纳米食品保鲜膜研究进展

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摘要：目的 综述纳米材料及其制备纳米保鲜膜，以及其在食品保鲜中研究和应用现状。**方法** 介绍常用纳米包装保鲜膜中常用的纳米材料，包括 ZnO 纳米粒子、TiO_2 纳米粒子、SiO_2 纳米粒子、介孔 SiO_2 纳米粒子、Ag 纳米粒子，以及纳米保鲜膜制备方法。**结果** 在传统膜或保鲜膜中添加纳米粒子，可以有效改善膜的力学性能、阻隔性能及抑菌性能，可有效延长食品货架期和贮藏保鲜期。**结论** 与传统膜相比，纳米膜在食品包装保鲜具有优异特性，具有巨大应用潜力。然而，如何改善光催化等纳米薄膜应用的局限性需要进一步研究。

关键词：纳米粒子；保鲜膜；制备；保鲜
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Research Progress of Nanomaterial Food Fresh-keeping Film

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ABSTRACT: The work aims to review the nanomaterial and the food fresh-keeping film prepared by nanomaterial as well as the research and application status of nanomaterial in food fresh-keeping. The nanomaterials commonly used in fresh-keeping films were introduced, including zinc oxide nanoparticles, titanium dioxide nanoparticles, silica nanoparticles, mesoporous silica nanoparticles and silver nanoparticles and the preparation methods of nano fresh-keeping films were expounded. Adding nanoparticles to traditional films or fresh-keeping films could effectively improve some film properties, such as mechanical property, barrier property and antibacterial property and extend the food shelf life and the storage period. Compared with the traditional film, the nano film has excellent properties in food packaging and fresh-keeping, and has great application potential. However, how to improve the application limitations of nano film such as photocatalysis needs further research.

KEY WORDS: nanoparticle; fresh-keeping film; preparation; fresh-keeping

食品的颜色、风味、营养素和生物活性化合物等品质特征随着贮藏时间增加而逐渐衰变，需要适当的保鲜处理以维持最佳生理品质[1]。塑料薄膜包装是商业销售普遍常用的方式，但其难降解而易对环境造成污染，因此，绿色、安全、可降解的保鲜膜技术逐渐受到研究者关注，特别是在保鲜膜中添加抗菌剂、抗氧化剂等可以有效缓解食品腐烂变质的程度，增强降解性能，减少环境污染[2]。其中，纳米食品保鲜膜通过纳米技术对保鲜膜进行修饰和改进，具有比普通保鲜膜更好的力学性能、气体阻隔性能、表面性能和抗菌性等[3-6]。纳米保鲜膜是指纳米级（1~100 nm）材料通过添加或改性与成膜基材制备成具有特殊性能

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和纳米尺度的纳米保鲜膜[7]。本文主要综述目前常用的几种制备保鲜膜的纳米材料和制备方法，对近几年来国内外研究进展进行总结，从而为纳米保鲜膜技术在食品包装领域提供方法和参考。

1　纳米材料

纳米技术是目前国内外迅速发展的新技术，纳米材料具有生物相容性、可生物降解性和无毒特性等优点，制备的纳米保鲜膜广泛应用于食品保鲜包装[8]。将纳米材料作为抗菌剂或与抗菌剂、抗氧化化合物结合可提高化合物的生物活性、赋予纳米材料更好的抗菌性或抗氧化性，从而延长食品保质期[1]。如 Azevedo 等[9]制备纳米蒙脱石–乳清分离蛋白复合膜可保持膜原有特性，减少苹果的酸度、水分活性、多酚氧化酶和过氧化物酶活性等；肖锡湘[10]制备的纳米硒复合膜的拉伸强度、抑菌性和透气性均高于普通保鲜膜；纳米纤维素膜拉伸强度最大可达到 38.6 MPa，冷鲜肉可保存 12 d[11]。目前，保鲜研究常用的纳米材料有纳米 ZnO、纳米 TiO_2、纳米 SiO_2、介孔 SiO_2（MSN）和纳米 Ag 等。

1.1　氧化锌纳米粒子

氧化锌纳米粒子（ZnO Nanoparticles，ZnO NPs）是一种多功能性的新型无机材料，低浓度 ZnO NPs 安全无毒[12]，美国食品药物监督管理局（FDA）已经将 ZnO NPs 列为安全材料，可将其添加到食品中[13]。ZnO NPs 比普通 ZnO 具有更好的热稳定性和抗氧化性，添加 ZnO NPs 能改善膜的力学性能、水阻隔性和热阻隔性[14]。ZnO NPs 通过离子作用可以严重损害细菌细胞膜，使细胞内容物完全释放，从而抑制细菌生长，达到保鲜效果[15]。研究表明，添加 ZnO NPs 制备的复合膜具有很好的抗氧化性[16]、保鲜性[17]和抑菌性[18]。

近年来，ZnO NPs 保鲜膜研究已取得一定成果。Li 等[19]制备的壳聚糖/ZnO NPs 复合膜对番茄的保鲜实验表明，与普通壳聚糖膜相比，ZnO NPs 壳聚糖膜拉伸强度明显提高，可显著增强对沙门氏菌（*Salmonella*）、大肠杆菌（*Escherichia coli*）、嗜酸耐热菌（*Alicyclobacillus acidoterrestris*）和金黄色葡萄球菌（*Staphylococcus aureus*）的抑菌性，降低番茄的呼吸强度，延缓代谢活性和成熟进程；将 ZnO NPs 添加到壳聚糖/阿拉伯胶薄膜中，可使香蕉的新鲜度保持超过 17 d，比对照组增加了 4 d[20]；将结合葡萄皮红的 ZnO NPs 和大豆分离蛋白制备的复合膜显著提高了对金黄色葡萄球菌和大肠杆菌的抑菌活性，比普通大豆分离蛋白膜拉伸强度提升了 1.91 MPa[21]。

虽然保鲜膜中添加 ZnO NPs 改善了膜的抗菌性和热稳定性[22]，但保鲜膜中添加 ZnO NPs 同样也降低了保鲜膜的透明度和包装的可视性[23]，另外其抑菌活性也必须在光照的条件下才能起到较好效果[24]。

1.2　二氧化钛纳米粒子

二氧化钛纳米粒子（TiO_2 Nanoparticles，TiO_2 NPs）是一种光催化纳米材料，在紫外光照射下对微生物有一定的抑制作用，从而防止食品变质[25]。其杀菌机理主要是 TiO_2 NPs 经紫外光辐照，与微生物细胞壁和保鲜膜成分发生反应，导致细胞渗透性紊乱，从而促进细胞死亡[26]。目前，认为低浓度的 TiO_2 NPs 在食品和化妆品中是安全的[27]，已广泛用于果蔬保鲜[28]。

研究表明，添加了 TiO_2 NPs 复合膜可有效降低水果的腐烂率、质量损失率[29]，提高抑菌率[30-31]、可溶性固形物及抗坏血酸含量[32]，同时，可以显著提高各种抗氧化酶活性[29,32]。例如，TiO_2 NPs/聚乳酸膜、TiO_2 NPs–壳聚糖/花青素复合膜对大肠杆菌和金黄色葡萄球菌抑制率均大于 90%[30-31]；TiO_2 NPs 保鲜膜处理的葡萄在贮藏 28 d 时，葡萄好果率、质量损失率和过氧化氢酶活性明显优于对照组的[29]；此外，添加 TiO_2 NPs 改性膜可改善薄膜的力学性能、热性能、结构性能和阻隔性能[33-34]。

研究还发现，随着 TiO_2 NPs 添加量增加，膜的抑菌效果增强，但高浓度的 TiO_2 NPs 也将带来食品安全问题[35]。低浓度的 TiO_2 NPs 膜是安全的，但其抑菌性受到光照、反应速度慢、催化效率低等影响[36]，因此，如何改善添加安全浓度 TiO_2 NPs 膜的高抑菌活性将是研究者亟待解决的问题。

1.3　二氧化硅纳米粒子

二氧化硅纳米粒子（SiO_2 Nanoparticles，SiO_2 NPs）是一种无毒无污染的非金属材料，也是光催化材料之一。它具有比表面积大、质量轻、耐高温、化学性能稳定、粒度小等特点[37]，因此，SiO_2 NPs 被广泛应用到食品保鲜中。SiO_2 NPs 中含有的硅氢键可有效地吸附空气中的 CO_2、O_2，调节微环境中气体浓度以抑制果蔬的呼吸强度，从而起到保鲜的作用[38]。

保鲜膜中添加 SiO_2 NPs 可提高膜的力学性能和阻隔性能[39]。研究发现，SiO_2 NPs 新型纳米复合膜，如 SiO_2 NPs/魔芋葡甘聚糖膜[40]、SiO_2 NPs/聚乙烯醇–肉桂醛膜[41]、SiO_2 NPs–羟丙基甲基纤维素/壳聚糖复合膜[42]等，改善了膜的物理性能，提高了膜的保鲜性能和抗菌能力等。在薄膜中适当增加 SiO_2 NPs 可使薄膜表面光滑[40,43]、截面致密，以及具有断裂伸长率高、抗湿性和抗氧性好等性能[40]；此外，薄膜中适量添加 TiO_2 NPs 可抑制果蔬表面的单核细胞增生李斯特氏菌（*Listeria monocytogenes*）、大肠杆菌和金黄色葡萄球菌[42,44]；可减少果蔬中总可溶性固形物和可溶

性蛋白的损失[41]，减低腐烂率和质量损失率，延长果蔬贮藏保鲜时间[40-41]。SiO_2 NPs 制备方法相对简单，但其复合膜的应用中仍存在需要光催化才能更好发挥抑菌效果的缺点。

1.4 介孔二氧化硅纳米粒子

介孔二氧化硅纳米粒子（Mesoporous Silica，MSNs）是一种多孔材料，具有比表面积大、孔结构可控、孔体积大、表面可化学修饰等特点[45]。MSNs 因其特有的内部孔道结构主要用于结合挥发性的抗菌或抗氧化性物质，可通过调节其孔径大小控制挥发性物质释放速率[46-47]；其特有的孔道结构使得制备的保鲜膜比普通 SiO_2 保鲜膜具有更高的透水性和负载量[48]。

已有的研究表明，MSNs 可以负载各种精油，如茶树精油[49]、广藿香精油[50]和牛至精油[51]，以及负载各种药物以完成药物的递送、控释[52]等。负载精油的 MSNs 通常与各种膜基质复合制备各种保鲜复合膜，常用的膜基质有聚丙烯酸[49]、海藻酸钠[51]和壳聚糖[53]。负载精油和抗氧化物质的 MSNs 复合膜在果蔬保鲜中表现出较好的效果，可有效抑制大肠杆菌、金黄色葡萄球菌和真菌[49-50,54]，减少细菌总数[51]。Derbalah 等[54]实验表明，MSNs 对茄链格孢菌（*Alternaria solani*）具有较高的抑菌活性，证明了 MSNs 有作为抑菌剂的潜能。包埋芳樟醇的 MSNs 在 48 h 后对金黄色葡萄球菌和单增李斯特菌最低杀菌浓度降为 8 mg/mL[55]。茶树油–MSNs 可改变大肠杆菌的细胞形态，破坏了细胞膜的完整性，导致细胞死亡，在自然环境下 50 d 仍对大肠杆菌具有抑制作用[56]。此外，研究还发现 MSNs 负载其他物质可有效增加果蔬硬度，抑制果蔬中抗氧化物质的减少，提高果蔬过氧化物酶、超氧化物歧化酶、过氧化氢酶的活性[51]，延长果蔬的贮藏期[49-54]。

1.5 银纳米粒子

银纳米粒子（Ag Nanoparticles，Ag NPs）与普通银离子相比，物理性能和抗菌性能都得到显著提升。Ag NPs 薄膜包装能有效改善果蔬外观指数、硬度和减少失水率，延缓叶绿素、V_C、可溶性固形物和可溶性蛋白质的损失，同时提高了过氧化氢酶和过氧化物酶的抗氧化活性[57]，抑制了果蔬的呼吸作用和氧化速度等[58]。添加了 Ag NPs 的薄膜可显著提高膜的阻隔性[59]、拉伸强度、断裂伸长度等[60]。与聚乙烯醇[59]、壳聚糖[60]、纤维素[58]等结合制备的 Ag NPs 膜已应用于牛肉[60]、黄骨鱼[61]、蜜桔[62]、虾[63]、蓝莓[58]、黄瓜[57]和鱼丸[64]等食品保鲜中，在适宜条件下，有效延长了食品贮藏保鲜期。

Ag NPs 膜杀菌和抑菌性能主要表现为 Ag NPs 释放 Ag^+吸附并破坏细菌细胞壁，抑制细菌生长，从而达到保鲜目的[65]。研究发现，添加了 Ag NPs 的膜对黑曲霉（*Aspergillus niger*）[59]、猪链球菌（*Streptococcus suis*）[66]和大肠杆菌[67]等均有很好的抑菌作用。研究还发现，Ag NPs 抗菌活性与其粒径大小有关，其粒径越小，抗菌活性越强[68]。高效杀菌性是 Ag NPs 主要的特点，Ag NPs 需要在光催化或接触反应下才能发挥出抗菌性能[69]。体外实验表明，Ag NPs 对皮肤、肝及生殖器官具有一定诱导作用[70]，因此 Ag NPs 在食品包装保鲜中应用的安全浓度问题仍需探讨。

2 复合纳米材料

复合纳米材料是由至少一种纳米粒子组成，利用不同纳米粒子不同特性，可弥补彼此之间的缺点或增强抑菌、保鲜效果，改善膜的特性等[71-73]。如 MSNs–Ag NPs 吸附制备成纳米复合膜，Ag NPs 无团聚现象[74]；纳米镁与纳米氧化铁制备的纳米复合涂层表面无裂纹，具有优异的耐腐蚀性，其抑菌性随着纳米氧化铁含量增加而增强[75]；添加 TiO_2 NPs 提高了纳米氧化铝壳聚糖膜力学性能[76]。常见的复合纳米材料主要由 Ag NPs、SiO_2 NPs、ZnO NPs 和 TiO_2 NPs 之间进行的复合制备[77-91]。

2.1 Ag NPs 复合纳米材料

Ag NPs 易团聚导致抗菌等性能降低，将其与化学性稳定的纳米材料结合可有效降低 Ag NPs 发生团聚的现象，降低成本、提高抗菌、力学和阻隔性能[77]。Ag NPs 与 SiO_2 NPs 结合，Ag/SiO_2 NPs 的稳定性明显增强，具有良好的荧光性能，但粒径和形貌与单一纳米材料相比无明显变化[78]。Ag/SiO_2 NPs 的淀粉复合膜，可改善其力学性能、水蒸气阻隔性能和表面疏水性，对金黄色葡萄球菌和大肠杆菌均表现出较好的抗菌活性[79]。经 Ag NPs–SiO_2 NPs 复合膜处理的苹果可有效抑制了蛋白质分解和褐变现象[80]。Ag/ZnO NPs 壳聚糖涂膜，可提高涂膜力学性能，增加对细菌细胞膜破坏程度[81]；Ag/ZnO NPs 琼脂膜不仅使膜具有良好的亲水性和力学性能，而且对金黄色葡萄球菌和大肠杆菌均具有良好的抗菌活性[82]。通过化学沉淀法制备的 Ag/ZnO NPs 海藻酸钠膜具有更高的紫外防护值、热稳定性和抑菌性[83]。

TiO_2 NPs 因其只在紫外光区内具有抑菌效果，限制了其应用范围。质量分数为 3%的 TiO_2 NPs–Ag 琼脂膜在冷藏下保鲜柑橘，其果实腐烂率、褐变时间和可溶性固形物等指标均优于对照组[84]；TiO_2–AgNPs 明胶膜无须紫外光照射，也对金黄色葡萄球菌和大肠杆菌表现较强抑菌活性[85]。不同质量分数的 TiO_2 NPs–Ag 表现出的抑菌性和水阻隔性不同，如质量分数为 0.5%的 TiO_2 NPs–Ag 抗菌性最强，质量分数为 0.4%的 TiO_2 NPs–Ag 水蒸气透过率最高[86]。此外，也有研究者将 Ag NPs 与 ZnO NPs、TiO_2 NPs 结合制

备聚乙烯膜，在 4 ℃下可延长竹笋保鲜期至 20 d，第 20 天与第 0 天相比，竹笋的呼吸强度，纤维素、木质素和亚硝酸盐含量均无显著变化[87]。

2.2　SiO_2 NPs 复合材料

SiO_2 NPs 特有的硅氢键能有效结合其他纳米材料，使 SiO_2 NPs 具有更高的抑菌性[38]，同时改善膜的透气性和力学性能[88]。在食品包装保鲜上主要体现为可抑制霉菌[89]、铜绿假单胞菌（*Pseudomonas aeruginosa*）、腐生链球菌（*Saprophytic streptococcus*）、单核细胞增多性乳杆菌（*Lactobacillus monocytogenes*）[90]、金黄色葡萄球菌和大肠杆菌[88]等生长；抑制食品脂肪和蛋白质氧化，缓解脂肪酶活性的增加[89]等。涂膜或制备薄膜的主要 SiO_2 NPs 复合材料包括 SiO_2/TiO_2–ZnO、SiO_2–TiO_2、SiO_2/Ag 等[88-91]；成膜基质有聚乙烯醇[90]、壳聚糖[88]和魔芋葡甘聚糖膜[40]。

3　纳米膜制备方法

传统食品塑料包装材料存在生物降解性低的问题，因此，研究者将目光放在天然、可食用和可生物降解的保鲜膜上。虽然食品膜对果蔬的感官和消费者的可接受性影响较小，但是由于这些单一的保鲜膜具有各种缺点，如耐水性差和力学性能差，使得它们应用受到限制，所以将普通的保鲜膜和纳米材料结合制备成涂膜或薄膜。通过赋予保鲜膜更优异的抗菌性和力学性能，来提高保鲜质量、食品安全、新鲜度和保质期，同时也改善膜的降解性能[92-93]。

3.1　涂膜

涂膜技术作为食品包装保鲜主要技术之一，通过浸泡或喷洒溶液的方式在果蔬表面形成薄膜，缓解水分流失和呼吸速率，抑制微生物生长[94]。在成膜溶液中加入纳米材料可提高涂膜的物理性能、抑菌性能以及提高果蔬的抗氧化酶活性，更有效地维持果蔬品质[95-102]。成膜溶液通常将成膜基质通过搅拌的方式溶于适当溶剂中，再将成膜液与纳米粒子按照优化比例搅拌并分散均匀即为复合涂膜液。目前，主要的涂膜基质有壳聚糖[95]、海藻酸钠[96-97]；其次为聚丙烯酸[98]、淀粉[99]、魔芋葡甘聚糖[100]等。在涂膜中添加的纳米材料包括纳米纤维素[101]、ZnO NPs[102-104]、纳米黏土[105]、Ag NPs[97,106]、TiO_2 NPs[107]、SiO_2 NPs[98,100]等。

壳聚糖作为常用的成膜基质之一，具有安全无毒、成膜性好、抑菌等优点[93]，壳聚糖溶于稀酸（盐酸和醋酸）溶液可制成可食性涂膜。已有研究表明，将壳聚糖与纳米材料结合制备的涂膜具有优异的力学性能、热稳定性能和光学性能[101]，在保鲜方面能有效缓解腐烂、抑制呼吸速率[60]、提高抗氧化酶活性[102]。此外，还发现壳聚糖纳米复合膜对大肠杆菌、沙门氏菌、霉菌和酵母菌（*Yeast*）等具有明显抑制效果[105]，48 h 后对革兰氏阴性菌抑制率仍可达到 80%以上[97]。

海藻酸钠是一种具有良好水溶性、成膜性和安全性的天然多糖[96]，具有形成透明、均匀、可溶于水的膜的特性[108]。海藻酸钠涂膜对脂肪、油和氧气的渗透性较低，可以延缓各种蔬菜和水果的脂肪氧化。海藻酸钠涂膜应用于草莓[103]、番石榴[104]和香蕉[97]等水果中，可显著提高抗氧化性和超氧化物歧化酶活性，有效延缓了果实的成熟度，达到良好的保鲜效果。研究表明，海藻酸钠与壳聚糖按照不同比例进行复配，然后与 ZnO NPs 结合制成的复合涂膜均可缓解水果腐烂程度，其中海藻酸钠与壳聚糖质量比为 1∶1 时，复合涂膜可延长货架期至 20 d[104]。此外，还有研究表明海藻酸钠与纳米材料之间存在较强的物理作用，使膜物理性能提升[107]。

壳聚糖和海藻酸盐由于其生物降解性、生物兼容性以及对生化和化学修饰的适应性，作为成膜基质广泛应用于涂膜制备[109-110]。其他成膜基质虽有研究，但仍存在一些需要解决的问题。如纤维素不溶于水，也很少溶于大多数极性溶剂。淀粉和果胶涂膜的力学性能和亲水性较差，易脆[111]；脂基薄膜力学性能和气体阻隔性差[112]；蛋白质基薄膜易碎，且还可能引起过敏问题[113]。因此，新的成膜基质还有待研究者发现。

3.2　薄膜

目前，市场上常用的薄膜主要有 2 种：缓释膜和普通薄膜。缓释膜将抗菌性、抗氧化性等挥发性物质以稳定的速率释放到包装食品的密闭空间中，提高抗氧化和抗菌等能力，从而保持果蔬良好状态，延长果蔬保鲜期[114]。目前，缓释膜在食品包装保鲜领域研究较少，但由于其优异的缓释作用、改善膜的性能和抑菌性能，在食品特别是果蔬保鲜中的应用潜力巨大。AgNPs–壳聚糖缓释膜具有 Ag^+离子的持续释放的能力和显著的抗菌活性，改善薄膜的拉伸强度和断裂伸长率[115]。纳米埃洛石负载香芹酚制备的聚乙烯缓释膜，可显著提高香芹酚释放时间和缓释膜的断裂伸长率，表现出很强的抗氧化活性[116]。ZnO NPs–海藻酸钠/壳聚糖缓释膜对姜黄素包封率超过 90%，在低 pH 值条件下可控姜黄素的释放量，从而提高了姜黄素的利用率[117]。

普通薄膜因其制备简单而研究较多。商品薄膜制备目前主要采用效率高、产量大的流延法制备，将成膜材料与添加剂按比例经加热搅拌，后经挤压冷却干燥得到薄膜[118]，而实验室研究大多采用铺膜法成型。壳聚糖和聚乙烯是制备薄膜常用的成膜基材。

壳聚糖以其抗菌、抗氧化、无毒、可生物降解和成膜潜力而闻名，这些特性促进了它在薄膜开发

中的广泛应用，将纳米材料如 SiO_2 NPs[118-119]和 TiO_2 NPs[120]制备的壳聚糖薄膜应用于鳄梨、番茄和甜椒[121-123]等保鲜中均取得良好的保鲜效果。此外研究表明，壳聚糖纳米薄膜比纯壳聚糖薄膜具有更高的拉伸强度、热性能和抑菌性[118-119,124]，可延长食品货架期[112]。

聚乙烯是一种来源广、无毒、易加工的树脂。聚乙烯膜的透水率低，但透气性较好，不适于呼吸跃变型水果保鲜，因此，将聚乙烯膜与纳米材料结合可有效解决此问题[125]。研究表明，质量分数为 5%聚乙烯纳米复合膜对大肠杆菌具有最好的杀菌效果[126]，SiO_2 NPs–聚乙烯薄膜 28 d 后对酵母菌和霉菌仍有较高的抑制活性[127]；徐庭巧等[128]制备的纳米碳酸钙–聚乙烯膜的硬度、总酚含量和可滴定酸比纯聚乙烯膜的分别高 5.69%、7.63%和 12.07%，有效缓解酶活性的降低，维持了果实的品质。

4 纳米保鲜膜应用

食品包装是保证食品货架期常用技术之一。近几年，随着纳米材料在食品中应用，纳米保鲜膜因其独特的物理化学性质和安全、可降解性，被逐渐应用于食品包装保鲜中。已有研究证明，纳米保鲜膜可应用于水果、蔬菜、肉类和海产品等食品中。常见的纳米保鲜膜有 ZnO NPs–壳聚糖纳米涂膜、TiO_2 NPs–海藻酸钠纳米薄膜、SiO_2 NPs–壳聚糖纳米薄膜和 Ag NPs–壳聚糖纳米薄膜。这些保鲜膜主要表现为抑菌性、抗氧化性、缓解食品腐烂变质和延长货架期等。目前，纳米保鲜膜仍处于研究和小范围应用的实验阶段，还存在诸如某些纳米粒子需要光催化、接触食品的安全性以及膜的透明度不好等问题。这些问题也是纳米保鲜材料应深入研究和探讨的问题。常见纳米保鲜膜在食品中应用和存在问题见表 1。

表 1 纳米保鲜膜在食品保鲜中应用
Tab.1 Application of nanomaterial fresh-keeping films in food preservation

纳米材料	成膜基质	应用对象	优点	存在问题	文献
氧化锌纳米粒子(ZnO NPs)	壳聚糖、阿拉伯胶、大豆分离蛋白、海藻酸钠	番茄、香蕉、草莓、猪肉、秋葵、黄瓜、番石榴	抗氧化性、保鲜性、抑菌性、热稳定性、力学性能好	需要光催化	[12-24]、[101]、[103-104]
二氧化钛纳米粒子(TiO_2 NPs)	聚乳酸、壳聚糖、海藻酸钠	葡萄、竹笋、蘑菇、苹果、哈密瓜、木瓜	降低了腐烂率和质量损失率，抑菌性好	高浓度存在食品安全问题，低浓度存在光催化问题	[25-36]、[107]
二氧化硅纳米粒子(SiO_2 NPs)	魔芋葡甘聚糖、聚乙烯醇、羟丙基甲基纤维素、壳聚糖	肉、枇杷、樱桃、芒果、哈密瓜	提高了膜力学性能、保鲜性、抗菌性、断裂伸长率、抗湿性和抗氧性	需要光催化	[38-41]、[100]、[119]
介孔二氧化硅纳米粒子(MSNs)	聚丙烯酸、海藻酸钠、壳聚糖	蘑菇、番茄	抑菌性好，能抑制果蔬中抗氧化物质的减少，提高了酶活性		[49-54]
银纳米粒子(Ag NPs)	聚乙烯醇、壳聚糖、纤维素	牛肉、黄骨鱼、蜜桔、虾、蓝莓、黄瓜、葡萄、香蕉	抑制呼吸作用和氧化速度，具有高效杀菌和抑菌性能	需要光催化或接触反应下才能发挥出性能，可能存在食品安全问题	[59-70]、[106]

5 结语

随着纳米技术的发展和应用领域的拓展，纳米材料逐渐应用于食品包装保鲜领域。纳米材料的独特性质，也逐渐赋予食品包装保鲜膜材料新的内涵，有效改善了传统膜材料的力学性能和阻隔性能；也赋予普通保鲜膜了新的抗菌、抑菌和杀菌特性，从而很好地延长了食品的货架期、果蔬贮藏保鲜期。虽然纳米纤维素膜、纳米碳酸钙膜和纳米银膜已在实践中应用，但作为一类新型保鲜材料，工艺技术改进、成本的降低和市场的认可度还有待提高。随着纳米技术在食品领域的应用范围拓展，其特有的物化特性，如发光、显色等也逐渐被应用于食品保质期的指示中，预示着纳米材料应用前景的巨大。总之，纳米膜作为一类新型膜包装材料，其优异的包装保鲜性能为食品包装保鲜提供了一个新途径，存在的问题也为研究者提供了新的研究思路。

参考文献：

[1] OLIVEIRA FILHO J G, MIRANDA M, FERREIRA M D, et al. Nanoemulsions as Edible Coatings: A Potential Strategy for Fresh Fruits and Vegetables Preservation[J]. Foods (Basel, Switzerland), 2021, 10(10): 2438.

[2] 张芮菡. 可降解塑料的种类与应用现状[J]. 当代化工

研究, 2019(1): 20-21.
ZHANG Rui-han. Types and Application Status of Degradable Plastics[J]. Modern Chemical Research, 2019(1): 20-21.
[3] 史君彦, 高丽朴, 左进华, 等. 纳米膜和 PVC 膜包装对西兰花贮藏保鲜的影响[J]. 食品工业科技, 2016, 37(19): 255-258.
SHI Jun-yan, GAO Li-pu, ZUO Jin-hua, et al. Effect of Nanofilm and PVC Film Packaging on Preservation of Broccoli during the Storage[J]. Science and Technology of Food Industry, 2016, 37(19): 255-258.
[4] ANUGRAH D S B, ALEXANDER H, PRAMITASRRI R, et al. A Review of Polysaccharide-Zinc Oxide Nanocomposites as Safe Coating for Fruits Preservation[J]. Coatings, 2020, 10(10): 988.
[5] MAKVANDI P, IFTEKHAR S, PIZZRTTI F, et al. Functionalization of Polymers and Nanomaterials for Water Treatment, Food Packaging, Textile and Biomedical Applications: A Review[J]. Environmental Chemistry Letters, 2021, 19(1): 583-611.
[6] 李喜泉, 杨巍巍. 纳米材料在食品包装中的应用及安全性评价[J]. 包装与食品机械, 2019, 37(5): 57-62.
LI Xi-quan, YANG Wei-wei. Application and Safety Evaluation of Nanomaterials in Food Packaging[J]. Packaging and Food Machinery, 2019, 37(5): 57-62.
[7] 郝梦玉, 于开源, 李思杰, 等. 二氧化钛光催化(P25)涂膜对果蔬保鲜研究进展[J]. 农产品加工(下半月), 2019(4): 59-61.
HAO Meng-yu, YU Kai-yuan, LI Si-jie, et al. Reviewed of Titania Photocatalyst (P25) Coating on Fruit and Vegetable Preservation[J]. Aem Roducts Rocessing, 2019(4): 59-61.
[8] NARAYAN R, NAYAK U Y, RAICHUR A M, et al. Mesoporous Silica Nanoparticles: A Comprehensive Review on Synthesis and Recent Advances[J]. Pharmaceutics, 2018, 10(3): 118.
[9] AZEVEDO V M, DIAS M V, SIQUEIRA E H H, et al. Effect of Whey Protein Isolate Films Incorporated with Montmorillonite and Citric Acid on the Preservation of Fresh-Cut Apples[J]. Food Research International (Ottawa, Ont), 2018, 107: 306-313.
[10] 肖锡湘. 纳米硒复合包装材料的制备及其在果蔬保鲜中的应用[D]. 福州: 华侨大学, 2020: 61-103.
XIAO Xi-xiang. Preparation of Nano-Selenium Composite Packaging Material and Its Application in Fruit and Vegetable Preservation[D]. Fuzhou: Huaqiao University, 2020: 61-103.
[11] QIAN Yuan, BIAN Lu-yao, WANG Ke-qin, et al. Preparation and Characterization of Curdlan/Nanocellulose Blended Film and Its Application to Chilled Meat Preservation[J]. Chemosphere, 2021, 266: 128948.
[12] JAYASURIYA A C, ARYAEI A, JAYATISSA A H. ZnO Nanoparticles Induced Effects on Nanomechanical Behavior and Cell Viability of Chitosan Films[J]. Materials Science & Engineering C, Materials for Biological Applications, 2013, 33(7): 3688-3696.
[13] JANANI N, ZARE E N, SALIMI F, et al. Antibacterial Tragacanth Gum-Based Nanocomposite Films Carrying Ascorbic Acid Antioxidant for Bioactive Food Packaging[J]. Carbohydrate Polymers, 2020, 247: 116678.
[14] SHAHVALIZADEH R, AHMADI R, DAVANDEH I, et al. Antimicrobial Bio-Nanocomposite Films Based on Gelatin, Tragacanth, and Zinc Oxide Nanoparticles - Microstructural, Mechanical, Thermo-Physical, and Barrier Properties[J]. Food Chemistry, 2021, 354: 129492.
[15] 张钧凯, 金学睿, 严吉, 等. 纳米氧化锌抑菌机制与应用进展[J]. 中国药学杂志, 2022, 57(24): 2045-2050.
ZHANG Jun-kai, JIN Xue-rui, YAN Ji, et al. Antibacterial Mechanism and Application Progress of Zinc Oxide Nanoparticles[J]. Chinese Pharmaceutical Journal, 2022, 57(24): 2045-2050.
[16] HEYDARI M M, GHANBARZADEH B, SHAHIDI N M, et al. A New Active Nanocomposite Film Based on PLA/ZnO Nanoparticle/Essential Oils for the Preservation of Refrigerated Otolithes Ruber Fillets[J]. Food Packaging and Shelf Life, 2019, 19: 94-103.
[17] SUO Biao, LI Hua-rong, WANG Yue-xia, et al. Effects of ZnO Nanoparticle-Coated Packaging Film on Pork Meat Quality During Cold Storage[J]. Journal of the Science of Food & Agriculture, 2016, 97(7): 2023.
[18] AL-NAAMANI L, DUTTA J, DOBRETSOV S. Nanocomposite Zinc Oxide-Chitosan Coatings on Polyethylene Films for Extending Storage Life of Okra (*Abelmoschus Esculentus*)[J]. Nanomaterials (Basel, Switzerland), 2018, 8(7): 479.
[19] LI Yu, ZHOU Yu, WANG Zhou-li, et al. Preparation and Characterization of Chitosan-Nano-ZnO Composite Films for Preservation of Cherry Tomatoes[J]. Foods (Basel, Switzerland), 2021, 10(12): 3135.
[20] LA D D, NGUYEN T P, LE K H, et al. Effects of Antibacterial ZnO Nanoparticles on the Performance of a Chitosan/Gum Arabic Edible Coating for Post-Harvest Banana Preservation[J]. Progress in Organic Coatings, 2021, 151: 106057.
[21] 冉锐敏, 王璐瑶, 何宾宾, 等. 纳米氧化锌/葡萄皮红改性大豆分离蛋白膜的制备与性能研究[J]. 农业工程学报, 2021, 37(14): 294-301.

RAN Rui-min, WANG Lu-yao, HE Bin-bin, et al. Preparation and Characterization of Soy Protein Isolate Films Modified by ZnO Nanoparticles and Grape-Skin Red[J]. Transactions of the Chinese Society of Agricultural Engineering, 2021, 37(14): 294-301.

[22] ESPITIA P J P, FÁTIMA F S N, TEÓFILO R F, et al. Physical-Mechanical and Antimicrobial Properties of Nanocomposite Films with Pediocin and ZnO Nanoparticles[J]. Carbohydrate Polymers, 2013, 94(1): 199-208.

[23] GHAROY A E, ABBASPOUR F M H, SHAHTAHMASSEBI N, et al. Preparation and Characterization of PVA/ZnO Nanocomposite[J]. Journal of Food Processing and preservation, 2015, 39(6): 1442-1451.

[24] 刘呈坤, 江志威, 毛雪, 等. 常见抗菌材料的研究进展[J]. 西安工程大学学报, 2020, 34(2): 37-46.
LIU Cheng-kun, JIANG Zhi-wei, MAO Xue, et al. Research Progress of Common Antibacterial Materials[J]. Journal of Xi'an Polytechnic University, 2020, 34(2): 37-46.

[25] QIAO Guo-hua, XIAO Hi-gang, DING Wen-xin, et al. Effect of Chitosan/Nano-titanium Dioxide/Thymol and Tween Films on Ready-to-eat Cantaloupe Fruit Quality[J]. Coatings, 2019, 9(12): 828.

[26] KUMARAVEL V, NAIR K M, MATHEW S, et al. Antimicrobial TiO(2) Nanocomposite Coatings for Surfaces, Dental and Orthopaedic Implants[J]. Chemical Engineering Journal (Lausanne, Switzerland: 1996), 2021, 416: 129071.

[27] SAMI R, ELHAKEM A, ALHARBI M, et al. Effect of Titanium Dioxide Nanocomposite Material and Antimicrobial Agents on Mushrooms Shelf-life Preservation[J]. Processes, 2020, 8(12): 1632.

[28] HASSAN A, KAYANI Z N, ANWAR M. Effect of Au Ions on Structural, Optical, Magnetic, Dielectric, and Antibacterial Properties of TiO_2 Dip-Coated Thin Films[J]. Journal of Materials Science: Materials in Electronics, 2021, 32(11): 14398-14419.

[29] 蒋佳男, 李海登, 李喜宏, 等. 纳米 TiO_2 可降解包装材料对葡萄的保鲜效果研究[J]. 包装工程, 2019, 40(21): 1-6.
JIANG Jia-nan, LI Hai-deng, LI Xi-hong, et al. Preservation Effect of Nano-TiO_2 Degradable Packaging Materials on Grapes[J]. Packaging Engineering, 2019, 40(21): 1-6.

[30] DONG Xiao-rong, LIANG Xue, ZHOU Yu-ting, et al. Preparation of Polylactic Acid/TiO(2)/GO Nano-Fibrous Films and Their Preservation Effect on Green Peppers[J]. International Journal of Biological Macromolecules, 2021, 177: 135-148.

[31] 崔鲁青. 基于离子液体的壳聚糖改性抑菌包装膜的制备及其抑菌性能研究[D]. 青岛: 青岛科技大学, 2019: 51-58.
CUI Lu-qing. Preparation and Antibacterial Properties of Chitosan Modified Antibacterial Packaging Film Based on Ionic Liquid[D]. Qingdao: Qingdao University of Science & Technology, 2019: 51-58.

[32] PETER A, NICULA C, MIHALY C L, et al. New Active Package Based on Titania Coated on Cardboard for Storage of Fresh Prepared Orange Juice[J]. Journal of Food Process Engineering, 2019, 42(2): 12965.

[33] DUAN Nuo, LI Qian, MENG Xiang-yi, et al. Preparation and Characterization of Kcarrageenan/Konjac Glucomannan/TiO_2 Nanocomposite Film with Efficient Anti-fungal Activity and Its Application in Strawberry Preservation[J]. Food Chemistry, 2021, 364(2): 130441.

[34] LIU Zi-tian, DU Mei-jun, LIU Hui-ping, et al. Chitosan Films Incorporating Litchi Peel Extract and Titanium Dioxide Nanoparticles and Their Application as Coatings on Watercored Apples[J]. Progress in Organic Coatings, 2021, 151: 106103.

[35] 谭靓, 胡长鹰, 王志伟. 纳米二氧化钛抗菌食品包装复合膜的研究进展[J]. 食品安全质量检测学报, 2020, 11(22): 8341-8350.
TAN Liang, HU Chang-ying, WANG Zhi-wei. Research Progress of Nano-Titanium Dioxide in Antimicrobial Food Packaging Composite Film[J]. Journal of Food Safety & Quality, 2020, 11(22): 8341-8350.

[36] 张红英, 王光惠. 纳米二氧化钛的研究概况[J]. 安徽化工, 2021, 47(5): 8-10.
ZHANG Hong-ying, WANG Guang-hui. General Situation of Research on Nano-Titanium Dioxide[J]. Anhui Chemical Industry, 2021, 47(5): 8-10.

[37] YANG Man-li, SHI Jin-sheng, XIA Yan-zhi. Effect of SiO_2, PVA and Glycerol Concentrations on Chemical and Mechanical Properties of Alginate-Based Films[J]. International Journal of Biological Macromolecules, 2018, 107: 2686-2694.

[38] SI Wen-hui, GAO Yue, MEI Xiao, et al. Mesoporous Silica Nanoparticles Loaded with Capsaicin and Their Oxidation Resistance in Meat Preservation[J]. Food Chemistry, 2021, 344: 128737.

[39] WANG Li, SHAO Shuang, MADEBO M P, et al. Effect of Nano-SiO_2 Packing on Postharvest Quality and Antioxidant Capacity of Loquat Fruit under Ambient Temperature Storage[J]. Food Chemistry, 2020, 315: 126295.

[40] XIANG Fei, XIA Yu-ting, WANG Yan, et al. Preparation of Konjac Glucomannan Based Films Reinforced with

Nanoparticles and its Effect on Cherry Tomatoes Preservation[J]. Food Packaging and Shelf Life, 2021, 29(1): 100701.

[41] 高红芳. 聚乙烯醇/二氧化硅/肉桂醛复合膜的制备及应用[J]. 食品与发酵工业, 2021, 47(5): 127-132.
GAO Hong-fang. Preparation and Application of Polyvinyl Alcohol/Silicon Dioxide/Cinnamaldehyde Composite Film[J]. Food and Fermentation Industries, 2021, 47(5): 127-132.

[42] LAI Hua-zhang, LIU Yang, HUANG Gui-ting, et al. Fabrication and Antibacterial Evaluation of Peppermint Oil-Loaded Composite Microcapsules by Chitosan-Decorated Silica Nanoparticles Stabilized Pickering Emulsion Templating[J]. International Journal of Biological Macromolecules, 2021, 183: 2314-2325.

[43] XU Lina, CAO Wen-hui, LI Rui, et al. Properties of Soy Protein Isolate/Nano-silica Films and Their Applications in the Preservation of Flammulina Velutipes[J]. Journal of Food Processing and Preservation, 2019, 43(11): 14177.

[44] 党秀洁. 二氧化硅—肉桂醛抗菌微胶囊及其可降解薄膜的制备与表征[D]. 南宁: 广西大学, 2019: 29-59.
DANG Xiu-jie. Preparation and Characterization of Silica-Cinnamaldehyde Antibacterial Microcapsules and Their Degradable Films[D]. Nanning: Guangxi University, 2019: 29-59.

[45] BAHRAMI F, ABDEKHODAIE M J, BEHROOZI F, et al. Nano Mesoporous Silica for Cancer Treatment: ROS-Responsive and Redox-Responsive Carriers[J]. Journal of Drug Delivery Science and Technology, 2020, 57: 101510.

[46] 张文君, 吕江维, 陈威, 等. 功能化SBA–15介孔二氧化硅的制备及在药物递送系统中的应用进展[J]. 材料导报, 2022, 36(18): 51-61.
ZHANG Wen-jun, LYU Jiang-wei, CHEN Wei, et al. Preparation of Functionalized SBA-15 Mesoporous Silica and Its Application in Drug Delivery System[J]. Materials Review, 2022, 36(18): 51-61.

[47] 吕江维, 王鹏光, 曲有鹏, 等. 盐酸小檗碱/介孔二氧化硅载体的制备与缓释行为研究[J]. 化工新型材料, 2021, 49(3): 173-176.
LYU Jiang-wei, WANG Peng-guang, QU You-peng, et al. Investigation on Preparation and Sustained Release Behavior of BBH/Mesoporous SiO_2 Carrier[J]. New Chemical Materials, 2021, 49(3): 173-176.

[48] ABDELSAMAD A M A, KHALIL A S G, ULBRICHT M. Influence of Controlled Functionalization of Mesoporous Silica Nanoparticles as Tailored Fillers for Thin-film Nanocomposite Membranes on Desalination Performance[J]. Journal of Membrane Science, 2018, 563: 149-161.

[49] ZHONG Xi-ming, GAO Fan, WEI Hong-jie, et al. Functionalization of Mesoporous Silica as an Effective Composite Carrier for Essential Oils with Improved Sustained Release Behavior and Long-Term Antibacterial Performance[J]. Nanotechnology, 2021, 33(3): 1-10.

[50] JIA Jing-fu, DUAN Shu-lei, ZHOU Xue, et al. Long-Term Antibacterial Film Nanocomposite Incorporated with Patchouli Essential Oil Prepared by Supercritical CO_2 Cyclic Impregnation for Wound Dressing[J]. Molecules (Basel, Switzerland), 2021, 26(16): 5005.

[51] 逯文倩, 王娟. 牛至精油–介孔纳米二氧化硅/海藻酸钠复合膜对双孢蘑菇保鲜效果研究[J]. 中国果菜, 2021, 41(4): 1-9.
LU Wen-qian, WANG Juan. Preservation Effect of OEO-MSNPS/Sodium Alginate Film on Agaricus Bisporus[J]. China Fruit AVegetable, 2021, 41(4): 1-9.

[52] POOSTFOROOSHAN J, BELBEKHOUCHE S, SHABAN M, et al. Aerosol-Assisted Synthesis of Tailor-Made Hollow Mesoporous Silica Microspheres for Controlled Release of Antibacterial and Anticancer Agents[J]. ACS Applied Materials & Interfaces, 2020, 12(6): 6885-6898.

[53] WU Chun-hua, ZHU Yang, WU Tian-tian, et al. Enhanced Functional Properties of Biopolymer Film Incorporated with Curcurmin-Loaded Mesoporous Silica Nanoparticles for Food Packaging[J]. Food Chemistry, 2019, 288: 139-145.

[54] DERBALAH A, SHENASHEN M, HAMZA A, et al. Antifungal Activity of Fabricated Mesoporous Silica Nanoparticles Against Early Blight of Tomato[J]. Egyptian Journal of Basic and Applied Sciences, 2018, 5(2): 145-150.

[55] 金礼. 基于介孔材料负载精油分子的研究: 合成、表征和杀菌性[D]. 上海: 上海海洋大学, 2020: 17-64.
JIN Li. Study on Essential Oil Molecules-functionalized Nanoparticles: Preparation, Characterization, and Bactericidal Activity[D]. Shanghai: Shanghai Ocean University, 2020: 17-64.

[56] GAO Fan, ZHOU Hong-jun, SHEN Zhi-chuan, et al. Long-Lasting Anti-Bacterial Activity and Bacteriostatic Mechanism of Tea Tree Oil Adsorbed on the Amino-Functionalized Mesoporous Silica-Coated by PAA[J]. Colloids and Surfaces B, Biointerfaces, 2020, 188: 110784.

[57] 史君彦, 高丽朴, 左进华, 等. 纳米银保鲜膜包装对

黄瓜保鲜效果的影响[J]. 食品工业, 2017, 38(1): 109-112.
SHI Jun-yan, GAO L P, ZUO Jin-hua, et al. Effect of Nano-Ag Film Packaging on Preservation of Cucumber[J]. The Food Industry, 2017, 38(1): 109-112.
[58] 陈啟原. 木质纤维素抗菌保鲜膜的制备与性能研究[D]. 哈尔滨: 东北林业大学, 2020: 62-79.
CHEN Qi-yuan. Preparation and Properties of Lignocellulose Antibacterial Preservative Film[D]. Harbin: Northeast Forestry University, 2020: 62-79.
[59] JING Deng, QI Chen, PENG Jue, et al. Nano-Silver-Containing Polyvinyl Alcohol Composite Film for Grape Fresh-Keeping[J]. Materials Express, 2019, 9(9): 985-992.
[60] 杨斌. 壳聚糖及纳米银 OSA 淀粉薄膜的制备及其对牛肉保鲜效果的影响[D]. 兰州: 甘肃农业大学, 2020: 29-47.
YANG Bin. Preparation of Chitosan and Nano-Silver OSA Starch Film and Its Effect on Beef Preservation[D]. Lanzhou: Gansu Agricultural University, 2020: 29-47.
[61] 翟纬坤, 王轩, 王源升, 等. 聚乙烯醇/纳米银薄膜的制备及其对黄骨鱼保鲜效果的研究[J]. 包装工程, 2020, 41(9): 44-50.
ZHAI Wei-kun, WANG Xuan, WANG Yuan-sheng, et al. Preparation of PVA/Nano-Silver Film and Its Effect on Preservation of Yellow Bone Fish[J]. Packaging Engineering, 2020, 41(9): 44-50.
[62] 王鑫. 纳米银–氧化淀粉涂膜对无籽露葡萄和南丰蜜桔的保鲜性及安全性探究[D]. 北京: 北京林业大学, 2020: 1-9.
WANG Xin. Study on the Preservation and Safety of Nano-Silver-Oxidized Starch Coating on Seedless Dew Grape and Nanfeng Tangerine[D]. Beijing: Beijing Forestry University, 2020: 1-9.
[63] 刘天红, 王颖, 唐欢欢, 等. 两种纳米材料抑菌效果及对虾的保鲜效果研究[J]. 食品安全质量检测学报, 2020, 11(5): 1483-1491.
LIU Tian-hong, WANG Ying, TANG Huan-huan, et al. Study on Antibacterial Effect of Two Nanomaterials and Fresh-Keeping Effect of Prawn[J]. Journal of Food Safety & Quality, 2020, 11(5): 1483-1491.
[64] 徐赵萌, 吴朝凌, 魏旭青, 等. 纳米 Ag/ZnO–壳聚糖复合涂膜对带鱼鱼丸的保鲜性能研究[J]. 渤海大学学报(自然科学版), 2020, 41(4): 303-307.
XU Zhao-meng, WU Chao-ling, WEI Xu-qing, et al. The Preservation Properties of Nano-Ag/Zno-Chitosan Coatings on Hairtail Fish Balls[J]. Journal of Bohai University(Natural Science Edition), 2020, 41(4): 303-307.
[65] GEETHA S R, DHIVYA P, RAJ P D, et al. Studies on Magnetron Sputtered ZnO-Ag Films: Adhesion Activity of S. Aureus[J]. International Journal of Nanoscience, 2016, 16(2): 1650026.
[66] 刘宝玲, 李春玲, 蒋智勇, 等. 纳米银对猪链球菌体外抗菌活性及其生物膜形成的影响[J]. 中国畜牧兽医, 2022, 49(3): 1172-1180.
LIU Bao-ling, LI Chun-ling, JIANG Zhi-yong, et al. Effects of Silver Nanparticles on the Activity of Streptococcus Suis and Its Biofilm Formation in Vitro[J]. China Animal Husbandry & Veterinary Medicine, 2022, 49(3): 1172-1180.
[67] ROJVIROON T, SIRIVITHAYAPAKORN S. E. Bacteriostatic Action Using TiO_2 Photocatalytic Reactions[J]. International Journal of Photoenergy, 2018, 2018: 1-12.
[68] LIAO Xiao-gang, LI Gang, XIANG Xiao-qian, et al. Fabrication of Ag-incorporated TiO_2 Film on TiNb Substrate and Evaluation on Its Antibacterial Activity Against E.coli[J]. IOP Conference Series: Materials Science and Engineering, 2020, 729(1): 1-7.
[69] NIE Chuan-xiong, YANG Ye, CHENG Chong, et al. Bioinspired and Biocompatible Carbon Nanotube-Ag Nanohybrid Coatings for Robust Antibacterial Applications[J]. Acta Biomaterialia, 2017, 51: 479-494.
[70] 高红芳. 纳米银抗菌包装膜的制备及其保藏应用研究进展[J]. 保鲜与加工, 2020, 20(5): 225-230.
GAO Hong-fang. Research Progress on Preparation and Preservation of Nanosilver Antibacterial Packaging Film[J]. Storage and Process, 2020, 20(5): 225-230.
[71] HE Xiao-jia, HWANG H M. Nanotechnology in Food Science: Functionality, Applicability, and Safety Assessment[J]. Journal of Food and Drug Analysis, 2016, 24(4): 671-681.
[72] VOICU A I, GÂREA S A, GHEBAUR A, et al. New Nanocarriers Based on Porous Clay Heterostructures (PCH) Designed for Methotrexate Delivery[J]. Microporous and Mesoporous Materials, 2021, 328: 111434.
[73] ZARE M, NAMRATHA K, ILYAS S, et al. Smart Fortified PHBV-CS Biopolymer with ZnO-Ag Nanocomposites for Enhanced Shelf Life of Food Packaging[J]. ACS Applied Materials & Interfaces, 2019, 11(51): 48309-48320.
[74] 李炳坤, 王超丽, 陈鹏, 等. 载银介孔纳米二氧化硅复合抗菌材料的制备及其性能研究[J]. 南开大学学报(自然科学版), 2018, 51(2): 31-38.
LI Bing-kun, WANG Chao-li, CHEN Peng, et al. Preparation and Properties of Silver-Loaded Mesoporous Nano-Silica Composite Antibacterial Material[J]. Acta

Scientiarum Naturalium Universitatis Nankaiensis, 2018, 51(2): 31-38.

[75] SINGH S, SINGH G, BALA N, et al. Characterization and Preparation of Fe_3O_4 Nanoparticles Loaded Bioglass-chitosan Nanocomposite Coating on Mg Alloy and in Vitro Bioactivity Assessment[J]. International Journal of Biological Macromolecules, 2020, 151: 519-528.

[76] SOLMAZ S S, NIGMET U, KEVSER K. Clarification of Apple Juice Using New Generation Nanocomposite Membranes Fabricated with TiO_2 and Al_2O_3 Nanoparticles[J]. Food and Bioprocess Technology: An International Journal, 2020, 13(11): 391-403.

[77] CHEN Wei, ZHANG Jun-ying. Ag Nanoparticles Hosted in Monolithic Mesoporous Silica by Thermal Decomposition Method[J]. Scripta Materialia, 2003, 49(4): 321-325.

[78] HUANG Feng-hua, HUANG Tao, WU Xiang-wei, et al. Synthesis and Characterization of ZnSe: Ag/SiO_2 Nanoparticles[C]. E3S Web of Conferences. EDP Sciences, 2021, 261: 02063.

[79] CHARANJIT S B, AARON J D, XI Bao-juan et al. Preparation of Ag/TiO_2/SiO_2 Films Via Photo-ASSISTED Deposition and Adsorptive Self-assembly for Catalytic Bactericidal Application[J]. Applied Surface Science, 2014, 311: 582-592.

[80] KARTHIK C, CAROLINE D G, DHANAM P M, et al. Synthesis, Characterization of Ag-SiO_2 Nanocomposite and Its Application in Food Packaging[J]. Journal of Inorganic and Organometallic Polymers and Materials, 2021, 31(6): 2532-2541.

[81] WEI Xu-qing, LI Qiu-ying, WU Chao-ling, et al. Preparation, Characterization and Antibacterial Mechanism of the Chitosan Coatings Modified by Ag/ZnO Microspheres[J]. Journal of the Science of Food and Agriculture, 2020, 100(15): 5527-5538.

[82] LI Wan-ting, HUANG Zi-xuan, CAI Rui, et al. Rational Design of Ag/ZnO Hybrid Nanoparticles on Sericin/Agarose Composite Film for Enhanced Antimicrobial Applications[J]. International Journal of Molecular Sciences, 2020, 22(1): 105.

[83] RAJABOOPATHI S, THAMBIDURAI S. Synthesis of Bio-surfactant Based Ag/ZnO Nanoparticles for Better Thermal, Photocatalytic and Antibacterial Activity[J]. Materials Chemistry and Physics, 2019, 223: 512-522.

[84] LONG Xiao-yi, BAI Ling, XIAO Wei. Antibacterial and Preservation Effects of Silver-doped TiO_2 Nanoparticles on Nanfeng Citrus[J]. Agricultural Biotechnology, 2013, 2(04): 19-22.

[85] 阳元梦. 鱼明胶抗菌复合膜的制备与理化性能及其对草莓保鲜效果的研究[D]. 雅安: 四川农业大学, 2020: 22-43.
YANG Yuan-meng. Preparation and Physicochemical Properties of Fish Gelatin Antibacterial Composite Film and Its Preservation Effect on Strawberries[D]. Yaan: Sichuan Agricultural University, 2020: 22-43.

[86] LIN De-rong, YANG Yuan-meng, WANG Jie, et al. Preparation and Characterization of TiO(2)-Ag Loaded Fish Gelatin-Chitosan Antibacterial Composite Film for Food Packaging[J]. International Journal of Biological Macromolecules, 2020, 154: 123-133.

[87] 张冬梅, 王素雅, 杨茉, 等. Ag–SiO_2–TiO_2 纳米包装对新鲜绿竹笋储藏品质的影响[J]. 食品与发酵工业, 2020, 46(15): 147-153.
ZHANG Dong-mei, WANG Su-ya, YANG Mo, et al. Effect of Ag-SiO_2-TiO_2 Nano-Packaging on Storage Quality of Fresh Bamboo Shoots[J]. Food and Fermentation Industries, 2020, 46(15): 147-153.

[88] WEI Xu-qing, LI Qiu-ying, HAO Han, et al. Preparation, Physicochemical and Preservation Properties of Ti/ZnO/in Situ SiO_x Chitosan Composite Coatings[J]. Journal of the Science of Food and Agriculture, 2020, 100(2): 570-577.

[89] WANG Fan, HU Qiu-hui, MUGAMBI M A, et al. Effect of Nano Packaging on Preservation Quality of Nanjing 9108 Rice Variety at High Temperature and Humidity[J]. Food Chemistry, 2018, 239: 23-31.

[90] 马清华, 蔡铭, 谢春芳, 等. 聚乙烯醇基 SiO_2/TiO_2 纳米包装膜制备及对双孢菇保鲜效果[J]. 食品科学, 2020, 41(9): 182-187.
MA Qing-hua, CAI Ming, XIE Chun-fang, et al. Evaluation of Polyvinyl Alcohol-Based SiO_2/TiO_2 Nanocomposite Films and Their Preservation Effect on Agaricus Bisporus[J]. Food Science, 2020, 41(9): 182-187.

[91] SINGH S, PARK I S, SHIN Y, et al. Comparative Study on Antimicrobial Efficiency of $AgSiO_2$, ZnAg, and Ag-Zeolite for the Application of Fishery Plastic Container[J]. Iranian Journal of Materials Science and Engineering, 2015, 4(2169): 2169-0022.

[92] ELIAS E, SARATHCHANDRAN C, JOSEPH S, et al. Photoassisted Degradation of Rhodamine B Using Poly(E-Caprolactone) Based Nanocomposites: Mechanistic and Kinetic Features[J]. Journal of Applied Polymer Science, 2021, 138(26): 50612.

[93] YI Shi-xiong, SUN Sheng, ZHANG Y, et al. Scalable Fabrication of Bimetal Modified Polyacrylonitrile (PAN) Nanofibrous Membranes for Photocatalytic Degradation of Dyes[J]. Journal of Colloid and Interface Science, 2020, 559: 134-142.

[94] KUMAR S, YE F, DOBRETSOV S, et al. Chitosan Na-

nocomposite Coatings for Food, Paints, and Water Treatment Applications[J]. Applied Sciences, 2019, 9(12): 2409.
[95] SHAH K H, YAMEEN M A, YOUSAF T, et al. Adsorption of Bacteria by Highly Efficient, Economic and Biodegradable Magnetic Coated Chitosan Adsorbent[J]. Journal of Solution Chemistry, 2020, 49(11): 1304-1318.
[96] ZHANG Bin, LIU Yang, WANG Huan-huan, et al. Effect of Sodium Alginate-agar Coating Containing Ginger Essential Oil on the Shelf Life and Quality of Beef[J]. Food Control, 2021, 130: 108216.
[97] ZHAO Hang, ZHANG Liang, ZHENG Sen, et al. Bacteriostatic Activity and Cytotoxicity of Bacterial Cellulose-Chitosan Film Loaded with In-Situ Synthesized Silver Nanoparticles[J]. Carbohydrate Polymers, 2022, 281: 119017.
[98] GAO Dang-ge, CHANG Rui, LYU Bin, et al. Synthesis of Raspberry-like SiO_2/Polyacrylate Nanocomposite Latexes Via a One-step Miniemulsion Polymerization and Its Film Properties[J]. Journal of Sol-Gel Science and Technology, 2019, 92(3).
[99] LI Kun, ZHANG Min, BHANDARI B, et al. Improving Storage Quality of Refrigerated Steamed Buns by Mung Bean Starch Composite Coating Enriched with Nano-Emulsified Essential Oils[J]. Journal of Food Process Engineering, 2020, 43(9): e13475.
[100]麦馨允，陈庆金，谭彦妮，等. 魔芋葡甘聚糖/纳米 SiO_2 复合涂膜配方及其对芒果贮藏品质的影响[J]. 食品与发酵工业, 2018, 44(1): 177-184.
MAI Xin-yun, CHEN Qing-jin, TAN Yan-ni, et al. Effect of Konjac Glucomannan / Nano-Silica Composite Coating on the Quality of Mango Fruit[J]. Food and Fermentation Industries, 2018, 44(1): 177-184.
[101]GHOSH T, TERAMOTO Y, KATIYAR V. Influence of Nontoxic Magnetic Cellulose Nanofibers on Chitosan Based Edible Nanocoating: A Candidate for Improved Mechanical, Thermal, Optical, and Texture Properties[J]. Journal of Agricultural and Food Chemistry, 2019, 67(15): 4289-4299.
[102]王锋，赵旗峰，张晓萍，等. 壳聚糖–纳米 ZnO–褪黑素复合涂膜对黄瓜冷害的影响及其机制研究[J]. 食品与发酵工业, 2022, 48(9): 201-207.
WANG Feng, ZHAO Qi-feng, ZHANG Xiao-ping, et al. Effect of Chitosan-Nano-ZnO-Melatonin Composite Coating on Cucumber Chilling Injury and Mechanism[J]. Food and Fermentation Industries, 2022, 48(9): 201-207.
[103]EMAMIFAR A, BAVAISI S. Nanocomposite Coating Based on Sodium Alginate and Nano-ZnO for Extending the Storage Life of Fresh Strawberries (Fragaria× Ananassa Duch.)[J]. Journal of Food Measurement and Characterization, 2020, 14(2): 1012-1024.
[104]ARROYO B J, BEZERRA A C, OLIVEIRA L L, et al. Antimicrobial Active Edible Coating of Alginate and Chitosan Add ZnO Nanoparticles Applied in Guavas (Psidium Guajava L.)[J]. Food Chemistry, 2020, 309: 125566.
[105]MOHAMMADZADEH-VAZIFEH M, HOSSEINI S M, MOHAMMADI A, et al. Investigation of the Antimicrobial Properties of Nanoclay and Chitosan Based Nanocomposite on the Microbial Characteristics of Gouda Cheese[J]. Iranian Journal of Microbiology, 2020, 12(2): 121-126.
[106]蓝娛娛，韦蕾，杜良伟，等. 海藻酸钠—银纳米粒子涂膜保鲜香蕉研究[J]. 南方农业学报，2020, 51(7): 1584-1590.
LAN Yuan-yuan, WEI Lei, DU Liang-wei, et al. Preservation Effect of Sodium Alginate-Silver Nanoparticles Composite Coating on Banana[J]. Journal of Southern Agriculture, 2020, 51(7): 1584-1590.
[107]郭欣，邱小明，陈莲. 海藻酸钠/纳米 TiO_2 复合涂膜对采后番木瓜果实软化及细胞壁降解影响[J]. 食品研究与开发, 2021, 42(6): 28-32.
GUO Xin, QIU Xiao-ming, CHEN Lian. Effect of Sodium Alginate/Nano-TiO_2 Compound Coating on Softening and Cell Wall Degradation of Post-Harvest Papaya Fruit[J]. Food Research and Development, 2021, 42(6): 28-32.
[108]MAHCENE Z, KHELIL A, HASNI S, et al. Development and Characterization of Sodium Alginate Based Active Edible Films Incorporated with Essential Oils of some Medicinal Plants[J]. International Journal of Biological Macromolecules, 2020, 145: 124-132.
[109]GUPTA V K, SOOD S, AGARWAL S, et al. Antioxidant Activity and Controlled Drug Delivery Potential of Tragacanth Gum-Cl- Poly(lactic acid-co-itaconic acid) Hydrogel[J]. International Journal of Biological Macromolecules, 2018, 107: 2534-2543.
[110]NAZARZADEH Z E, MAKVANDI P, TAY F R. Recent Progress in the Industrial and Biomedical Applications of Tragacanth Gum: A Review[J]. Carbohydrate Polymers, 2019, 212: 450-467.
[111]ZHU Fan. Polysaccharide Based Films and Coatings for Food Packaging: Effect of Added Polyphenols[J]. Food Chemistry, 2021, 359: 129871.
[112]GALUS S, KADZIŃSKA J. Food Applications of Emulsion-based Edible Films and Coatings[J]. Trends in Food Science & Technology, 2015, 45(2): 273-283.
[113]ARNON R H, POVERENOV E. Improving Food Prod-

ucts' Quality and Storability by Using Layer by Layer Edible Coatings[J]. Trends in Food Science & Technology, 2018, 75: 81-92.

[114]KHANEGHAH A M, HASHEMI S M B, LIMBO S. Antimicrobial Agents and Packaging Systems in Antimicrobial Active Food Packaging: An Overview of Approaches and Interactions[J]. Food and Bioproducts Processing, 2018, 111: 1-19.

[115]KADAM D, MOMIN B, PALAMTHODI S, et al. Physicochemical and Functional Properties of Chitosan-Based Nano-Composite Films Incorporated with Biogenic Silver Nanoparticles[J]. Carbohydrate Polymers, 2019, 211: 124-132.

[116]苏英杰. 纳米埃洛石负载香芹酚气相缓释抗菌抗氧化包装膜制备[D]. 无锡: 江南大学, 2021: 14-49.
SU Ying-jie. Preparation of Nano-Halloysite-Loaded Carvacrol Gas-Phase Sustained-Release Antibacterial and Antioxidant Packaging Film[D]. Wuxi: Jiangnan University, 2021: 14-49.

[117]王和平. 海藻酸钠/壳聚糖 ZnO 复合材料的制备及其在药物缓释、食品保鲜中的应用研究[D]. 太原: 太原理工大学, 2019: 16-48.
WANG He-ping. Preparation of Sodium Alginate/Chitosan ZnO Composite and Its Application in Drug Sustained Release and Food Preservation[D]. Taiyuan: Taiyuan University of Technology, 2019: 16-48.

[118]JEEVAHAN J J, CHANDRASEKARAN M, VENKATESAN S P, et al. Scaling Up Difficulties and Commercial Aspects of Edible Films for Food Packaging: A Review[J]. Trends in Food Science & Technology, 2020, 100: 210-222.

[119]SAMI R, KHOJAH E, ELHAKEM A, et al. Performance Study of Nano/SiO_2 Films and the Antimicrobial Application on Cantaloupe Fruit Shelf-life[J]. Applied Sciences, 2021, 11(9): 3879.

[120]APJOK R, MIHALY C A, PETER A, et al. Active Packaging Based on Cellulose-chitosan-Ag/TiO_2 Nanocomposite for Storage of Clarified Butter[J]. Cellulose, 2019, 26(3): 1923-1946.

[121]CORREA P Z N, BAUTISTA B S, VAALLE M M Á, et al. The Effect of Nanostructured Chitosan and Chitosan-thyme Essential Oil Coatings on Colletotrichum Gloeosporioides Growth in Vitro and on Cv Hass Avocado and Fruit Quality[J]. Journal of Phytopathology, 2017, 165(5): 297-305.

[122]DE J S M E, VICENTE A, PINHEIRO A C, et al. Application of Edible Nanolaminate Coatings with Antimicrobial Extract of Flourensia Cernua to Extend the Shelf-life of Tomato (Solanum Lycopersicum L.) fruit[J]. Postharvest Biology and Technology, 2019, 150: 19-27.

[123]GONZÁLEZ S A, BARRERA N L L, VENTURA A R I, et al. Extension of the Postharvest Quality of Bell Pepper by Applying Nanostructured Coatings of Chitosan with Byrsonima Crassifolia Extract (L.) Kunth[J]. Postharvest Biology and Technology, 2019, 149: 74-82.

[124]罗爱国, 庆祎帆, 胡变芳, 等. 纳米二氧化硅改性藻多糖与壳聚糖复合膜的性能研究[J]. 食品工业科技, 2022, 43(9): 243-250.
LUO Ai-guo, QING Yi-fan, HU Bian-fang, et al. Properties of Nano-Silica Modified Spirulina Platensis Polysaccharide and Chitosan Composite Film[J]. Science and Technology of Food Industry, 2022, 43(9): 243-250.

[125]陆刚. 聚乙烯塑料性能特点及其注塑工艺详解[J]. 塑料包装, 2017, 27(6): 51-54.
LU Gang. Performance Characteristics of Polyethylene Plastics and Its Injection Molding Process[J]. Plastics Packaging, 2017, 27(6): 51-54.

[126]TAJEDDIN B, AZADSHAHRAKI F, RAFIEE D Z. The Effect of Modified Atmosphere Packaging on the Shelf-Life of Greenhouse-Grown Tomato[J]. Journal of Food Biosciences and Technology, 2020, 10(2): 75-90.

[127]何奎, 贠建民, 毕阳, 等. 纳米膜包装真姬菇贮藏期间挥发性风味成分变化分析[J]. 食品科学, 2021, 42(20): 160-166.
HE Kui, YUN Jian-min, BI Yang, et al. Changes of Volatile Flavor Components in Hypsizygus Marmoreus Packaged with Nano-Film during Storage[J]. Food Science, 2021, 42(20): 160-166.

[128]徐庭巧, 魏云潇, 王毅, 等. 纳米碳酸钙改性聚乙烯膜对杨梅贮藏品质和生理的影响[J]. 现代食品科技, 2016, 32(10): 205-210.
XU Ting-qiao, WEI Yun-xiao, WANG Yi, et al. Effects of Nano-$CaCO_3$-Modified Low-Density Polyethylene Films Packaging on the Quality and Physiology of Chinese Bayberry[J]. Modern Food Science and Technology, 2016, 32(10): 205-210.

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