刘若冰, 宿玲绮, 刘波, 等. 协同处理技术抑制鲜切果蔬褐变的研究进展 [J]. 食品工业科技, 2026, 47(2): 480−487. doi: 10.13386/j.issn1002-0306.2025020203

LIU Ruobing, SU Lingqi, LIU Bo, et al. Research Progress on Browning Inhibition of Fresh-cut Fruits and Vegetables by Synergistic Treatment Technology[J]. Science and Technology of Food Industry, 2026, 47(2): 480−487. (in Chinese with English abstract). doi: 10.13386/j.issn1002-0306.2025020203

· 专题综述 ·

协同处理技术抑制鲜切果蔬褐变的研究进展

刘若冰[1], 宿玲绮[1], 刘　波[2], 傅佳立[1], 张　耸[1], 魏　珉[3], 张小燕[1,*], 彭　勇[1,*]

（1.山东农业大学食品科学与工程学院, 山东 泰安 271018;
2.诸城市农业农村局, 山东 潍坊 262200;
3.山东农业大学园艺科学与工程学院, 山东 泰安 271018）

摘　要: 鲜切果蔬富含维生素、矿物质、膳食纤维等营养物质，受到消费者广泛青睐。但部分鲜切果蔬在贮运、加工、销售过程中易发生褐变，从而影响其营养价值及感官品质。近年来，鲜切果蔬褐变控制技术多采用化学、物理及理化协同等方式，本文综述了各类协同处理方式在鲜切果蔬中的应用效果及其可能的调控机理，重点分析了化学协同处理、物理协同处理、理化协同处理、协同涂膜处理等方式方法，发现协同植物源或生物源提取物以及协同物理手段都有着较好的保鲜效果。此外，本文分析了当前协同处理技术存在的主要问题，并指出了协同处理技术的未来发展方向在于绿色、天然、安全、低成本、可持续。本文旨在通过多学科交叉融合推动协同处理手段和调控机制的研究，以期为鲜切果蔬的保鲜提供技术支持和理论参考。

关键词: 鲜切果蔬, 褐变, 控制技术, 物化协同, 调控机理

中图分类号: TS255.36　　**文献标识码:** A　　**文章编号:** 1002−0306(2026)02−0480−08

DOI: 10.13386/j.issn1002-0306.2025020203　　本文网刊:

Research Progress on Browning Inhibition of Fresh-cut Fruits and Vegetables by Synergistic Treatment Technology

LIU Ruobing[1], SU Lingqi[1], LIU Bo[2], FU Jiali[1], ZHANG Song[1], WEI Min[3], ZHANG Xiaoyan[1,*], PENG Yong[1,*]

（1.College of Food Science and Engineering, Shandong Agricultural University, Tai'an 271018, China;
2.Zhucheng Agriculture and Rural Bureau, Weifang 262200, China;
3.College of Horticulture Science and Engineering, Shandong Agricultural University, Taian 271018, China）

Abstract: Fresh-cut fruits and vegetables are rich in nutrients such as vitamins, minerals and dietary fiber, and are widely popular among consumers. However, some products are prone to browning during storage, processing and marketing, which greatly reduces their nutritional value and sensory quality. In recent years, the most commonly adopted browning control technologies of fresh-cut fruits and vegetables are chemical, physical and physicochemical synergistic approaches. In this paper, we reviews the application effects of various types of synergistic treatments in fresh-cut fruits and vegetables and their possible regulatory mechanisms. We focuses on the synergistic methods such as chemical synergistic treatment, physical synergistic treatment, physicochemical synergistic treatment and combines coating treatment. The study finds that combinations involving plant-derived or biological extracts, as well as synergistic physical methods, demonstrate promising preservation effects. Additionally, this paper analyzes the current problems of synergistic technology and pointes out the future direction lying in green, natural, safety, low-cost and sustainable development. This paper aims to promote related-research on synergistic technologies and regulatory mechanisms through multidisciplinary integration and provides technology and theoretical references for fresh-cut fruits and vegetables industry.

收稿日期: 2025−02−26

基金项目: 国家自然科学基金青年基金（32302178）; 山东省重点研发计划（2023TZXD026、2024TZXD044）。

作者简介: 刘若冰（2002−）, 女, 硕士研究生, 研究方向: 果蔬采后贮藏, E-mail: lrb5720724@163.com。

*** 通信作者:** 张小燕（1983−）, 女, 博士, 副教授, 研究方向: 食品营养与健康, E-mail: zhangxiaoyan@sdau.edu.cn。

彭勇（1980−）, 男, 博士, 副教授, 研究方向: 果蔬采后贮藏, E-mail: pengyongxyz@sina.com。

Key words: fresh-cut fruits and vegetables; browning; control technology; physicochemical synergistic; regulation mechanism

鲜切果蔬由于具有方便、新鲜和营养等优点，日益受到消费者的青睐。特别是近年来，随着新零售模式的快速发展，鲜切果蔬的消费量正逐年增加。然而，部分鲜切果蔬加工过程中的机械损伤易引起产品表面褐变，显著影响产品外观及消费者接受度，降低商品价值[1−2]。因此，研发安全、低量、高效的褐变控制技术具有重要的现实意义。通常认为鲜切果蔬的褐变主要为酶促褐变，涉及活性氧代谢及多酚氧化酶（Polyphenol Oxidase, PPO）、过氧化物酶（Peroxidase, POD）、苯丙氨酸解氨酶（Phenylalanine Ammonia-Lyase, PAL）等褐变相关酶的调节作用，也与果蔬自身抗氧化能力有关[3−5]。当前，控制鲜切果蔬褐变技术主要是通过化学、物理或生物的方法对鲜切产品进行处理，减轻机械损伤、抑制褐变相关酶的活性，从而延缓鲜切果蔬的褐变。虽然化学方法操作简便，但由于化学残留存在安全风险，也可能影响产品的口感风味[6]；物理和生物方法安全无残留，但一般成本较高，且通常效果较差[7−9]。近年来，许多研究表明协同处理可避免单一方法的缺点，实现低量、高效、安全的目的，更好地控制鲜切果蔬褐变，保留其营养品质和商品价值。本文针对鲜切果蔬褐变的协同控制技术，综述了近年来各类协同方法对鲜切果蔬的保鲜效果，并对现今存在的问题及未来发展方向进行了展望，以期为鲜切果蔬的保鲜提供参考。

1　化学方法之间的协同

化学方法是控制鲜切果蔬褐变最常用的方法，常用的护色剂包括无机物和有机物两大类。前者如亚硫酸盐、氯化钙、氯化钠、偏磷酸钠等，后者主要包括柠檬酸、抗坏血酸、各类氨基酸、植物提取物等。将几种护色剂协同处理可以起到协同增效的作用。例如，控制鲜切苹果褐变的常用化学组合有抗坏血酸和氯化钙[10]、抗坏血酸、柠檬酸和草酸[11]、抗坏血酸和乙醇[12]、柠檬酸、抗坏血酸和氯化钙[13] 等。在鲜切马铃薯上，常用的化学组合有抗坏血酸和柠檬酸[14]、1-MCP 和壳聚糖[15] 等，此外，在其他果蔬中，常用的化学组合也包括异抗坏血酸与氯化钙[16]（鲜切芒果）、抗坏血酸钙和柠檬酸[17]（鲜切生菜）、抗坏血酸和乙醇[18−19]（鲜切莲藕、鲜切山药）等，这些化学试剂组合的类型、剂量和方式依果蔬种类的不同而有差异。一般认为，化学协同处理调控鲜切果蔬褐变的机制主要是通过各类护色剂的酸化作用、还原作用、螯合作用等协同调控 PPO 的活性中心，与 PPO 蛋白中的氨基酸残基发生相互作用，或与底物结合形成复合物等方式有效抑制褐变相关酶的活性，延迟鲜切果蔬的褐变[3,13]。也可以通过协同调控酚类物质的积累和果蔬的抗氧化能力，间接调控鲜切果蔬的褐变[20]。

近年来，随着科学技术的进步，减量、高效、安全的化学组合手段仍然是控制鲜切果蔬褐变的发展方向[21]，其中，植物提取物由于其天然、安全，正成为研究的热点之一，不仅能够提升鲜切产品的品质，也能促进消费者的健康。将植物提取物与常用的护色剂结合可以提高使用效果[22]。研究发现，绿茶提取物含有较多的儿茶素，不仅可以增强果蔬抗氧化能力，而且能够维持抗坏血酸的稳定性，与单一处理相比，两者协同处理之后未发生褐变，使鲜切苹果的货架期延长至 14 d[23]。马黛茶提取物含有大量抗氧化物质，与抗坏血酸和柠檬酸协同处理同样能有效地抑制酶促褐变的发生[24]。除了植物提取物与化学试剂结合外，植物提取物成分之间也表现出协同作用。Li 等[25] 发现苦荞幼苗中的黄酮类化合物和蛋白质能够协同抑制鲜切马铃薯的褐变，芦丁、山奈酚-3-O 芸香苷、槲皮素等黄酮类化合物对 PPO 的抑制是非竞争性的，三者复配对 PPO 抑制率仅为 49.1%，与蛋白质协同处理后对 PPO 抑制率达到 68.3%，显著提高了抑制效果，其原因可能是黄酮类化合物的巯基与醌类物质结合形成无色络合物，而其酚羟基与蛋白质的巯基可以协同螯合 PPO 活性中心的铜离子，进而抑制 PPO 活性。此外，植物多酚之间也存在协同抗褐变作用。如儿茶素和表儿茶素可竞争性抑制酪氨酸酶活性，而氧化白藜芦醇非竞争性抑制该酶活性，在 1:1 配比时，对酪氨酸酶的抑制率可以提高 30% 左右，其协同调控的机制在于调节了酶催化口袋周围的疏水微环境，并与酚羟基的数量和位置相关[26]。

最近研究表明，氨基酸也可以通过与醌类物质结合或与络合物结合形成无色化合物来减缓酶促褐变进程[27]。将抗坏血酸、草酸、氯化钠与 L-半胱氨酸协同处理鲜切苹果，其中，抗坏血酸和草酸能够降低体系的 pH，氯化钠能够抑制酶蛋白活性，而 L-半胱氨酸作为含巯基氨基酸，可通过进一步与醌类物质结合形成稳定的无色物质，协同抑制鲜切苹果的褐变，并有效防止了腐败现象发生[28]。将赖氨酸与精氨酸混合处理鲜切苹果，同样可协同抑制鲜切苹果褐变[29]。并且，研究发现，鲜切马铃薯自身氨基酸水平与褐变密切相关，但与 PPO 活性关系不大[30]。此外有研究发现，将 1-MCP 处理鲜切桃子后，再将桃子在预冷的植酸溶液中浸泡，提高了总酚含量，抑制了与 PPO 和 POD 活性相关的酶促褐变，抗褐变效果较好[31]（表 1）。

2　物理和化学方法的协同

控制鲜切果蔬褐变的物理手段有很多，低温、超声、紫外、脉冲光、电解水、辐照等处理都可以一定程度上抑制鲜切果蔬的褐变[32]，近年来的研究表明将这些物理手段与化学试剂相结合可以起到协同增效的作用。例如利用声波技术的空化作用协同护色剂

表 1 协同处理对鲜切果蔬的保鲜效果

Table 1 Effect of synergistic treatment on fresh-cut fruits and vegetables

协同类型	鲜切果蔬	处理方式	保鲜效果	参考文献
化学方法之间的协同	苹果	1%柠檬酸+0.02%草酸或1%抗坏血酸+0.02%草酸	抗氧化能力↑, PPO活性↓	[11]
	苹果	30%乙醇+1%抗坏血酸	L^*、颜色↑ b^*、好氧菌、霉菌和酵母菌↓	[12]
	苹果	1.5%壳聚糖+1-MCP	SOD、POD活性、L^*、维生素C↑ 呼吸强度、MDA、PPO活性、失重率↓	[15]
	芒果	1% 异抗坏血酸+0.5%氯化钙	类胡萝卜素、抗坏血酸、SOD、CAT、APX活性↑, 呼吸速率、细胞渗透率、褐变指数、POD、PPO活性↓	[16]
	生菜	0.1%柠檬酸+0.5%抗坏血酸钙	感官评价↑, 褐变指数↓	[17]
	苹果	3%抗坏血酸+0.1%绿茶提取物	白度、硬度、抗坏血酸↑	[23]
	苹果	1.2%马黛茶+0.9%柠檬酸+1.0%抗坏血酸	a^*、总酚、抗氧化能力、CO_2↑ L^*、褐变、O_2↓	[24]
	苹果	2.0%赖氨酸+1.0%精氨酸	L^*、感官评分、pH↑ 褐变度、PPO活性↓	[29]
	桃子	1 μL/L 1-MCP+0.05%植酸混合溶液	TPC、DPPH 自由基清除能力↑ PPO、POD、SQC、H_2O_2、O_2^-、MDA↓	[31]
物理和化学方法的协同	莲藕	0.01%半胱氨酸+超声(40 kHz, 200 W)处理2 min	白度、硬度↑ b^*、ΔE^*、色度、BI、PPO活性↓	[34]
	马铃薯	2 g/L半胱氨酸+超声(28 kHz, 360 W) 6 min	DPPH自由基清除率↑ BI、PPO、POD、PAL活性、总酚、MDA↓	[35]
	马铃薯	0.2%抗坏血酸+超声(40 kHz, 200 W)3 min	L^*、硬度、总酚、pH、AsA↑ a^*、ΔE、PPO、POD、PAL活性、MDA↓	[36]
	山药	0.1%氯化钙+1%抗坏血酸+6.84 kJ/m^2 UV-C照射	总酚含量↑ BI、PPO、POD活性↓	[39]
	桃子	1.46 kJ/m^2 UV-B照射+1 μL/L 1- MCP熏蒸	L^*、TPC、ATP酶、Ca^{2+}-ATP酶活性↑ 褐变度、硬度、呼吸速率、失重率、PPO、 POD、SDH活性、MDA、H_2O_2↓	[40]
	苹果	1%抗坏血酸+0.1%氯化钙+71.6 J/cm^2 脉冲光照射	BI、好氧嗜温种群、霉菌和酵母菌↓	[41]
	苹果	1% N-乙酰半胱氨酸+0.5%氯化钙+8 或 16 J/cm^{2}脉冲光	L^*、抗氧化能力、总酚、类黄酮、维生素C↑ 嗜温微生物和嗜冷微生物、霉菌和酵母菌↓	[42]
物理方法之间的协同	蘑菇	酸性电解水+超声(40 kHz, 200 W)	L^*、总酚、可溶性蛋白↑ ΔE、BI、MDA、PPO、POD活性、细菌总数和霉菌↓	[45]
	菠萝	酸性电解水+低压静电场(1000 Hz, 150 V)	L^*、硬度、抗坏血酸、总酚、PAL、SOD、CAT活性↑ 质量损失、PPO活性、LOX、MDA含量、H_2O_2↓	[46]
	胡萝卜	气调(80% O_2+10% CO_2)+2 kJ/m^2 UV-C	硬度、抗坏血酸、总类胡萝卜素、γ-氨基丁酸含量↑ 失重、呼吸速率、乙烯生成速率、总活菌、总酚、 木质素、MDA、PAL、PPO、POD活性↓	[47]
生物和物理方法的协同	生菜	0.5 g/L ε-聚赖氨酸溶液+0.5 kJ/m^2 UV-C	可溶性蛋白↑ ΔE、总酚、PPO、POD活性↓	[50]
生物和化学方法的协同	生菜	50 mg/L微酸性电解水+300 mg/L乳酸链球菌素	叶绿素含量、L^*↑ 褐变指数、a^*、b^*、总酚、MDA、SOD、 PPO、PAL、POD活性↓	[51]

注: ↑代表活性或含量增加, ↓代表活性或含量减少。

可以加快 PPO 失活, 更好地抑制鲜切果蔬的褐变[33]。将鲜切莲藕和鲜切马铃薯在半胱氨酸溶液中超声处理可促进半胱氨酸的作用, 显著抑制 PPO 活性和黑色素前体左旋多巴的产生, 褐变度比单一处理低 10%~35%[34−35]。将鲜切马铃薯片在抗坏血酸溶液中进行超声处理, 与单独抗坏血酸或单独超声处理相比, 具有明显协同抑制 PPO 活性和褐变的效果[36]。

紫外线照射可以杀灭微生物, 延长鲜切果蔬的保鲜期。研究发现, UV-A、UV-B 和 UV-C 照射均可刺激鲜切果蔬产生非生物胁迫, 提高自身的抗氧化能力。并且紫外线也与果蔬氨基酸残基的光氧化有关, 可引发高分子量聚集体的形成和酶的变性, 进而抑制鲜切果蔬的褐变[37−38]。将鲜切山药片先浸泡在抗坏血酸和氯化钙溶液中处理, 然后用 UV-C 照射, 与单一浸泡处理相比, 更能有效抑制鲜切山药的酶促褐变[39]。鲜切桃子用 1-MCP 熏蒸结合 UV-B 照射, 能够协同抑制 PPO 和 POD 活性, 保持较高水平的总酚和抗氧化能力, 抑制了鲜切桃子褐变[40]。

脉冲光通过利用光化学效应在短时间内高效率灭活微生物, 达到保鲜的目的。Gómez 等[41] 将鲜切苹果片浸入抗坏血酸和氯化钙的混合溶液中, 并用脉冲光照射, 褐变度由单一处理的 2.7 降至 2.1, 有效抑制了鲜切苹果片褐变。将苹果片浸入含有 N-乙酰半胱氨酸和氯化钙溶液中, 并结合脉冲光处理也能维持较好的果实品质及抗氧化能力[42]。

此外, 酸性电解水安全、无残留, 可通过降低 pH 和改变氧化还原电位钝化酶活性杀灭微生物, 也可以抑制鲜切果蔬的褐变, 抑制褐变效果与 20 mg/L

的草酸或柠檬酸相当[43−44]，因此，综合考虑酸性电解水的处理时间、处理温度和处理方式，可以协同护色剂起到抑制褐变的效果，是未来有前景的物化处理方式之一。

3　物理方法之间的协同

物理手段之间的协同同样能够抑制鲜切果蔬的褐变。研究发现，酸性电解水可与其他物理手段结合具有协同抗褐变的效果。将切片的蘑菇浸入酸性电解水中超声，可协同抑制鲜切蘑菇的 PPO 和 POD 活性，延缓其褐变[45]。采用酸性电解水和低压静电场协同处理鲜切菠萝与单一处理相比，有效减缓了酚类底物的代谢，抑制了鲜切菠萝酶促褐变的发生[46]。此外，Li 等[47] 将鲜切胡萝卜处于高氧的气调下，并结合 UV-C 照射处理，能够保持鲜切胡萝卜 15 d 的贮藏品质，抑制其 PPO、PAL 和 POD 等褐变相关酶活性及其基因表达量，降低总酚含量，延迟褐变。除了这些之外，其他物理协同手段抑制鲜切果蔬褐变的报道还比较少，可能受限于技术条件、处理成本、保鲜效果等因素的影响。

4　生物方法与物理或化学方法的协同

抑制鲜切果蔬褐变的生物手段主要包括使用天然安全的微生物菌群或它们产生的活性物质、酶抑制剂等，生物手段的调节主要在于其对有害微生物的拮抗作用，间接地调控褐变，或者其产生的活性成分能抑制褐变相关酶的活性[48]。将这些生物试剂与其他理化条件结合可以延长鲜切果蔬的货架期，抑制微生物生长[49]。Zhang 等[50] 将鲜切生菜在 ε-聚赖氨酸溶液中浸泡后，然后用 UV-C 紫外线照射，与仅施用 ε-聚赖氨酸溶液相比，PPO 和 POD 活性分别下降约 19% 和 37%，有效保持了鲜切生菜良好的色泽，延长了货架期。将微酸性电解水和乳酸链球菌素结合处理生菜，降低了 PPO、POD 等褐变相关酶的活性，同单一处理相比，褐变指数下降约 32.1%，有效控制了其褐变[51]。

5　协同涂膜处理

涂膜处理是鲜切果蔬常用的保鲜手段之一，鲜切果蔬涂膜之后，可以在表面形成一层很薄的膜，能起到阻隔氧气、减少水分蒸发、抑制呼吸的作用。目前，用于鲜切果蔬的涂膜材料主要是安全性高的可食性材料，包括壳聚糖、淀粉、果胶、海藻酸钠、羧甲基纤维素等成膜基材及抗菌剂、抗氧化剂等一些添加剂[52−54]。

近年来，利用成膜材料包容性强的优势，协同各种护色剂有效地提高鲜切果蔬保鲜的效果。如将鲜切芦笋采用含抗坏血酸、L-半胱氨酸的羧甲基纤维素钠涂膜处理，相比于单独处理，更有效地抑制了其 PPO、POD 活性及褐变酶相关基因的表达，促进了抗氧化酶相关基因的表达，起到了抗褐变效果[55]。类似地，在鲜切莲藕上，结合 L-半胱氨酸和柠檬酸的海藻酸钠涂膜有着更好地抑制褐变效果，贮藏 14 d 的总色差值与单独使用护色剂 4 d 的相当，并可有效抑制鲜切莲藕酶促褐变相关酶活性以及微生物的生长[56]。添加乙酸己酯及氯化钙可以进一步增强海藻酸钠的抗褐变效果，能够有效控制鲜切苹果褐变[57]。在所有的涂膜材料中，由于存在氨基阳离子，壳聚糖展现出最好的抗褐变效果，将 L-半胱氨酸、柠檬酸等护色剂结合壳聚糖涂膜处理，显著提高了对鲜切马铃薯褐变的抑制效果[58]。最近发现，将壳聚糖和酪蛋白磷酸肽涂膜在等离子体修饰的低密度聚乙烯上，用于保鲜鲜切梨片可有效地抑制梨片的褐变和软化，保鲜期延长了 2 倍[59]。

近年来，结合植物提取物的可食用涂膜也有较好的抗褐变效果[60]。与未添加提取物相比，结合 1.5% 沙棘叶提取物的羧甲基纤维素涂膜处理可显著抑制鲜切苹果的褐变和 PPO 活性[61]。类似地，将番石榴叶提取物与羧甲基壳聚糖结合、核桃绿壳提取物与壳聚糖和瓜尔豆胶结合，均可有效地抑制鲜切苹果的褐变，维持良好的色泽和质地[62−63]。最近，Zhao 等[64] 将石榴皮提取物添加到大豆分离蛋白和沙蒿胶的复合膜溶液中，同样显著地提高了对鲜切苹果褐变的抑制。此外，将蔓越莓提取物与乳酸乳球菌共同添加到结冷胶溶液中，可协同清除自由基，提升抗氧化能力，延迟鲜切马铃薯和苹果的褐变[9]。

为了进一步提高膜溶液的性能和保鲜效果，纳米涂膜材料近年来被开发利用。研究表明纳米材料粒径更小，包埋效果更好，协同涂膜处理有着更好的抗菌、抗褐变效果[65]。将含有芳樟醇的 β-乳球蛋白纳米颗粒添加到羧甲基壳聚糖膜溶液中，有效地抑制了鲜切苹果的褐变，可将货架期延长 6 d[66]。类似地，将纳米 TiO_2/CuO 与细菌纤维素混合并添加到结冷胶溶液中，可使复合膜的自由基清除率提高 6~8 倍，延缓鲜切辣椒的褐变，维持贮藏期内较好的色泽和感官品质[67]（表 2）。

表 2　协同涂膜处理对鲜切果蔬的保鲜效果

Table 2　Effect of combined coating treatment on fresh-cut fruits and vegetables

涂膜种类	鲜切果蔬	处理方式	膜性能、保鲜效果	参考文献
羧甲基纤维素	芦笋	0.38%抗坏血酸+0.85% L-半胱氨酸+0.67%羧甲基纤维素钠	叶绿素A、总叶绿素、可滴定酸、SOD、APX活性、H_2O_2、PPO、POD、Chl-POX酶活性↑ a^*、ΔE、可溶性固形物、LsCCS、LsPPOI-1↓	[55]
羧甲基纤维素	苹果	1.5%沙棘叶提取液+1%羧甲基纤维素	硬度、可滴定酸度、抗坏血酸、总酚、总黄酮、DPPH、$ABTS^+$自由基清除率、POD、SOD活性↑ ΔE、BI、可溶性固形物、PPO活性、总细菌数、酵母和霉菌数↓	[61]

续表 2

涂膜种类	鲜切果蔬	处理方式	膜性能、保鲜效果	参考文献
壳聚糖	梨	2%壳聚糖+0.3%酪蛋白磷酸肽, 涂覆低密度聚乙烯上	DPPH自由基清除率、抑菌率、O_2含量、总酚↑ 失重率、BI、硬度损失、细菌总数、CO_2含量、呼吸速率、MDA、PPO、PLD、LOX活性↓	[59]
壳聚糖	马铃薯	3%马铃薯淀粉+0.07% L-半胱氨酸+0.02%壳聚糖+ 1.5%柠檬酸	PPO活性、BI, 膜水蒸气渗透率、膜氧气透过率、膜不透明度↓	[58]
壳聚糖	苹果	羧甲基壳聚糖+β-乳球蛋白纳米颗粒+芳樟醇	膜机械性能、膜附着力, 硬度↑ 失重率、BI、PPO、MDA、菌落总数↓	[66]
壳聚糖	苹果	2%羧甲基壳聚糖+0、2、8 %番石榴叶提取物	抗菌活性、抗氧化能力、硬度、抗坏血酸、总酚↑ 膜疏水性, 重量损失、褐变发生率↓	[62]
壳聚糖和瓜尔胶	苹果	4 %核桃绿壳提取物+15%壳聚糖和85%瓜尔胶	膜拉伸强度、断裂伸长率, 硬度、可溶性固形物↑ 膜含水率、膜水溶性, 失重率、细菌总数、霉菌、酵母菌数↓	[63]
海藻酸钠	莲藕	0.27% L-半胱氨酸+0.76%柠檬酸+0.5%海藻酸钠	L^*、可滴定酸、AsA、SOD、CAT、APX活性↑ ΔE、还原糖、可溶性固形物、酚类化合物、H_2O_2、POD、PAL、LOX活性、MDA、菌落总数↓	[56]
海藻酸钠	苹果	1.25%海藻酸钠+0.03%乙酸已酯+4%氯化钙	膜断裂伸长率, 可溶性固形物↑ 膜水蒸气渗透率、膜透氧率, 呼吸速率、失重率、BI、可滴定酸、酵母菌和霉菌↓	[57]
沙蒿胶	苹果	沙蒿胶与蛋白质1∶1混合+1-3%石榴皮提取物	膜拉伸强度、膜断裂伸长率, 总酚、DPPH、$ABTS^+$自由基清除率、硬度、可滴定酸度↑ 膜含水率、膜水溶性、膜水蒸气渗透率、膜透氧率, 失重率、BI、pH、可溶性固形物↓	[64]
结冷胶	苹果和马铃薯	结冷胶+0.5%蔓越莓提取物+2.0%乳酸乳球菌	抗菌性、抗氧化活性、膜拉伸强度↑	[9]
结冷胶	辣椒	0.4 % TiO2+0.4%纳米CuO+结冷胶-细菌纤维素	膜厚度、膜拉伸强度、膜断裂伸长率, 硬度、DPPH自由基清除率、可滴定酸度↑ 膜水蒸气渗透率, 失重率、腐烂率↓	[67]

注: ↑代表活性或含量增加, ↓代表活性或含量减少。

6 结论与展望

与单一处理相比, 多种技术协同处理能更有效地抑制鲜切果蔬的褐变, 但多种技术的协同效应复杂, 各因素间相互作用机制不明确, 导致难以精准调控, 比如紫外、化学护色剂协同使用时, 紫外导致的温度变化会影响护色剂的活性与功能, 实际应用效果不稳定。部分协同处理在抑制褐变的同时, 会对果蔬品质产生潜在影响, 如化学护色剂协同处理可能会改变鲜切果蔬风味, 影响口感和营养价值, 且化学物质残留还存在安全问题, 不同国家和地区标准不同, 使用不当易违规, 影响产品流通和消费者信任。此外, 一些物理的协同处理技术成本过高, 设备购置、维护以及研发等投入巨大, 而且处理效果不理想, 在市场竞争中难以实现成本与效益的平衡。

未来, 随着消费者对健康食品要求的提升, 协同处理技术在抑制鲜切果蔬褐变领域有着广阔的发展前景, 绿色、天然、低成本、可持续的协同处理技术将成为未来发展趋势。从天然植物、微生物中提取生物活性物质, 结合物理保鲜技术的协同处理将会是未来发展方向之一。借助传感器、大数据和人工智能, 精准协同保鲜技术将实现对贮藏环境和鲜切果蔬品质的实时监测与精准调控。食品科学、生物工程、材料科学、信息技术等多学科交叉融合, 加快协同调控机制的研究, 将为协同处理技术带来新的思路。同时, 建立标准化操作流程和质量控制体系, 加强产学研合作, 促进技术从实验室到产业化转化, 将推动鲜切果蔬产业健康发展。

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