

徐重新, 谢雅晶, 何鑫, 等. 凝集素在农业和食品领域中的应用研究进展[J]. 江苏农业学报, 2022, 38(4): 1135-1144.
doi: 10.3969/j.issn.1000-4440.2022.04.033

凝集素在农业和食品领域中的应用研究进展

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摘要: 凝集素是一类能与糖及糖类物质特异性非共价可逆结合的蛋白质或糖蛋白,广泛存在于动植物和微生物体内。部分凝集素具有抗虫、抗菌、抗病毒以及靶向识别特定微生物种类等功能,因而成为农业绿色防控和食品防腐保鲜及致病微生物筛查检测领域研究的热点。本文系统梳理了国内外有关凝集素在农业病虫害防控、农业生产调节、食源性致病微生物防控及筛查检测等方面的应用研究状况,并探讨了其在这些方面的应用前景、存在问题及解决问题的对策,旨在为农业绿色防控和食品防腐保鲜及农产品质量安全检测研究提供最新的文献资料和思路。

关键词: 凝集素; 农作物病虫害; 农业生物防控; 食源性致病微生物; 食品质量安全

中图分类号: Q946.1 **文献标识码:** A **文章编号:** 1000-4440(2022)04-1135-10

Research progress of the application of lectin in agriculture and food

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Abstract: Lectin is a kind of protein or glycoprotein which can combine with sugars and saccharides in a specific, non-covalent and reversible manner, and it is widely found in animals, plants and microorganisms. Partial lectins have the functions of anti-insect, anti-bacterial, anti-virus and targeted recognition of specific microbial species. Therefore, they have become the research focus in the fields of agricultural green prevention and control, food anti-corrosion and preservation, and screening and detection of pathogenic microorganisms. In this paper, the application and research status of lectins in the prevention and control of agricultural diseases and pests, regulation of agricultural production, and prevention, control, screening and detection of foodborne pathogenic microorganisms were systematically reviewed. The application prospect, existing problems and solutions were also discussed to provide the latest references and potential innovative ideas for agricultural green prevention and control, food anti-corrosion and preservation and quality safety testing research of agricultural products.

Key words: lectin; crop diseases and pests; agricultural biological control; foodborne pathogenic microorganisms; food quality safety

收稿日期: 2021-12-25

基金项目: 国家自然科学基金项目(31972292, 31701724, 31630061)

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凝集素(Lectin)是广泛存在于自然界生物体内非免疫来源的一类具有特异性非共价靶向可逆结合糖及糖类分子的蛋白质或糖蛋白类物质,其来源广、种类多,具有巨大的应用潜力:不仅可以作为研究细胞膜结构的工具,也能充当类似“抗体”角色对靶标受体进行“免疫”治疗、诊断或检测。有研究结果表明,在生物医药、农业病虫害以及食品防腐保鲜的新

材料创制领域,可以借助凝集素凝集细胞、结合或抑制特定功能性糖蛋白、糖脂等功能,研发抗癌^[1]、抗虫^[2]、抗病菌^[3-4]、抗氧化^[5]及促进作物生长发育^[6]的新型蛋白质或糖蛋白类药物;也可以利用凝集素对糖及糖类分子具有多价结合的能力,通过偶联生物素、荧光素、酶、铁蛋白、胶体金及磁珠颗粒等示踪性或特征性功能物质,用于诊断或示踪病症^[7]以及对致病微生物进行筛查检测^[8]等。

农业和食品是民生的基础,关乎国计民生。病虫害和致病微生物是威胁农业生产和食品安全的最关键危害物,传统依赖化学农药对病虫害的防控和依赖抗生素类化学药物对致病微生物的防控,尽管有效,但它们带来的毒副作用也相当严重,不仅危害人类健康更威胁生态安全^[9-10]。绿色生产及防控是农业和食品生产可持续健康发展的必然要求,近年来持续受到政府决策部门和学术界的高度重视。凝集素是农业和食品绿色生产及防控创新材料挖掘和利用的重点研究对象,近年来在农业病虫害

防控和食源性致病微生物防控及筛查检测等方面的研究蓬勃发展。基于此,本文通过系统梳理凝集素在农业病虫害防控及农业生产调节、食源性致病微生物防控及筛查检测等方面的相关研究状况,进一步探讨有关凝集素应用技术、最新研究动向以及未来可能的发展趋势,以期凝集素在农业和食品领域中的应用研究提供参考。

1 凝集素在农业领域中的应用研究

1.1 防控农业病害

近年来凝集素已成为农业病害绿色防控新材料挖掘的新兴热点,部分研究成果逐渐展示出直接或潜在的应用价值。目前凝集素在农业病害防控中的应用研究,主要聚焦在植物凝集素上,动物和微生物凝集素也有所涉及,防控对象以农作物中的真菌性病害(如赤霉病、黑斑病、纹枯病、软腐病等)为主,而对畜牧和水产业病害的防控研究则相对较少;相关代表性应用研究实例如表 1 所示。

表 1 凝集素在农业病害防控上的代表性应用研究实例

Table 1 Representative application of lectins in agricultural disease control

凝集素类型	来源	防控对象	应用效果	参考文献
植物凝集素	小麦(<i>Triticum aestivum</i>)	禾谷镰刀菌	对禾谷镰刀菌抑制率可达 77.77%	[11]
	鹰嘴豆(<i>Chickpea</i>)	白菜黑斑病	鹰嘴豆凝集素转基因芥菜对白菜黑斑病防控效果达到 36%~60%,同时还能适应高盐及干旱胁迫	[12]
	大蒜(<i>Allium sativum</i>)	水稻纹枯病	大蒜凝集素突变体转基因水稻能有效抵御水稻纹枯病,发病率降低了 55%	[13]
	埃及麻风树(<i>Jatropha curcas</i>)	尖孢镰刀菌	对尖孢镰刀菌具有一定抑菌活性,其最低抑菌质量浓度为 70 $\mu\text{g/ml}$	[14]
	向日葵(<i>Sunflower</i>)	向日葵菌核病	能与向日葵菌核病原菌孢子表面相互作用,诱导氧化应激,导致菌核病原菌细胞死亡	[15]
	马齿苋(<i>Portulaca elatior</i>)	胡萝卜软腐病	能强烈抑制胡萝卜软腐病原菌生长繁殖,最低抑菌质量浓度为 0.185 $\mu\text{g/ml}$	[16]
动物凝集素	鸡(<i>Chicken</i>)	鸡支气管炎	对鸡支气管炎病原具有较强的抗病毒活性	[17]
	蛇(<i>Bothrops pauloensis</i>)	畜牧弓形虫病	能有效抑制刚地弓形虫活力,从而减弱虫体入侵宿主细胞的能力	[18]
微生物凝集素	墨汁鬼伞菌(<i>Coprinopsis cinerea</i>)	灰葡萄霉病菌、丁香假单胞菌	墨汁鬼伞菌凝集素转基因拟南芥对 2 种常见农作物病原菌灰葡萄霉病菌和丁香假单胞菌具有显著抗性	[19]
	绣球菌菇(<i>Sparassis latifolia</i>)	尖孢镰刀菌、腐皮镰刀菌	能明显抑制尖孢镰刀菌和腐皮镰刀菌菌丝萌发和生长	[20]
	茶树菇(<i>Agrocybe aegerita</i>)	烟草花叶病毒	对烟草花叶病毒抑制率可达 84.3%	[21]

1.2 防控农业虫害

虫害对农业特别是种植业生产及其产品质量安全与品质的威胁程度几乎可与病害比肩,对害虫的有效防控是确保农业稳产、增产必不可少的重要手段。凝集素是探寻和挖掘新型生物抗虫材料领域关注的重点,相关研究发展蓬勃。目前有关凝集素在农业虫害防控中的应

用研究,已涵盖动植物源和微生物源凝集素,其中尤以植物凝集素最多且应用最广;而就防控对象而言,已涉及种植业中常见害虫种类,如线虫、蚜虫、棉铃虫、象虫以及螟类、蛾类、粉虱和粉蚧类害虫等,部分研究成果已作为生物农药制剂或转基因抗虫作物开始应用于对靶标害虫的防控。相关代表性应用研究实例如表 2 所示。

表 2 凝集素在农业虫害防控上的代表性应用研究实例

Table 2 Representative application of lectins in agriculture pest control

凝集素类型	来源	防控对象	应用效果	参考文献
植物凝集素	扁豆(Lentil)	芥菜蚜虫	扁豆凝集素与鹰嘴蛋白酶抑制剂融合蛋白质转基因芥菜对蚜虫幼虫抑制率达 40%	[22]
	大豆(Soybean)	小麦蚜虫	对蚜虫的防控率达到 50%	[23]
	蔓草虫豆(<i>Cajanus scarabaeoides</i>)	棉铃虫	显著抑制棉铃虫幼虫的生长发育	[24]
	大蒜(<i>Allium sativum</i>)	黄茎螟、折叶螟、褐飞虱	大蒜凝集素与 Bt Cry 毒素融合蛋白质转基因水稻对供试害虫具有明显致死作用	[25]
		棉铃虫、粉虱	大蒜凝集素与 Bt Vip3Aa 毒素串联融合蛋白质转基因棉对棉铃虫致死率达到 78%~100%;对粉虱致死率达到 95%	[26]
	洋葱(Onion)	棉花粉蚧、桃蚜、烟粉虱	洋葱凝集素与蜘蛛神经毒素融合蛋白质转基因烟草对供试害虫致死率达到 100%	[27]
		烟草粉蚧	洋葱凝集素转基因烟草对粉蚧室内生测致死率达到 80%以上	[28]
	春蓼(<i>Polygonum persicaria</i>)	芥菜粉蝶幼虫	显著抑制芥菜粉蝶幼虫生长发育(体质量低于正常虫体 12.5%),明显降低幼虫存活率	[29]
		棉铃虫	显著降低棉铃虫幼虫的体质量和存活率	[30]
	斑龙芋(<i>Sauromatum guttatum</i>)	瓜实蝇	有效抑制瓜实蝇的化蛹率和羽化率,分别比对照(100%)降低 44.0%和 7.9%	[31]
	半夏(<i>Pinellia pedatisecta</i>)	小麦蚜虫	半夏凝集素转基因小麦能显著抑制蚜虫生长和繁殖,防控率达 50%	[32]
	药西瓜(<i>Citrullus colocynthis</i>)	石榴螟	明显抑制石榴螟产卵率和孵化率	[33-34]
	辣木(<i>Moringa oleifera</i>)	地中海粉螟	能破坏地中海粉螟幼虫肠道细胞、影响消化酶活性,显著抑制虫体生长发育	[35]
	单蕊羊蹄甲(<i>Bauhinia monandra</i>)	地中海粉螟、豆象	能抑制 3 种害虫幼虫生长发育,对它们的致死率均能达到 50%以上	[36]
	苋菜(<i>Amaranthus caudatus</i>)	棉蚜	苋菜凝集素与雪花莲凝集素串联融合蛋白质转基因棉对棉蚜的抑制率可达 36.0%~55.5%	[37]
	雪花莲(<i>Galanthus nivalis</i>)	甜菜夜蛾、云杉色卷蛾	雪花莲凝集素与 RNA 干扰(RNAi)联合应用,能显著提升 RNAi 对 2 种供试昆虫的致死率	[38]
		棉花蚜、小菜蛾	雪花莲凝集素转基因拟南芥和转基因棉对小菜蛾和棉花蚜的致死率均显著提高	[39]
	水仙(<i>Narcissus tazetta</i>)	小麦蚜虫	水仙凝集素转基因小麦对小麦蚜虫的致死率达到 53.1%~59.4%	[40]
	美洲格尼帕树(<i>Genipa americana</i>)	赤拟谷盗	含有美洲格尼帕树凝集素的植物提取物对赤拟谷盗幼虫孵化的抑制率高达 96.3%	[41]
	南非醉茄(<i>Withania somnifera</i>)	全须夜蛾、印度红蜡	南非醉茄凝集素能破坏 2 种昆虫的中肠细胞,中断消化过程,抑制生长发育	[42]
	巴西胡椒木(<i>Schinus terebinthifolius</i>)	玉米象	对玉米象的防控率接近 40%	[43]
动物凝集素	海绵(<i>Fasciospongia cavernosa</i>)	豇豆蚜、花生蚜	海绵凝集素对豇豆蚜和花生蚜具有较强的致死作用	[44]
微生物凝集素	小皮伞菌(<i>Marasmius oreades</i>)	甜菜孢囊线虫、南方根结线虫、小菜蛾	小皮伞菌凝集素转基因拟南芥对甜菜孢囊线虫防治率最高达 93%,且能明显抑制南方根结线虫虫卵萌发,抑制小菜蛾幼虫生长发育	[45]
	墨汁鬼伞菌(<i>Coprinopsis cinerea</i>)	秀丽隐杆线虫、黑腹果蝇	对秀丽隐杆线虫和黑腹果蝇均具有明显毒性	[46]
	立枯丝核菌(<i>Rhizoctonia solani</i> Kühn)	大菜粉蝶	能抑制大菜粉蝶的消化酶活性,从而干扰虫体生长发育	[47]
	齐整小核菌(<i>Sclerotium rolfsii</i>)	番茄根结线虫	能明显提升番茄对根结线虫的抗性水平,促进植株生长	[48]
		棉蚜、斜纹夜蛾	齐整小核菌转基因棉对棉蚜和斜纹夜蛾的最高防控率分别达到 69%和 100%	[49]
		斜纹夜蛾、桃蚜	齐整小核菌转基因烟草对斜纹夜蛾和桃蚜的最高防控率分别达到 90.0%和 81.9%	[50]

1.3 在农业领域其他方面的应用

目前凝集素在农业领域的应用研究主要集中在防控农业病虫害上,此外在农作物生长调节、品种抗逆性改良、产地环境治理等方面也有报道。其中 Sousa 等^[51]从黄野百合中分离的凝集素能有效促进针叶樱桃花粉管形成从而促进更多的花粉萌发,有利于提高针叶樱桃产量; Alenkina 等^[52-53]从固氮螺菌中分离出的凝集素能调节小麦幼苗根系抗氧化酶活性,提升植株对异常气温、干旱以及盐胁迫的适应能力,促进作物生长和细胞生物量积累; Kumar 等^[12]将鹰嘴豆凝集素基因导入芥菜植株, Lambin 等^[54]将卫矛凝集素基因导入水稻植株,均能增强相应转基因作物对干旱和高盐等逆境的抗性,促进农作物在逆境胁迫中生长发育,而 Sreevidya 等^[55]将源于豌豆和野大豆的 2 个凝集素基因导入水稻,能极大促进根瘤菌在转基因水稻根系的定殖,从而促进侧根增殖,有利于作物生长;李丹彤等^[56]以裙带菜凝集素注射日本对虾,田园等^[57]以刀豆凝集素投喂菲律宾蛤仔,发现供试生物体的血细胞吞噬活性

和溶菌酶、碱性磷酸酶及超氧化物歧化酶等功能蛋白酶活性显著提升,均能明显提高机体非特异性免疫力,对水产养殖具有重要价值;而 Freitas 等^[58]依托水溶性辣木凝集素联合硫酸铝使污水样品的浊度和生态毒性显著降低,且该凝集素能同步降低铝离子残留量,从而减少投入品产生的次生污染,这对农田和水产环境治理具有重要意义。

2 凝集素在食品领域中的应用研究

2.1 防控食源性致病微生物

食源性致病微生物是引起食物腐败变质、诱发食物中毒的最主要因素,是食品质量监管和防控的重要对象^[59]。目前均有有用动植物和微生物凝集素防控食源性致病微生物的报道,其中动植物凝集素较多,防控对象则以食源性致病细菌(金黄色葡萄球菌、大肠杆菌、李斯特菌、沙门氏菌等)为主,也略有涉及食源性真菌(霉菌、念珠菌、酵母菌等),目前的研究尚未涉及食源性病毒。供试的凝集素抑菌效果参差不齐,相关代表性应用研究实例如表 3 所示。

表 3 凝集素在食源性致病微生物防控上的代表性应用研究实例

Table 3 Representative application of lectins in foodborne pathogenic microorganisms control

凝集素类型	来源	防控对象	防控效果	参考文献
植物凝集素	石榴(<i>Punica granatum</i>)	李斯特菌	能有效抑制李斯特菌生长,破坏生物膜的形成,促进菌体细胞死亡	[60]
	药用植物马缨丹(<i>Lantana camara</i>)	大肠杆菌、黑曲霉	对大肠杆菌和黑曲霉的抑菌圈直径分别达到 6.9 mm 和 12.0 mm	[61]
	辣木(<i>Moringa oleifera</i>)	荧光假单胞菌、蜡样芽孢杆菌、黏质沙雷氏菌	对供试致病菌均具有明显的抑制活性	[62]
	红果仔(<i>Eugenia uniflora</i>)	金黄色葡萄球菌、大肠杆菌	能明显抑制金黄色葡萄球菌和大肠杆菌的生长繁殖	[63]
		金黄色葡萄球菌、绿脓杆菌、克雷伯氏菌、大肠杆菌	能强烈抑制 3 种致病菌,最低抑菌质量浓度均为 1.5 $\mu\text{g/ml}$;对大肠杆菌有一定抑制作用,最低抑菌质量浓度为 16.5 $\mu\text{g/ml}$	[64]
	短沟对虾(<i>Penaeus semisulcatus</i>)	副溶血性弧菌、嗜水气单胞菌	对副溶血性弧菌和嗜水气单胞菌均具有一定的抑制作用	[65]
动物凝集素	海绵(<i>Fasciospongia cavernosa</i>)	青霉菌、白色念珠菌	对青霉菌和白色念珠菌具有较强的抑制作用	[44]
	菲律宾蛤仔(<i>Puditapes philippinarum</i>)	腐败希瓦氏菌	通过影响腐败希瓦氏菌体内氨基酸合成、丙酮酸代谢和柠檬酸循环等抑制其生长	[66]
	香港牡蛎(<i>Crassostrea hongkongensis</i>)	溶藻弧菌	能显著抑制溶藻弧菌生长	[67]
	梭子蟹(<i>Portunus pelagicus</i>)	变形杆菌、铜绿假单胞菌、粪肠球菌、短小芽孢杆菌	与银纳米颗粒螯合物对 4 种食源性致病微生物均具有抗菌活性	[68]
	中华绒螯蟹(<i>Eriocheir sinensis</i>)	金黄色葡萄球菌、大肠杆菌	其质量浓度达到 150 mg/ml 时,对 2 种致病菌具有强烈抑制作用	[69]
	蘑菇(<i>Sparassis latifolia</i>)	铜绿假单胞菌、大肠杆菌、金黄色葡萄球菌、白色念珠菌	对铜绿假单胞菌、大肠杆菌、金黄色葡萄球菌的最低抑菌质量浓度分别为 50 $\mu\text{g/ml}$ 、100 $\mu\text{g/ml}$ 、200 $\mu\text{g/ml}$,同时还能明显抑制白色念珠菌菌丝萌发和生长	[20]
微生物凝集素	鼠李糖乳杆菌(<i>Lactobacillus rhamnosus</i>)	大肠杆菌、沙门氏菌	能有效抑制大肠杆菌和沙门氏菌生物膜形成,从而抑制菌体活性	[70]

2.2 筛查检测食源性致病微生物

食源性致病微生物筛查检测方法主要分为通过微生物活体培养方式鉴定的生物法和基于微生物细胞或特征性物质的免疫学、光谱学、核酸、生物传感等方式检测的生化法两大类型^[71]。依托凝集素对食源性致病微生物的筛查检测均属于生化法,主要是借助凝集素具有凝集或沉淀特定微生物细胞、结

合或识别微生物细胞表面特定蛋白质或糖蛋白类物质等功能而实现的。目前的研究动植物源凝集素均有涉及,而以植物凝集素为主,其中研究和应用最多的是大豆凝集素和麦胚凝集素,筛查检测对象涵盖大肠杆菌、金黄色葡萄球菌、沙门氏菌、李斯特菌、粪肠球菌、变形链球菌、甲型肝炎病毒以及弓形虫卵囊等。相关代表性应用研究实例如表4所示。

表4 凝集素在食源性致病微生物检测上的代表性应用实例

Table 4 Representative application of lectins in foodborne pathogenic microorganisms detection

凝集素类型	来源	名称	检测对象	检测效果	参考文献
植物凝集素	洋刀豆 (<i>Canavalia ensiformis</i>)	刀豆蛋白 A 凝集素	沙门氏菌	基于刀豆蛋白 A 凝集素的微流控和恒温扩增技术,对沙门氏菌的最低检出限为 5 CFU/ml	[72]
			粪肠球菌、沙门氏菌、大肠杆菌、变形链球菌	基于刀豆蛋白 A 凝集素的纳米化学电阻阵列法,对粪肠球菌、沙门氏菌、大肠杆菌、变形链球菌的最低检出限分别为 25.0 CFU/ml、6.3×10 ² CFU/ml、4.7×10 ³ CFU/ml 和 7.4×10 ⁴ CFU/ml	[73]
				刀豆蛋白 A 凝集素经磁珠-甘露糖复合物修饰的双色流式细胞法对大肠杆菌的最低检出限为 7 CFU/ml	[74]
				刀豆蛋白 A 凝集素与铂-石墨烯-铂偶联的生物传感器对大肠杆菌的最低检出限为 39 CFU/ml	[75]
			大肠杆菌	基于刀豆蛋白 A 凝集素的比色传感技术对大肠杆菌的最低检出限为 41 CFU/ml	[76]
				基于刀豆蛋白 A 凝集素的电化学阻抗生物传感器对大肠杆菌的最低检出限为 75 CFU/ml	[77]
				基于刀豆蛋白 A 凝集素-ZnO 纳米阵列的荧光成像技术对大肠杆菌的最低检出限为 90 CFU/ml	[78]
	扁豆 (<i>Lens culinaris</i>)	扁豆凝集素	金黄色葡萄球菌、大肠杆菌	扁豆凝集素与银纳米颗粒融合对金黄色葡萄球菌和大肠杆菌的最低检出限分别为 5×10 ³ CFU/ml 和 5×10 ⁴ CFU/ml	[79]
	大豆(Soybean)	大豆凝集素	甲型肝炎病毒	基于大豆凝集素偶联磁珠分离并结合 RT-PCR 法对甲型肝炎病毒的线性检测范围是 1~10 ³ PFU/ml	[80]
	银白齿凤梨 (<i>Hechtia argentea</i>)	银白齿凤梨凝集素	沙门氏菌	基于银白齿凤梨凝集素的阻抗滴定生物传感器对沙门氏菌的最低检出限为 5 CFU/ml	[81]
	小麦 (<i>Triticum vulgare</i>)	麦胚凝集素	金黄色葡萄球菌、李斯特菌	基于麦胚凝集素的表面增强拉曼光谱技术对金黄色葡萄球菌和李斯特菌的最低检出限分别为 3 CFU/ml 和 5 CFU/ml	[82]
			李斯特菌	基于麦胚凝集素的表面等离子体共振技术对李斯特菌的最低检出限为 100 μl 3.25 CFU	[83]
			大肠杆菌	基于麦胚凝集素的电化学阻抗免疫传感器技术对大肠杆菌的最低检出限为 1×10 ² CFU/ml	[84]
				基于麦胚凝集素的表面等离子体共振生物传感技术对大肠杆菌的最低检出限为 3×10 ³ CFU/ml	[85]
			金黄色葡萄球菌	麦胚凝集素与银纳米颗粒融合对金黄色葡萄球菌的最低检出限为 1×10 ³ CFU/ml	[79]
				麦胚凝集素偶联多孔硅生物传感器对金黄色葡萄球菌的最低检出限为 1×10 ³ CFU/ml	[86]
			弓形虫卵囊	麦胚凝集素趋磁分离方法能可视化检测水体中的弓形虫卵囊	[87]
动物凝集素	鸡蛋壳 (Hen egg shell)	C 型凝集素	金黄色葡萄球菌	鸡蛋壳 C 型凝集素偶联 Ag-CdSe 量子点的检测方法对金黄色葡萄球菌的检测范围是 1×10 ³ ~1×10 ⁷ CFU/ml	[88]

2.3 在食品领域其他方面的应用

目前凝集素在食品抗氧化保鲜以及污染物消减等方面也有一些直接或间接的研究报道。如杨晴晴

等^[89]将菲律宾蛤仔凝集素作为保鲜剂用于小黄鱼冷藏,其感官评价要好于对照组,且鱼体菌落总数、pH 值、挥发性盐基氮和硫代巴比妥酸含量都显著低

于对照组; Carrasco-Castilla 等^[90]分离的菜豆凝集素、Saha 等^[91]分离的扁豆凝集素、Lacerda 等^[92]分离的巴西利马豆凝集素和 Wu 等^[5]分离的褐藻羊栖菜凝集素均具有较强的抗氧化活性, 由于它们源于食用农产品的属性特征, 因此均有望作为抗氧化剂用于食品保鲜。此外 Freitas 等^[58]分离的水溶性辣木凝集素对水体除浊和絮凝沉降毒性物质具有良好的辅助作用, Rajalakshmi 等^[93]分离的马钱子凝集素对水体中的氟离子具有良好絮凝清除作用, 这些凝集素均有望用于饮用水中相应危害物的消减或清除, 从而提升饮用水及水产养殖产品的质量安全水平。

3 展望

凝集素作为蛋白质或糖蛋白类物质在助推农业生产和保障农产品、食品质量安全方面具有独特的优势和极大的应用潜力, 但在实际应用过程中也普遍存在如表达制备困难、生物活性不强、稳定性较差等一系列有待进一步解决的共性短板问题。

在农业领域方面, 凝集素的优势主要集中在病虫害防控上, 特别是具备特殊生物学功能的蛋白质类凝集素, 不仅可以通过离体药剂形式用于靶标病虫害防控, 也可以通过转基因手段培育抗病虫害作物品种, 能最大程度发挥其应用价值。不过原始离体的凝集素甚至其转基因作物在病虫害防控效果上仍然不尽如人意, 绝大多数尚不足以与同等功效的化学农药相媲美; 特别是在害虫防控上, 效果普遍较差, 防控率大多为 30%~50%^[22-23, 29, 31-32, 37, 40, 43], 甚至更低^[24, 30, 33-35, 48]。目前改进其活性最直接的方式就是串联其他活性更好的生物材料, 如 Bt 抗虫蛋白^[26]、蜘蛛神经毒素^[27], 不仅可以增强对靶标害虫的联合防控效果, 同时也能减少或延缓靶标害虫抗性发生频率。此外借鉴抗体体外改造技术如基因水平上的定点突变^[94]、易错 PCR^[95]和蛋白质翻译后的泛素化修饰^[96]、糖基化修饰^[97]等, 从分子水平上对凝集素进行成熟修饰, 也是提升其活性的潜在有效手段。

在食品领域方面, 凝集素在食源性致病微生物防控和检测上的应用研究较多, 而在抗氧化保鲜上的研究较少。值得注意的是, 相当一部分凝集素对金黄色葡萄球菌、大肠杆菌、李斯特菌、沙门氏菌、芽孢杆菌、霉菌等常见的食源性致病微生物具有或多或少的广谱抗菌作用^[4, 20, 44, 62-64, 68-70], 其在食品防腐

保鲜上具有良好的应用前景。食品质量关乎老百姓“吃”的大事, 因此对凝集素作为食品防腐保鲜剂使用的安全性和必要性上可能更谨慎, 目前在中国尚无这类产品作为食品添加剂登记使用。尽管如此, 随着对凝集素的深入研究, 未来在充分的风险评估数据支撑的前提下, 特别是源于可食用生物体如刀豆^[4]、菜豆^[90]、扁豆^[91]、马齿苋^[16]、虾^[65]、牡蛎^[67]、褐藻羊栖菜^[5]等的食源性凝集素势必为业界和社会大众所接受, 在食品防腐保鲜上率先发挥应有价值。而对于食源性致病微生物的筛查检测, 无论是在物种特异性精度还是在灵敏度上, 基于凝集素的检测方法均无法与同等功效的抗体免疫法和仪器分析法相比^[71], 基于凝集素的检测优势主要体现在对致病微生物的活体筛查以及由其介导或辅助改善的创新生物传感法上, 其中涉及刀豆凝集素和麦胚凝集素的研究最多, 有望在实际应用中取得突破。

参考文献:

- [1] MAJEED M, HAKEEM K R, REHMAN R U. Mistletoe lectins: from interconnecting proteins to potential tumour inhibiting agents [J]. *Phytomedicine Plus*, 2021, 1(3): 100039.
- [2] LACERDA J T, LACERDA R R, ASSUNCAO N A, et al. New insights into lectin from *Abelmoschus esculentus* seeds as a kunitz-type inhibitor and its toxic effects on *Ceratitis capitata* and root-knot nematodes *Meloidogyne* spp. [J]. *Process Biochemistry*, 2017, 63: 96-104.
- [3] SONG P W, ZHANG L F, WU L L, et al. A ricin B-like lectin protein physically interacts with TaPFT and is involved in resistance to fusarium head blight in wheat [J]. *Phytopathology*, 2021, 111(12): 2309-2316.
- [4] JIN X, LEE Y J, HONG S H. Canavalia ensiformis-derived lectin inhibits biofilm formation of enterohemorrhagic *Escherichia coli* and *Listeria monocytogenes* [J]. *Journal of Applied Microbiology*, 2019, 126(1): 300-310.
- [5] WU M J, TONG C Q, WU Y, et al. A novel thyroglobulin-binding lectin from the brown alga *Hizikia fusiformis* and its antioxidant activities [J]. *Food Chemistry*, 2016, 201: 7-13.
- [6] HE Z Y, ZOU T, XIAO Q, et al. An L-type lectin receptor-like kinase promotes starch accumulation during rice pollen maturation [J]. *Development*, 2021, 148(6): 196378.
- [7] SILVA M L S. Lectin-based biosensors as analytical tools for clinical oncology [J]. *Cancer Letters*, 2018, 436: 63-74.
- [8] MI F, GUAN M, HU C M, et al. Application of lectin-based biosensor technology in the detection of foodborne pathogenic bacteria: a review [J]. *Analyst*, 2021, 146(2): 429-443.
- [9] SHARMA A, KUMAR V, SHAHZAD B, et al. Worldwide pesti-

- cide usage and its impacts on ecosystem [J]. SN Applied Sciences, 2019, 1(11): 1446.
- [10] BEN Y, FU C, HU M, et al. Human health risk assessment of antibiotic resistance associated with antibiotic residues in the environment: a review [J]. Environmental Research, 2019, 169: 483-493.
 - [11] ALSALOOM A N. Biochemical characterization of wheat seed lectin and its antifungal activity against seed-borne *Fusarium graminearum* *in-vitro* and *in-situ* [J]. Pakistan Journal of Botany, 2021, 53(2): 741-747.
 - [12] KUMAR D, SHEKHAR S, BISHT S, et al. Ectopic overexpression of lectin in transgenic *Brassica juncea* plants exhibit resistance to fungal phytopathogen and showed alleviation to salt and drought stress [J]. Journal of Bioengineering and Biomedical Science, 2015, 5(1): 147-154.
 - [13] GHOSH P, SEN S, CHAKRABORTY J, et al. Monitoring the efficacy of mutated *Allium sativum* leaf lectin in transgenic rice against *Rhizoctonia solani* [J]. BMC Biotechnology, 2016, 16: 24-33.
 - [14] AL-SAMAN M A, FARFOUR S A, TAYEL A A, et al. Bioactivity of lectin from Egyptian *Jatropha curcas* seeds and its potentiality as antifungal agent [J]. Global Advanced Research Journal of Microbiology, 2015, 4(7): 87-97.
 - [15] RIO M D, CANAL L, PINEDO M, et al. Internalization of a sunflower mannose-binding lectin into phytopathogenic fungal cells induces cytotoxicity [J]. Journal of Plant Physiology, 2018, 221: 22-31.
 - [16] SILVA S P, SILVA J D, COSTA C B, et al. Purification, characterization, and assessment of antimicrobial activity and toxicity of *Portulaca elatior* leaf lectin (PeLL) [J]. Probiotics and Antimicrobial Proteins, 2021, <https://doi.org/10.1007/s12602-021-09837>.
 - [17] ZHANG W, BOUWMAN K M, BEURDEN S J, et al. Chicken mannose binding lectin has antiviral activity towards infectious bronchitis virus [J]. Virology, 2017, 509: 252-259.
 - [18] CASTANHEIRA L, SOUZA D L, SILVA R J, et al. Insights into anti-parasitism induced by a C-type lectin from *Bothrops pauloensis* venom on *Toxoplasma gondii* [J]. International Journal of Biological Macromolecules, 2015, 74: 568-574.
 - [19] MORADI A, EL-SHETEHY M, GAMIR J, et al. Expression of a fungal lectin in *Arabidopsis* enhances plant growth and resistance toward microbial pathogens and a plant-parasitic nematode [J]. Frontiers in Plant Science, 2021, 12: 657451.
 - [20] CHANDRASEKARAN G, LEE Y C, PARK H, et al. Antibacterial and antifungal activities of lectin extracted from fruiting bodies of the Korean cauliflower medicinal mushroom, *Sparassis latifolia* (Agaricomycetes) [J]. International Journal of Medicinal Mushrooms, 2016, 18(4): 291-299.
 - [21] SUN H, ZHAO C G, TONG X, et al. A lectin with mycelia differentiation and antiphytovirus: activities from the edible mushroom *Agrocybe aegerita* [J]. Journal of Biochemistry and Molecular Biology, 2003, 36(2): 214-222.
 - [22] RANI S, SHARMA V, HADA A, et al. Fusion gene construct preparation with lectin and protease inhibitor genes against aphids and efficient genetic transformation of *Brassica juncea* using cotyledons explants [J]. Acta Physiologiae Plantarum, 2017, 39(5): 115-127.
 - [23] 周英, 谢红卫, 刘长爱, 等. 豆科凝集素基因 *Le4* 的克隆及其表达产物对蚜虫的抗性 [J]. 基因组学与应用生物学, 2016, 35(12): 3474-3480.
 - [24] NGUGI-DAWIT A, HOANG T M, WILLIAMS B, et al. A wild *Cajanus scarabaeoides* L., Thouars, IBS 3471, for improved insect-resistance in *Cultivated Pigeonpea* [J]. Agronomy, 2020, 10(4): 517-531.
 - [25] BODDUPALLY D, TAMIRISA S, GUNDRAS R, et al. Expression of hybrid fusion protein (Cry1Ac; ASAL) in transgenic rice plants imparts resistance against multiple insect pests [J]. Scientific Reports, 2018, 8(1): 8458.
 - [26] DIN S U, AZAM S, RAO A Q, et al. Development of broad-spectrum and sustainable resistance in cotton against major insects through the combination of *Bt* and plant lectin genes [J]. Plant Cell Reports, 2021, 40(4): 707-721.
 - [27] JAVAID S, AMIN I, JANDER G, et al. A transgenic approach to control hemipteran insects by expressing insecticidal genes under phloem-specific promoters [J]. Scientific Reports, 2016, 6: 34706.
 - [28] AHMED M, SHAH A D, RAUF M, et al. Ectopic expression of the *Leptochloa fusca* and *Allium cepa* lectin genes in tobacco plant for resistance against Mealybug (*Phenococcus solenopsis*) [J]. Journal of Genetics and Genomes, 2017, 1(2): 108-114.
 - [29] ZIBAE A, ALBORZI Z, KARIMI-MALATI A, et al. Effects of a lectin from *Polygonum Persicaria* L. on *Pieris Brassicae* L. (Lepidoptera: Pieridae) [J]. Journal of Plant Protection Research, 2014, 54(3): 250-257.
 - [30] RAHIMI V, HAJIZADEH J, ZIBAE A, et al. Toxicity and physiological effects of an extracted lectin from *Polygonum persicaria* L. on *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae) [J]. Physiological and Molecular Plant Pathology, 2018, 101: 38-44.
 - [31] KAUR M, THAKUR K, KAMBOJ S S, et al. Assessment of *Saurum guttatum* lectin toxicity against *Bactrocera cucurbitae* [J]. Journal of Environmental Biology, 2015, 36(6): 1263-1268.
 - [32] DUAN X, HOU Q, LIU G, et al. Expression of *Pinellia pedatisecta* lectin gene in transgenic wheat enhances resistance to wheat aphids [J]. Molecules, 2018, 23(4): 748-757.
 - [33] RAMZI S, SAHRAGARD A, SENDI J J, et al. Effect of *Citrullus colocynthis* L. (Cucurbitaceae) agglutinin on gene expression of caspases in *Ectomyelois ceratoniae* Zeller (Lepidoptera: Crambidae) [J]. Journal of Entomological and Acarological Research, 2016, 48(3): 304-307.
 - [34] RAMZI S, SAHRAGARD A, SENDI J J, et al. Effect of *Citrullus colocynthis* (Cucurbitaceae) agglutinin on the life table parameters

- of *Apomyelois ceratoniae* (Lepidoptera: Pyralidae) [J]. Journal of Crop Protection, 2015, 5(1): 19-31.
- [35] OLIVEIRA C F R, MOURA M C, NAPOLEAO T H, et al. A chitin-binding lectin from *Moringa oleifera* seeds (WSMoL) impairs the digestive physiology of the Mediterranean flour larvae, *Anagasta kuehniella* [J]. Pesticide Biochemistry and Physiology, 2017, 142: 67-76.
- [36] MACEDO M L, FREIRE M, SILVA M B, et al. Insecticidal action of *Bauhinia monandra* leaf lectin (BmoLL) against *Anagasta kuehniella* (Lepidoptera: Pyralidae), *Zabrotes subfasciatus* and *Callosobruchus maculatus* (Coleoptera: Bruchidae) [J]. Comparative Biochemistry and Physiology, 2007, 146(4): 486-498.
- [37] 赵亚楠, 李刚强, 王楠, 等. 转 GNA 和 ACA 双基因抗蚜虫棉花新材料的创制 [J]. 分子植物育种, 2021, 19(20): 6731-6740.
- [38] MARTINEZ Z, SCHUTTER K D, DAMME E J, et al. Accelerated delivery of dsRNA in lepidopteran midgut cells by a *Galanthus nivalis* lectin (GNA)-dsRNA-binding domain fusion protein [J]. Pesticide Biochemistry and Physiology, 2021, 175: 104853.
- [39] HE P, WU S, TIAN L, et al. Expression of modified snowdrop lectin (*Galanthus nivalis* agglutinin) protein confers insect resistance in *Arabidopsis* and cotton [J]. Research Square, 2020, <https://doi.org/10.21203/rs.3.rs-32036/v1>.
- [40] DUAN X, HOU Q. Expression of two synthetic lectin genes sGNA and sNTL in transgenic wheat enhanced resistance to aphids [J]. Research Journal of Biotechnology, 2015, 10(7): 11-18.
- [41] LIMA J K, CHICUTA C P, COSTA M M, et al. Biototoxicity of aqueous extract of *Genipa americana* L. bark on red flour beetle *Tribolium castaneum* (Herbst) [J]. Industrial Crops and Products, 2020, 156: 112874.
- [42] GEORGE B S, SILAMBARASAN S, SENTHIL K, et al. Characterization of an insecticidal protein from *Withania somnifera* against Lepidopteran and Hemipteran pest [J]. Molecular Biotechnology, 2018, 60(4): 290-301.
- [43] CAMAROTI J R, ALMEIDA W A, BELMONTE B R, et al. Sitophilus zeamais adults have survival and nutrition affected by *Schinus terebinthifolius* leaf extract and its lectin (SteLL) [J]. Industrial Crops and Products, 2018, 116: 81-89.
- [44] SADANANDAN R, RAUF A A. Antifungal and insecticidal activity of a lectin isolated from marine sponge *Fasciospongia cavernosa* [J]. Journal of Advances in Biological Science, 2021, 8(1): 19-25.
- [45] MORADI A, AUSTERLITZ T, DAHLIN P, et al. Marasmius oreades agglutinin enhances resistance of *Arabidopsis* against plant-parasitic nematodes and a herbivorous insect [J]. BMC Plant Biology, 2021, 21(1): 402-411.
- [46] BLEULER-MARTINEZ S, STUTZ K, SIEBER R, et al. Dimerization of the fungal defense lectin CCL2 is essential for its toxicity against nematodes [J]. Glycobiology, 2017, 27(5): 486-500.
- [47] ALBORZI Z, ZIBAEI A, RAMZI S, et al. Effects of the two extracted agglutinins from *Rhizoctonia solani* Kühn (Cantharellales; Ceratobasidiaceae) on digestive A-amylase of *Pieris brassicae* L. (Lepidoptera: Pieridae) [J]. Journal of Nutrition and Food Sciences, 2016, 6(4): 526-532.
- [48] BHAGAT Y S, BHAT R S, KOLEKAR R M, et al. *Remusatia vivipara* lectin and *Sclerotium rolfsii* lectin interfere with the development and gall formation activity of *Meloidogyne incognita* in transgenic tomato [J]. Transgenic Research, 2019, 28(3/4): 299-315.
- [49] VANTI G L, KATAGERI I S, INAMDAR S R, et al. Potent insect gut binding lectin from *Sclerotium rolfsii* impart resistance to sucking and chewing type insects in cotton [J]. Journal of Biotechnology, 2018, 278: 20-27.
- [50] VANTI G L, VISHWANATHREDDY V H, BHAT G G, et al. *Sclerotium rolfsii* lectin expressed in tobacco confers protection against *Spodoptera litura* and *Myzus persicae* [J]. Journal of Pest Science, 2015, 89(2): 591-602.
- [51] SOUSA A S, REGAO E J L, SANTOS F A. Viability and action of CPL lectin on *in vitro* germinability of pollen grains of *Malpighia emarginata* DC. (Malpighiaceae) [J]. American Journal of Plant Sciences, 2013, 4(7): 53-58.
- [52] ALENKINA S A, ROMANOV N I, NIKITINA V E. Regulation by *Azospirillum* lectins of the activity of antioxidant enzymes in wheat seedling roots under short-term stresses [J]. Brazilian Journal of Botany, 2018, 41(3): 579-587.
- [53] ALENKINA S A, KUPRYASHINA M A. Influence of *Azospirillum* lectins on the antioxidant system response in wheat seedling roots during abiotic stress [J/OL]. Soil Research, 2021, <https://doi.org/10.1071/SR21092>.
- [54] LAMBIN J, ASCI S D, DUBIEL M, et al. OsEUL lectin gene expression in rice: stress regulation, subcellular localization and tissue specificity [J]. Frontiers in Plant Science, 2020, 11: 185-200.
- [55] SREEVIDYA V S, HERNANDEZ-OANE R J, SO R B, et al. Expression of the legume symbiotic lectin genes *psl* and *gs52* promotes rhizobial colonization of roots in rice [J]. Plant Science, 2005, 169(4): 726-736.
- [56] 李丹彤, 张静, 陈国栋, 等. 裙带菜凝集素对日本对虾非特异性免疫因子的影响 [J]. 大连水产学院学报, 2009, 24(3): 274-278.
- [57] 田园, 李莹, 张艳丽, 等. 外源刀豆凝集素对菲律宾蛤仔免疫机能的影响 [J]. 现代农业科技, 2020, 27(8): 221-223.
- [58] FREITAS J, SANTANA K V, NASCIMENTO A C C, et al. Evaluation of using aluminum sulfate and water-soluble *Moringa oleifera* seed lectin to reduce turbidity and toxicity of polluted stream water [J]. Chemosphere, 2016, 163: 133-141.
- [59] 徐重新, 张存政, 刘媛, 等. 食源性致病微生物危害风险及其防控用抗菌生物活性肽研究进展 [J]. 生物技术通报, 2019, 35(7): 202-212.
- [60] SILVA P M, SILVA J N O, SILVA B R, et al. Antibacterial

- effects of the lectin from pomegranate sarcotesta (PgTeL) against *Listeria monocytogenes* [J]. Journal of Applied Microbiology, 2021, 131(2): 671-681.
- [61] HIREMATH K Y, JAGADEESH N, BELUR S, et al. A lectin with anti-microbial and anti proliferative activities from *Lantana camara*, a medicinal plant[J]. Protein Expression and Purification, 2020, 170: 105574.
- [62] MOURA M C, NAPOLEAO T H, CORIOLANO M C, et al. Water-soluble *Moringa oleifera* lectin interferes with growth, survival and cell permeability of corrosive and pathogenic bacteria [J]. Journal of Applied Microbiology, 2015, 119(3): 666-676.
- [63] FERREIRA R S, NAPOLEAO T H, SANTOS A F, et al. Coagulant and antibacterial activities of the water-soluble seed lectin from *Moringa oleifera* [J]. Letters in Applied Microbiology, 2011, 53(2): 186-192.
- [64] OLIVEIRA M D, ANDRADE C A, SANTOS-MAGALHAES N S, et al. Purification of a lectin from *Eugenia uniflora* L. seeds and its potential antibacterial activity [J]. Letters in Applied Microbiology, 2008, 46(3): 371-376.
- [65] PREETHAM E, LAKSHMI S, WONGPANYA R, et al. Antibiofilm and immunological properties of lectin purified from shrimp *Penaeus semisulcatus* [J]. Fish and Shellfish Immunology, 2020, 106: 776-782.
- [66] 杨晴晴,金祎雯,李 伟,等. 基于蛋白质组学的菲律宾蛤仔凝集素(CL-T)抑制腐败希瓦氏菌机理研究[J]. 大连海洋大学学报, 2021, 36(4): 653-660.
- [67] 赵泽慧,爱 娇,杨雨澄,等. 香港牡蛎(*Crassostrea hongkongensis*)新型凝集素 ChPerlucin 的基因克隆与功能研究[J]. 热带海洋学报, 2022, 41(1): 42-51.
- [68] JAYANTHI S, SHANTHI S, VASEEHARAN B, et al. Growth inhibition and antibiofilm potential of Ag nanoparticles coated with lectin, an arthropod immune molecule [J]. Journal of Photochemistry and Photobiology B: Biology, 2017, 170: 208-216.
- [69] FANG Z Y, LI D, LI X J, et al. A single CRD C-type lectin from *Eriocheir sinensis* (EsLecB) with microbial-binding, antibacterial prophenoloxidase activation and hem-encapsulation activities [J]. Fish and Shellfish Immunology, 2016, 50: 175-190.
- [70] PETROVA M I, IMHOLZ N C, VERHOEVEN T L, et al. Lectin-like molecules of *Lactobacillus rhamnosus* GG inhibit pathogenic *Escherichia coli* and *Salmonella* biofilm formation [J]. PLoS One, 2016, 11(8): e0161337.
- [71] SARAVANAN A, KUMAR P S, HEMAVATHY R V, et al. Methods of detection of food-borne pathogens: a review [J]. Environmental Chemistry Letters, 2021, 19(1): 189-207.
- [72] DAO T N T, YOON J, JIN C E, et al. Rapid and sensitive detection of *Salmonella* based on microfluidic enrichment with a label-free nanobiosensing platform [J]. Sensors Actuators B: Chemical, 2018, 262: 588-594.
- [73] SAUCEDO N M, GAO Y, PHAM T, et al. Lectin-and saccharide-functionalized nano-chemiresistor arrays for detection and identification of pathogenic bacteria infection [J]. Biosensors, 2018, 8(3): 63-73.
- [74] HE X, ZHOU L, HE D, et al. Rapid and ultrasensitive *E. coli* O157:H7 quantitation by combination of ligandmagnetic nanoparticles enrichment with fluorescent nanoparticles based two-color flow cytometry [J]. Analyst, 2011, 136(20): 4183-4191.
- [75] ANN G C. Real-time detection of *Escherichia coli* using biosensors functionalized with lectin and carbon-hydrogel nanostructures [D]. Texas (USA): Texas A & M University, 2016.
- [76] XU X H, YUAN Y W, HU G X, et al. Exploiting pH-regulated dimer-tetramer transformation of concanavalin A to develop colorimetric biosensing of bacteria [J]. Scientific Reports, 2017, 7(1): 1-8.
- [77] YANG H Y, ZHOU H F, HAO H Y, et al. Detection of *Escherichia coli* with a label-free impedimetric biosensor based on lectin functionalized mixed self-assembled monolayer [J]. Sensors Actuators B: Chemical, 2016, 229: 297-304.
- [78] ZHENG L, WAN Y, QI P, et al. Lectin functionalized ZnO nanoarrays as a 3D nano-biointerface for bacterial detection [J]. Talanta, 2017, 167: 600-606.
- [79] MIKAELIAN M V, POGHOSYAN G G, HENDRICKSON O D, et al. Wheat germ agglutinin and *Lens culinaris* agglutinin sensitized anisotropic silver nanoparticles in detection of bacteria: a simple photometric assay [J]. Analytica Chimica Acta, 2017, 981: 80-85.
- [80] KO S M, KWON J, VAIDYA B, et al. Development of lectin-linked immunomagnetic separation for the detection of hepatitis A virus [J]. Viruses, 2014, 6(3): 1037-1048.
- [81] LOPEZ-TELLEZ J, SANCHEZ-ORTEGA I, HORNUNG-LEONI CT, et al. Impedimetric biosensor based on a *Hechtia argentea* lectin for the detection of *Salmonella* spp. [J]. Chemosensors, 2020, 8(4): 115-126.
- [82] CHENG S, TU Z, ZHENG S, et al. An efficient SERS platform for the ultrasensitive detection of *Staphylococcus aureus* and *Listeria monocytogenes* via wheat germ agglutinin-modified magnetic SERS substrate and streptavidin/aptamer co-functionalized SERS tags [J]. Analytica Chimica Acta, 2021, 1187: 339155.
- [83] RAGHU H V, KUMAR N. Rapid detection of *Listeria monocytogenes* in milk by surface plasmon resonance using wheat germ agglutinin [J]. Food Analytical Methods, 2020, 13(4): 982-991.
- [84] LI Z, FU Y, FANG W, et al. Electrochemical impedance immunosensor based on self-assembled monolayers for rapid detection of *Escherichia coli* O157:H7 with signal amplification using lectin [J]. Sensors, 2015, 15(8): 19212-19224.
- [85] WANG Y, Y E C, SI Z F, et al. Monitoring of *Escherichia coli* O157:H7 in food samples using lectin based surface plasmon resonance biosensor [J]. Food Chemistry, 2013, 136(3/4): 1303-1308.
- [86] YAGHOUBI M, RAHIMI F, NEGAHDARI B, et al. A lectin-coupled porous silicon-based biosensor: label-free optical detection of

- bacteria in a real-time mode [J]. Scientific Reports, 2020, 10 (1): 16017.
- [87] HARITO J B, CAMPBELL A T, TYSNES K R, et al. Use of lectin-magnetic separation (LMS) for detecting *Toxoplasma gondii* oocysts in environmental water samples [J]. Water Research, 2017, 127: 68-76.
- [88] HOVHANNISYAN V A, BAZUKYAN I L, GASPARYAN V K. Application of silver nanoparticles and CdSe quantum dots sensitized with of C-like lectin for detection of *St. aureus*. comparison of various approaches [J]. Talanta, 2017, 175: 366-369.
- [89] 杨晴晴, 陈悦, 李伟, 等. 菲律宾蛤仔凝集素在小黄鱼保鲜中的应用研究 [J]. 江苏农业科学, 2018, 46(20): 219-221.
- [90] CARRASCO-CASTILLA J, HERNANDEZ-ÁLVAREZ A J, JIMENEZ-MARTINEZ C, et al. Antioxidant and metal chelating activities of *Phaseolus vulgaris* L. var. Jamapa protein isolates, phaseolin and lectin hydrolysates [J]. Food Chemistry, 2012, 131(4): 1157-1164.
- [91] SAHA R K, TUHIN S H M, ROY N J, et al. Antibacterial and antioxidant activities of a food lectin isolated from the seeds of *Labiab purpureous* [J]. American Journal of Ethnomedicine, 2014, 24(1): 8-17.
- [92] LACERDA E L, NASCIMENTO E S, LACERDA J T, et al. Lectin from seeds of a Brazilian lima bean variety (*Phaseolus lunatus* L. var. cascavel) presents antioxidant, antitumour and gastroprotective activities [J]. International Journal of Biological Macromolecules, 2017, 95: 1072-1081.
- [93] RAJALAKSHMI B S, VASANTHY M, RAJAKANNAN V, et al. Defluoridation of water with a coagulant, *Strychnos potatorum* L. seed-agglutinin [J]. Environmental Technology & Innovation, 2021, 24: 101983.
- [94] ZHANG A, NAKANISHI J. Improved anti-cancer effect of epidermal growth factor-gold nanoparticle conjugates by protein orientation through site-specific mutagenesis [J]. Science and Technology of Advanced Materials, 2021, 22(1): 616-626.
- [95] SINHA R, SHUKLA P. Current trends in protein engineering: updates and progress [J]. Current Protein and Peptide Science, 2019, 20(5): 398-407.
- [96] GUI W, DAVIDSON G A, ZHUANG Z. Chemical methods for protein site-specific ubiquitination [J]. RSC Chemical Biology, 2021, 2(2): 450-467.
- [97] ZHANG Q, LI L, LAN Q, et al. Protein glycosylation: a promising way to modify the functional properties and extend the application in food system [J]. Critical Reviews in Food Science and Nutrition, 2019, 59(15): 2506-2533.

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