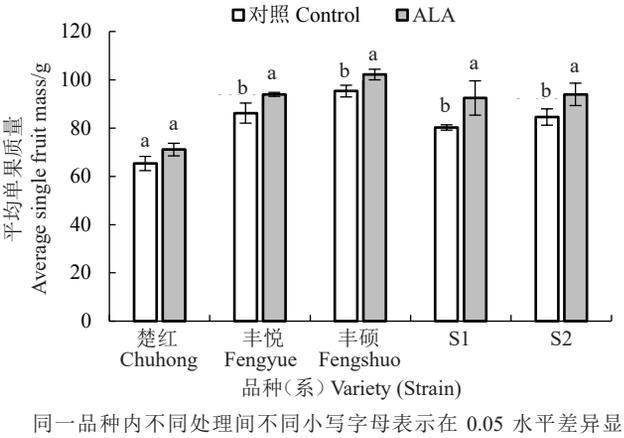
品种 Cultivar	处理 Treatment	w（可溶性糖） Soluble sugar content/%	过氧化物酶活性 POD activity/（U·g^{-1}·min^{-1}）	超氧化物酶活性 SOD activity/（U·g^{-1}）	b（丙二醛） MDA content/（nmol·g^{-1}）
楚红 Chuhong	对照Control	1.72±0.02 bA	570.78±40 aA	53.84±0.70 bA	21.49±0.22 aA
	ALA	1.91±0.02 aA	619.39±20 aA	58.42±3.81 aA	18.04±0.28 bB
丰悦 Fengyue	对照Control	1.57±0.07 aA	827.84±12 bB	46.67±1.53 bA	18.36±0.22 aA
	ALA	1.59±0.02 aA	1 605.96±60 aA	50.52±1.41 aA	16.52±0.52 bB
丰硕 Fengshuo	对照Control	1.54±0.06 aA	283.28±11 bB	47.04±2.54 bA	18.49±0.39 aA
	ALA	1.54±0.05 aA	2 083.62±87 aA	53.19±2.44 aA	14.01±0.13 bB

注：同一品种内不同处理间不同大写字母表示在0.01水平差异极显著。

Note: Different capital letters between different treatments within the same variety indicate extremely significant difference at 0.01 level.

2.2 喷施ALA对猕猴桃果实品质的影响

2.2.1 喷施ALA对平均单果质量和果形指数的影响 从图1可以看出，ALA处理后3个品种和2个品系的平均单果质量均高于对照，S1的单果质量增幅达15.23%。各品种（系）的增幅大小依次为S1>S2>丰悦>楚红>丰硕。楚红的单果质量与对照差异不显著，其他4个品种（系）与对照差异显著。楚红属于小果型品种（系），其他4个品种（系）单果质量都在80 g以上，属于大果类型。可见，ALA处理对猕猴桃单果质量的影响表现出大果型品种



同一品种内不同处理间不同小写字母表示在0.05水平差异显著。下同。

The different small letters between treatments in a cultivar indicate significant difference at 0.05 level. The same below.

图1 喷施ALA对猕猴桃平均单果质量的影响

Fig. 1 Effects of foliar spraying ALA on kiwifruit average single fruit mass

（系）比小果型品种（系）更为显著。同时，丰硕、丰悦、S1和S2的果形指数都比对照有所增加（图2），其中，S1、S2与对照的差异达显著水平，其他品种（系）与对照无显著差异，楚红的果形指数比对照低。这表明ALA处理对果形指数的影响因品种（系）而异。

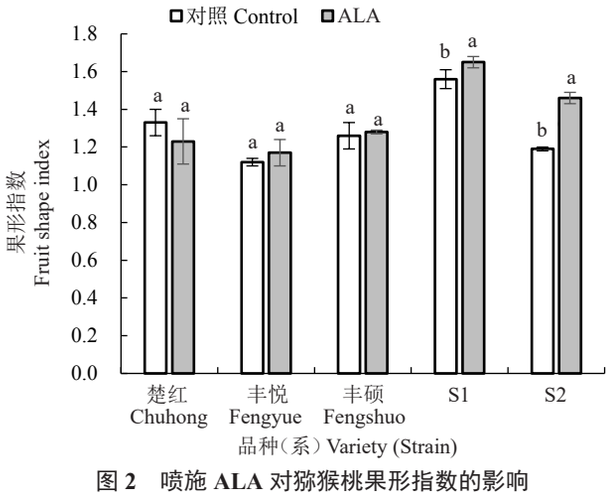


图2　喷施ALA对猕猴桃果形指数的影响

Fig. 2　Effects of foliar spraying ALA on fruit shape index

2.2.2　喷施ALA对可溶性固形物和干物质含量的影响　图3和图4显示，ALA处理后，各品种（系）果实的可溶性固形物含量（SSC）和干物质含量均显著高于对照，以S2的增幅最大，其SSC比对照提高10.65%，干物质含量比对照提高14.03%，丰硕的SSC增幅（3.87%）和楚红的干物质含量增幅（3.53%）最小。各品种（系）的SSC增幅依次为S2＞S1＞丰悦＞楚红＞丰硕，干物质含量的增幅依次为S2＞丰悦＞丰硕＞S1＞楚红。楚红的正常采收期为9月上中旬，软熟时果实的SSC通常在17.0%以上，属于高糖类型，其他4个品种为9月中下旬采收，软熟时果实的SSC为13.5%~15.5%，属低糖类型。可见，ALA处理对不同品种的果实干物质含量的响影响表现为低糖类型比高糖类型品种（系）更为明显的趋势。

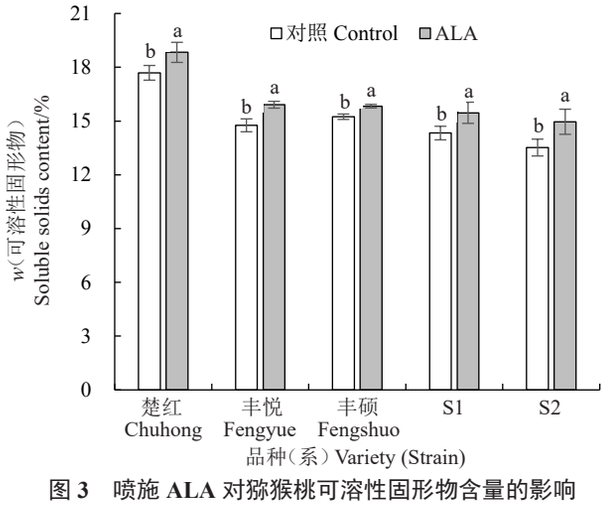


图3　喷施ALA对猕猴桃可溶性固形物含量的影响

Fig. 3　Effects of foliar spraying ALA on fruit soluble solids content

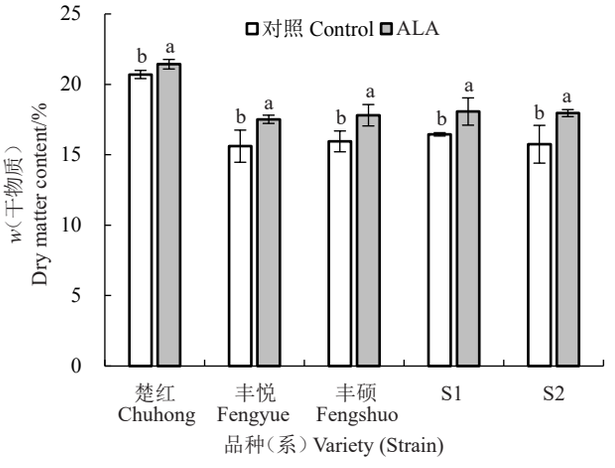


图4　喷施ALA对猕猴桃干物质含量的影响

Fig. 4　Effects of foliar spraying ALA on fruit dry matter content

3　讨　论

ALA是植物叶绿素和动物血红素生物合成的共同关键前体，参与叶绿素的生物合成，对调节植物生长发育具有一定作用。相关研究表明，在甜瓜[7]、草莓[10]、苹果[12-13]、黄瓜[18]和葡萄[19]等植物上喷施ALA后，提高了植株叶片的叶绿素含量，增强了光合积累能力。对翠玉猕猴桃喷施ALA，30 d后的叶绿素含量增加8.52%，净光合速率提高40.52%[14]。本研究结果发现，喷施ALA后，楚红和丰硕的叶绿素和类胡萝卜素含量显著增加，而丰悦变化不明显。可见，ALA对猕猴桃叶片光合色素含量的影响因品种而异。

SS含量、SOD和POD活性以及MDA含量是反映植物抗逆性的重要指标。诸多研究表明，在逆境胁迫环境下，随着时间的延长，植株叶片的SS含量、SOD和POD活性总体上表现出先上升到达峰值一定时间后再降低的规律，而MDA含量变化则与SOD和POD活性呈负相关[20-22]。汤佳乐等[23]对猕猴桃耐热性综合评价发现，耐热性强弱依次为丰硕＞楚红＞丰悦。本试验结果表明，ALA处理对叶片SS含量和POD活性的响应在不同品种上表现出差异性：楚红叶片的SS含量显著高于对照，丰硕和丰悦

叶片POD活性对ALA的响应比楚红更为剧烈；SOD活性和MDA含量在3个不同品种上则表现了一致性。笔者在本研究中发现，丰硕对ALA处理的响应在POD和SOD活性以及MDA含量这3个指标上表现最为明显，因此，ALA处理更能提高耐热性强的猕猴桃品种的耐热主要指标。

外源ALA处理对提升包括葡萄[19]、番石榴[24]等多种果树在内的果实品质效果显著，对提高翠玉猕猴桃单果质量、可溶性固形物含量和果形指数也具有一定效果[14]。在本试验中，ALA处理也提高了各品种（系）的单果质量及SSC和干物质含量。笔者在本研究中还发现，ALA处理对大果型品种比小果型品种的猕猴桃单果质量增加更为显著，不同品种（系）果实干物质含量的响应则表现为低糖类型的猕猴桃品种（系）比高糖类型更为明显的趋势。

4 结 论

叶面喷施ALA可有效提高楚红和丰硕猕猴桃叶片光合色素含量，在不同程度上提高了楚红、丰悦和丰硕叶片的POD和SOD活性，降低了MDA含量，也提高了果实的单果质量、SS含量和可溶性固形物含量，对调控叶片的耐热性相关生理指标及提高果实品质产生了积极效果。喷施外源ALA能显著提高耐热性强的猕猴桃品种的耐热关键指标，更能显著增加大果型猕猴桃品种的单果质量，以及更能显著提高低糖类型猕猴桃品种的果实干物质含量。因此，叶面喷施ALA可作为一种抗高温、提品质的栽培技术措施应用于猕猴桃生产。

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