热带作物学报 2024, 45(11): 2427−2437
Chinese Journal of Tropical Crops

UV-C 处理在水果采后保鲜上的应用进展

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摘　要：UV-C 照射处理属于非生物胁迫下非电离辐射和非加热的物理处理技术。果实在能接受的合适剂量内经过 UV-C 照射后，可以表面杀菌，抑制腐烂变质，保持化学物质含量、感官品质和营养品质，诱导提高果实的抗氧化成分含量和抗氧化能力，从而增强果实自身的抗病性，最终改善果实的贮藏品质，延长货架期。与其他处理如 1-MCP、涂膜和气调包装等结合使用，形成耦合的栅栏技术，可以起到叠加的保鲜效果。另外，UV-C 处理技术对环境友好、成本低、效益好、易于推广、处理手段简单易行，已逐步成为农产品保鲜的主推技术，在电商流通过程中可以用于商品化前处理。本研究综述了近 5 年 UV-C 处理在采后保鲜和鲜切水果上的应用效果，并对未来的使用进行展望，以期对 UV-C 技术的推广应用提供理论支持。

关键词：感官品质；理化品质；次生代谢；货架期

中图分类号：TS255.3　　　**文献标志码：**A

Recent Advances of UV-C Treatment on Fruits of Postharvest

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Abstract: UV-C treatment is an emerging and abiotic stress technology, and is a non-ionizing and non-thermal physicaltechnology. By using proper dose of UV-C treatment, it can be used to inactivate microbes on the surfaces of food, reduce the decay rate, maintain phytonutrients content and organoleptic quality.According to the research, the application of UV-C treatment is effective in increasing the levels of antioxidants content and the antioxidant capacity of fruits, then it can enhance resistance ability of some fruits, and which makes storage qualities better and extend the shelf life. Combining UV-C treatment with other technologies, such as 1-methylcyclopropene (1-MCP), and coating with all kinds of active compositions, and different packaging so on, it can form a hurdle technique which is a combination by two or more treatment, it can result in synergistic or additive interactions when compared to any single preservation technique in some horticulture. In addition, UV-C treatment is an eco-friendly and a cost effective technology which can be carried out easily without complex equipment on post-harvest and logistics and transportation for their commercialization. This critical review aims to summarize the research conducted on the effects of UV-C treatment on postharvest fruits in the past five years, the review draws the current challenges as well as future perspectives. It is hoped to provide valuable insights for the widespread adoption of UV-C treatment technology.

Keywords: organoleptic quality; physicochemical quality; secondary metabolism; shelf life

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收稿日期　2024-05-10；**修回日期**　2024-05-22

基金项目　海南省自然科学基金项目（No. 321MS0765）；农业农村部南亚热带果树生物学与遗传资源利用重点实验室开放课题（No. 202104）；海南省热带园艺品质采后生理与保鲜重点实验室开放课题。

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DOI: 10.3969/j.issn.1000-2561.2024.11.021

近年来，随着人民生活和物流水平的提高，新鲜水果成为人们饮食中不可或缺的一部分，其栽培量和消费量都在不断提升，然而，有些水果采后极易失水和腐烂[1]，造成极大的损失。有研究认为为 13 亿 t 浪费的食物中，有 44%（约 5.72 亿 t）是由果蔬腐烂造成[2-5]，而且这种损失是整个价值链的损失，包括水资源、能源、燃料、肥料和其他的一切投入资源，最终影响到环境[6-7]。因此，寻找一些健康、绿色和可持续发展的保鲜措施，成为了环保意识提高的现代人的追求。

果蔬采后保鲜措施要求对环境友好，成本低，效益好，能保证甚至提高水果的感官品质和营养品质等，还尽可能地延长其货架期，为减少采后损失创造时间条件，这样的措施被称为“新兴”技术[8], MOSTAFIDI 等[9]和 NARADISORN 等[10]认为短波紫外线（short-wave ultraviolet, UV-C）就是这样一种技术。UV-C 是紫外线中波长范围为 200~280 nm 的光源，被定义为一种非生物胁迫下非电离辐射和非热加工的物理保鲜技术,合适剂量对清除病毒、细菌和微生物有效[11-12]，此技术逐步成为农产品保鲜的主推技术之一。美国食品药品监督局和欧洲食品安全局同意用 UV-C 照射处理食品[13-15]。

UV-C 在采后上的应用很早，可以追溯到 40 年前，但有研究证明，在不同品种水果、不同贮藏条件和不同处理剂量下，作用结果不同[16]。随着现代检测新技术、基因组和代谢组等组学的发展,可以深入研究造成这些不同作用结果的内因，同时，UV-C 和其他技术联合作用的机理还少有人研究，因此在水果保鲜上仍存在着探索意义。

本文综合分析近 5 年国内外学者的研究进展,对 UV-C 在采后保鲜上的应用效果展开论述，以期对 UV-C 在果蔬采后保鲜产业上的应用提供新的思路和出发点。

1 UV-C 单独处理在水果保鲜中的应用

UV-C 单独处理果蔬可以一定程度地保持产品的感官品质和营养品质,抑制果实的生理代谢，最终提高果实的贮藏品质，可以表面杀菌，抑制果实的采后病原性腐烂，可以诱导果实的次生代谢提高抗氧化物质含量，延迟果实的衰老。

1.1 保持果实感观品质，延长货架期

水果感官品质主要包括五官能感受到的色泽、亮度、香味、腐烂情况、褐变和萎蔫等属性变化，UV-C 处理能不同程度地提高水果的某一感官属性。

4.3 kJ/m^2 的 UV-C 处理，可以抑制树莓的失重率[17]，而要抑制香蕉的失重率，有效剂量仅需 0.02 kJ/m^2[18], 这说明不同的产品对应的作用剂量不同，也可能跟贮藏温度不同有关。UV-C（1 kJ/m^2）处理人参果，5 ℃贮藏，可以有效减轻人参果的冷害症状[19-20]，但是冷害的机理还有待研究。陈晨等[21]用紫外灯（254 nm）35 cm 高处照射鲜切梨或者切片后照射，均照射 5 min，发现能有效抑制梨切片的褐变程度，其中切片后照射，效果更好，因此可以推广 UV-C 在鲜切水果中的应用。1、3、6 kJ/m^2 的 UV-C 处理均可以抑制椰枣的褐变[22]。还有研究发现，不同处理剂量均不同程度地提高了鲜切芒果、哈密瓜、甜瓜和巴西枣果[23-26]的贮藏品质，但是处理效果跟剂量和果实以及果实切块[27-28]大小有关，这可能是因为合适的剂量可以杀灭微生物[29]，减少微生物腐烂，并能抑制内部酶的氧化褐变和色素降解，保持果实原有的色泽[18, 23]，从而提高果实的外观品质。

1.2 保持果品的营养物质含量，提高营养价值

水果采摘之后仍是活的有机体，会继续呼吸、代谢和后熟，消耗营养化学物质，破坏组织和结构的完整性，最终使产品衰老腐烂。如何抑制营养物质降解，钝化果实采后的生理生化反应成了保鲜的关键。

UV-C（0.75、1.0 kJ/m^2）和 UV-C（1.2、2.4、4.8、6.0 kJ/m^2）处理能够分别增加火龙果[30]和刺梨[31]的可溶性固形物（TSS）的含量，0.02 kJ/m^2 的 UV-C 能够保持香蕉[32]的固有香气。ZHAO 等[33]用 1.5 kJ/m^2 的 UV-C 处理人参果，也得出了同样的结论，这可能与 UV-C 处理能够抑制果实的成熟和衰老有关。有研究发现，UV-C 单独或者分别结合高猛酸钾和二氧化钛，能够组成乙烯清除系统，氧化分解乙烯[34-36]。众所周知，乙烯有促进水果成熟和呼吸的作用，因此采后环境中去除乙烯或者抑制乙烯的释放和作用成为了采后研究中的重点。也有人推测这些营养化学物质的保持是跟 UV-C 抑制了果实的呼吸作用有关，因为李

丽等[37]推测经适当的 UV-C 照射后，在灭菌的同时，可以使表皮组织发生轻微的变化，并在表面形成对空气有一定隔绝作用的膜，从而抑制果实自身的呼吸，最终抑制呼吸底物的消耗量，保持果实的营养物质，保持 TSS 和可滴定酸（TA）的含量，保持果实原有的色素含量和色泽[33, 38-39]，最终保持细胞膜的完整性。

综合来看，合适剂量的 UV-C 处理能够提高水果的 TSS、TA、花青素和叶绿素等营养物质的含量，抑制果实的呼吸，保持果实原有的绿色，延缓果实的衰老。

1.3　表面杀菌，诱导抗病性，抑制水果的病原性腐烂

据统计，每年收获的水果，大约有 20%~25% 是由于不同属的病原体引起的腐烂而丢失，这些病原体包括青霉菌、霉菌、根霉菌、链霉菌、曲霉菌、镰刀菌、球菌和毛霉菌等[40]。UV-C 处理对某些病原菌有很好的破坏作用，从而控制果实的腐烂和变质，但是杀菌效果跟剂量和材料种类有关。UV-C（4、6 kJ/m^2）处理能抑制猕猴桃的灰霉菌[41]，10 kJ/m^2 的 UV-C 处理能抑制无核蜜柑指状青霉[42]的生长，4.9 kJ/m^2 剂量的 UV-C 处理可以很好地控制芒果的蒂腐病[43]，但是对于接种亚洲镰孢菌和小新壳梭孢菌的板栗，需要在 30 cm 高度照射 12 h，才对生长的菌丝有抑制作用[44]。UV-C 的杀菌作用由 2 方面组成，一是光照本身可以破坏病原体的核酸结构[45]，对果实表面的细菌产生细胞毒性作用，二是某些波长的紫外光照射到空气中，可以氧化空气中的氧气成为臭氧，臭氧是一种强氧化剂，可以同时对果蔬表面的细菌起到氧化毒性作用，降低果实的腐烂率。JIA 等[46]发现，5 kJ/cm^2 的 UV-C 处理可以降低枣的腐烂指数，SENGUPTA 等[47]同样发现该处理能抑制印度醋栗的病害指数。

UV-C 抑制果实采后腐烂还与其能诱导果实产生自身抗性有关，CHENG 等[41]发现，6.0 kJ/m^2 的 UV-C 处理能诱导猕猴桃果实防御相关基因 *CHI* 和 *GLU* 的表达。还有研究发现，UV-C 处理可以提高山竹果实[48]抗病相关酶如苯丙氨酸解氨酶（PAL）、过氧化物酶（POD）和 β-1,3-葡聚糖酶（β-GLU）等的活性，形成天然防御机制以应对外界不利环境对自身造成的伤害，从而提高果实的防御系统[49]和抗病性。因此，UV-C 可以作为一种有效且有前途的杀菌技术[50-51]，利用本身除菌和诱导抗病性的双重作用，替代采后某些有害的化学保鲜技术，延迟果实腐烂，提高货架期的好果率。

1.4　诱导次生代谢，提高抗氧化活性，延缓果实的衰老

果实的成熟衰老是一个自然的且不可逆的过程，除了与营养物质的消耗外，还与活性氧（ROS）的积累和细胞膜的氧化损伤密切相关，所以增强果实采后的抗氧化能力，及时清除这些多余的 ROS 自由基，就能延缓衰老，增加水果的贮藏寿命。

果实采后的抗氧化系统主要分为酶促抗氧化系统和非酶抗氧化系统。酚类物质、黄酮类物质、维生素类等物质组成非酶抗氧化系统，超氧化物歧化酶（SOD）、过氧化氢酶（CAT）、POD、抗坏血酸过氧化物酶（APX）等组成酶促抗氧化系统[52]，共同发挥对新鲜和鲜切水果贮藏品质的调节作用。果实的抗氧化系统越强，清除自由基和活性氧的能力越强，延缓果实衰老的能力也越强。

一定剂量的 UV-C 胁迫，可以提高樱桃和葡萄[53-56]的抗氧化物质，如总酚、类黄酮或花青素的含量（表 1），增加干物质含量[57]。这与 UV-C 胁迫可以诱导水果的次生代谢有关[58]，诱导效果仍然受到剂量和处理果实的种类的影响，不正确的剂量会产生深度的氧化胁迫[59]。激发酶促抗氧化系统的相关酶活性和上调编码相关酶的关键基因，也是 UV-C 提高桃和油桃[60-62]等果实采后抗氧化能力的有效途径（表 1），比如提高 SOD、CAT 和 APX 等酶的活性，提高 *PAL1*、*PAL2*、*CHS*、*F3H*、*DFR*、*ANS*、*UFGT* 等相关基因的表达量，从而提高果实活性氧自由基[63-64]的清除能力，保证细胞膜的完整性，最终延缓果实的衰老。

除了直接处理水果，刺激次生代谢，提高抗氧化能力外，UV-C 还可以作为辅助手段在采前或加工前使用[65]，使采后或者加工后的产品，提高抗氧化物质的含量[66]。通过采后处理，提高总酚、花青素和类黄酮等物质的含量，弥补亏缺灌溉造成的果实品质缺陷[67]。PINTO 等[68]发现，UV-C（65.6 J/m^2）结合种植方式可以提高葡萄加工成葡萄酒中的总酚或者总花青素的含量，加深传统种植葡萄加工成葡萄酒的颜色。综合研究发现，采后处理鲜食果实，剂量要控制在 1~10 kJ/m^2 范围之内，如果只是为了提高产物的抗氧化物质含量，衍生功能食品，可以适当地增加处理剂量。

表 1 UV-C 处理对果蔬抗氧化性能的影响

Tab. 1 Effects of UV-C treatment onantioxidant activities of fruits and vegetables

水果材料 Fruit material	处理 Treatment	结果 Result	参考文献 Reference
甜樱桃	600 s，不同温度下贮藏 14 d	增加类黄酮含量	[53]
甜樱桃	3.0、6.0 kJ/m^2	抗氧化能力增强，黄酮和酚类物质增加	[54]
葡萄‘	65.6 J/m^2，采前处理	总酚和花青素含量增加，跟种植方式有关	[55]
甜樱桃	2.10 kJ/m^2，25 ℃贮藏 6 d	类黄酮、总酚和花青素含量增加，苯丙烷途径相关酶活性增强，相关基因表达上调	[55]
不同成熟期葡萄	28.8 kJ/m^2	增加酚类物质的含量，上调酚类合成相关基因	[56]
桃	1.5 kJ/m^2	PAL 增强、酚类增加、花青素含量增加、类黄酮含量增加、4-香豆酸:辅酶 a 连接酶增强	[60-61]
油桃	3 kJ/m^2	SOD、CAT、APX 活性增强，酚类、总黄酮、花青素增加	[62]
蓝莓	4.6 kJ/m^2，4 ℃	自由基清除能力增强、总酚含量增加	[63]
苹果切片	4.5 kJ/m^2，4 ℃贮藏 10 d	降低·O_2^-产生速率和 H_2O_2、MDA 含量，提高 SOD、CAT、APX 和 GR 活力	[64-65]

1.5 UV-C 处理的负作用

前面提到 UV-C 处理可以诱导果实的次生代谢，产生抗氧化物质，这主要与 UV-C 照射会对果蔬产生“Hormesis”效应有关，医学上也叫“低剂量毒物兴奋作用”，即低剂量可以产生适量的 ROS[69]，从而诱导果实合成生物活性防御物质，提高果实的质量和抗氧化功能，产生积极的作用，但高剂量则会导致负面的作用，如表面褐变伤害、生理失调甚至细胞凋亡[69]等现象。有研究者称这种作用为生物剂量双相毒性作用[11]，这可能因为高剂量处理氧化性增强，破坏细胞膜的透性，造成组织结构损伤有关。研究发现，不合适的 UV-C 剂量处理能使不同品种的芒果细胞损伤[44]和硬度下降[27]，SÁNCHEZ 等[70]用 11.4 kJ/m^2 UV-C 处理 O'Neal 蓝莓，发现果实失重率增加和果皮细胞的结构破坏，因此在采后使用过程中，要进行预试验，选择合适的处理剂量。

2 UV-C 与其他措施的耦合应用

单一的 UV-C 处理穿透性能弱，要想达到理想的效果，需要增加作用时间和处理剂量，这必然会引起表面变色和细胞结构损伤等副作用。因此可以考虑和其他技术联合应用处理水果，专业上称这种措施为栅栏技术，即 2 种或多种方法耦合处理，这种技术能够协同作用或者使效果叠加，与单一方法相比，更好地保持果实的贮藏品质[71-72]。UV-C 和其他技术的结合应用在果实采后保鲜上也得到了实践（表 2）。

2.1 UV-C 和涂膜或包装的结合使用

无论是薄膜包装还是涂膜包装及其衍生产品如活性包装等，都可以有效阻止果品水分挥发，持久释放有效物质，降低透氧率，可以抑制某些氧化酶的活性和营养底物被氧化，保持果品的营养品质。UV-C 与各种涂膜[73-76]以及 UV-C 结合不同形式的气调包装[77-79]既可以防止水分损失，又起到杀菌和诱导抗病性的作用，与每个单独处理相比，更好地抑制了番木瓜、圣女果和葡萄等水果的失重率（表 2），提高了果实的贮藏品质。

2.2 UV-C 和 1-MCP 的结合使用

1-MCP 作用于水果，可以竞争乙烯受体，阻碍乙烯作用，延缓果实的成熟衰老。与 UV-C 结合使用可以互为补充，即增加了杀菌效果，又抑制了乙烯的产生，能理论控制果实的成熟衰老。与单独处理相比，阚娟等[80]发现，2 μL/L 的 1-MCP+2.5 kJ/m^2 UV-C 处理显著提高了红富士苹果果实的 PAL、SOD 和 CAT 的活性，UV-C 和 1-MCP 的结合使用还显著降低了刺梨的腐烂率、失重率、呼吸强度、MDA 含量及 PPO 活性[81]，也使小白杏[82]的营养物质的含量保持高于 1-MCP 或者 UV-C 单独处理（表 2）。

2.3 UV-C 和其他处理的结合使用

除了前面两大类之外，UV-C 结合抗坏血酸钙处理 Langra 芒果[83]，结合高压处理菠萝汁[84]，结合 2%的柠檬酸、0.2%的山梨酸、酸性电解水、0.2%苯甲酸处理 Malvina 草莓[85]，不同程度提高

表 2　UV-C 处理与其他措施结合的应用

Tab. 2　Effects of UV-C treatment and other technologies on fruits

水果材料 Frui tmaterial	处理 Treatment	结果 Result	参考文献 Reference
番木瓜	UV-C+壳聚糖-木薯淀粉（包含二氧化钛）	失重率降低，保持绿色、硬度、TSS、pH、Vc 的含量，延迟成熟	[73]
圣女果	UV-C（层流柜照射 8 min，15 cm 高度）+白心火龙果肉粘液提取物（1：3），4 ℃下贮藏 21 d	减少失重率，抑制颜色变化，抑制微生物，提高总酚含量、总类黄酮含量，总抗坏血酸含量，延长货架期	[74]
Michele Palieri 葡萄	1%的壳聚糖+UV-C（8 根低压蒸汽灯下方 25 cm，5 min）	抑制失重率，保持感官品质，植物化学物质含量增加，延迟衰老	[75]
蓝莓	壳聚糖/百里香精油涂膜+UV-C	果胶，纤维素和半纤维素含量增加，PG, PME, Cx 和 β-Gal 活性降低	[76]
无花果	10 kJ/m^2 的 UV-C+气调包装	植物化学物质和生物活性物质含量增加，硬度增加，总酚含量增加	[77]
红树莓	4 kJ/cm^2+MAP2（透氧率 902 mL/d、透 CO_2 率 785 mL/d），6 ℃贮藏	保持硬度和色度，生物活性物质含量增加，失重率降低，抑制腐烂，延长贮藏期	[78]
草莓	360 J/m^2+真空包装	延长货架期	[79]
红富士苹果	2 μL/L 的 1-MCP+2.5 kJ/m^2 UV-C，4 ℃下贮藏 28 d	Vc 含量，酚类和类黄酮物质的含量增加	[80]
刺梨	0.75 μL/L 的 1-MCP+2.4 kJ/m^2 的 UV-C，(4±1)℃贮藏	腐烂率、失重率、呼吸强度、MDA 含量及 PPO 活性降低，硬度、TSS 和 Vc 含量及 SOD 活性升高	[81]
小白杏	1-MCP (1 μL/L) +UV-C (1.25 kJ/m^2)	酯类、醇类、萜类和酮类物质含量增加，醛类物质含量下降	[82]
Langra 芒果	5、10 kJ/m^2 的 UV-C 结合 1.5%抗坏血酸钙	硬度增加，CAT 和 PAL 活性增强，总酚含量增加，抗氧化能力增强	[83]
菠萝汁	3 kJ/cm^2 UV-C+高压	好氧性微生物的活菌数，酵母菌和霉菌小于限定值，保持胡萝卜素和蛋白质含量	[84].
Malvina 草莓	2 kJ/cm^2 的 UV-C 分别结合 2%柠檬酸、0.2%山梨酸、酸性电解水、0.2%苯甲酸，8 ℃贮藏 21 d	失重率降低，保持硬度	[85]
水蜜桃	UV-C+新型生物保鲜纸	腐烂率、失重率、MDA 含量和 PPO 活性降低，硬度和 TSS 增加，推迟呼吸高峰	[86]
葡萄	123 mJ/cm^2 的 UV-C+1.3%过氧化氢+臭氧	抑制腐败霉菌传输	[87]
草莓	UV-C+搅拌的气泡水+过乙酸	对李斯特单核芽孢杆菌和肠道沙门菌的杀菌效果跟次氯酸钠一样	[88]

了果蔬的贮藏品质（表 2）。李晓宇等[86]用 UV-C 结合新型生物保鲜纸处理水蜜桃，可以将呼吸高峰从第 4 天推迟至第 10 天。这可能跟不同处理可以协同诱导抗病性或者抗氧化活性有关，有关机理鲜有进一步研究。

除了直接用于采后保鲜，UV-C 结合其他处理还可以用于商业化清洗。UV-C+1.3%的过氧化氢，结合臭氧产生羟基自由基高级气相氧化系统清洗葡萄[87]，可以抑制腐败霉菌的传输；UV-C+过乙酸结合搅拌的水清洗草莓[88-89]，对李斯特单核芽孢杆菌和肠道沙门菌的杀菌效果和次氯酸钠一样，一定程度上减少了微生物的危害；UV-C 在循环的水中照射苹果皮，可以降低果皮的含菌量，并使水中的残留菌数量减少，增加了水的循环利用次数[90]，可以节约能源。

由以上研究结论可知，UV-C 结合其他处理可以弥补 UV-C 的剂量依赖性，提高杀菌效果，抑制果实的呼吸作用，保持果实的营养物质，更好地提高了水果的贮藏品质。同时开拓了 UV-C 的辅助作用，用于水果采后商品化处理，或者果实物流运输前的预杀菌。

3　应用前景与结论

研究证明，UV-C 处理采后新鲜或者鲜切水

果，能起到杀菌，诱导抗病性，诱导次生代谢产生抗氧化能力和防御机制，提高水果采后营养品质和延长贮藏期的作用。但是 UV-C 杀菌效果和诱导植物化学物质含量的程度均取决于处理剂量、产品种类、产品成熟度和加工程度、贮藏条件、处理设备等。作者在研究中也发现，单纯依靠灯管处理，会出现作用时间长和不同位置照射强度不一致以及大面积果实照射不均匀等问题。因此，对采后处理设备和处理措施的研究值得关注。其次，综合前人研究发现，所有研究均报道了处理的有效剂量，未给出针对某种水果的临界值，后续可以进行临界值的研究，可以避免在商业化使用中产生不必要的损失，同时，通过研究确定一种水果抗氧化物质含量或者抗氧化能力较高的时间点，可以提高水果的附加利用价值。最后，UV-C 处理杀菌的原理是破坏细菌的 DNA 分子结构，但是 UV-C 对处理果品材料的核酸破坏程度还未有全面且深入的研究。从果品营养和伤害程度来看，可以作为一个研究方向，研究结果将可作为 UV-C 使用安全性的补充，并且近几年研究进展多是聚集在贮藏品质和诱导抗氧化性方面，对 UV-C 在采后的分子调控方面研究较少。

因此，在未来的采后领域中，UV-C 处理仍然有不可替代的研究意义，如结合分子生物学、多组学分析等手段，探究 UV-C 的作用机理和调控路径，找出关键光信号受体以及调控因子；探究如何有效杀菌又能避免表面伤害的机制，结合基因编辑、缺失基因[91]等方式，提高 UV-C 的作用效果；结合栅栏技术，多波长（UV-A、UV-B 和 UV-C）包括真空范围波长探索联合应用，使用采前[92]加采后，以及少量多次[93]的周期性处理方法来共同解决目前存在的问题，创新处理方法和设备，统一技术处理单位，推广采后商品化和物流中使用该技术，使 UV-C 技术更便利、更可控地实现保鲜或者保持水果品质的目的。

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