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谷物多酚的提取及在水产品保鲜中的应用

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摘要:谷物多酚多以游离态或结合态的形式存在,包含酚酸和黄酮两大类,其含量受谷物品种、萌芽情况、加工方式和贮藏条件等因素影响。谷物多酚的提取方法主要有酸法、碱法、酶解法和超临界流体萃取法等。文章围绕影响谷物多酚种类、提取方式及其含量与效价等的因素进行了综述,并对其在水产品保鲜中的应用进行了展望。

关键词:谷物多酚;游离酚;结合酚;生物活性;水产品保鲜

Extraction of cereal polyphenols and their application in aquatic products

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Abstract: Cereal polyphenols mainly exist in free or bound states, including two major categories: phenolic acids and flavonoids. Their contents are affected by factors including cereal varieties, germination conditions, processing methods, and storage conditions. The extraction methods of cereal polyphenols are mainly acid, alkali, enzymatic hydrolysis, and supercritical fluid extraction methods. This paper reviews factors affecting the cereal polyphenol types, extraction methods, contents, and titers. Additionally, this paper looks forward to their application in aquatic product preservation.

Keywords: grain polyphenol; free phenol; bound phenol; biological activity; aquatic product preservation

谷物是中国的主要粮食作物,包括玉蜀黍、麦类、稻谷、高粱等,其除含有碳水化合物、维生素、脂肪、蛋白质等营养成分外,还富含活性肽、γ-氨基丁酸、多酚等活性物质[1]。谷物多酚以游离态或结合态形式存在于麸皮、胚芽和胚乳等部位,具有调控肠道菌群[2]、降糖降脂[3]、抗病毒[4]和抗氧化[5]等生物功效。随着人们对化学型食品添加剂的担忧与日俱增,谷物多酚作为一种天然抗氧化剂和抗菌剂,在食品保鲜中的应用前景日益广阔。文章拟围绕谷物多酚的种类、含量和提取,从谷物品种、谷物发芽、物理加工、化学加工、贮藏条件等影响谷物多酚含量的因素出发,从抗氧化、抗菌等生物功能活性视角,挖掘其在食品保鲜中的潜在应用,以期为谷物多酚在水产品保鲜中的高效利用提供依据。

1 谷物多酚的种类与分布

1.1 谷物多酚的存在状态及化学分类

多酚是一类在自然界中广泛存在的生物活性物质,通常以游离态和结合态两种形式存在[6]。游离态多酚可直接溶于水或有机溶剂,结合态多酚可与谷物细胞壁中的纤维

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素、木质素或蛋白质等成分结合紧密[7],通常需要通过化学或酶解方法才能释放出来[8]。谷物中的多酚种类繁多,主要包括酚酸、黄酮、花青素等[9]。多酚主要以酚酸的形式存在,如在大麦籽粒中,酚酸类物质占多酚类化合物的69%~85%[10]。青稞籽粒中主要的多酚为没食子酸、苯甲酸、丁香酸、4-香豆酸、柚皮素、橙皮苷、芦丁、(+)-儿茶素和槲皮素[11]。玉米中的酚酸类物质大多以结合态形式存在,黄酮和花色苷类物质则主要以游离态形式存在[12]。绿豆的游离酚占比较高,主要为芦丁、槲皮素、槲皮苷和四羟黄酮,其中芦丁含量最高[13]。豌豆多酚主要有白杨素、山奈酚、槲皮素、对香豆酸、芥子酸、阿魏酸和儿茶素[14]。

酚酸包括水杨酸和羟基肉桂酸两类衍生物[15]。水杨酸衍生物主要包括对羟基苯甲酸、儿茶酸、香草酸、丁香酸和没食子酸[16];羟基肉桂酸衍生物包括香豆酸、咖啡酸、阿魏酸和芥子酸[17]。这些酚酸类化合物在谷物的抗氧化防御机制中发挥重要作用,同时也为谷物提供了独特的风味和颜色。其中,阿魏酸是一种重要的酚酸类化合物,广泛存在于谷物中,尤其是在小麦、玉米和燕麦等谷物的麸皮中含量较高,束缚态的阿魏酸含量显著高于水溶态和脂溶态[18]。

除酚酸类化合物外,黄酮类化合物也是谷物中重要的多酚类型。黄酮类化合物包括黄酮、黄酮醇、黄烷醇等,其在谷物的抗氧化防御机制中发挥重要作用[19]。例如,芦丁是一种广泛存在于谷物中的常见黄酮类化合物,具有显著的抗氧化和抗炎活性[20]。此外,花青素类化合物可赋予谷物鲜艳的颜色[21],同时也具有抗氧化和抗菌特性[22]。花青素的含量和种类因谷物品种和生长环境的不同而存在显著差异,例如在一些有色谷物中,花青素含量较高[23]。常见的谷物多酚化合物的分类如表1所示。

1.2　谷物多酚的分布

谷物多酚的分布因谷物种类、品种和生长环境的不同而存在显著差异。不同谷物中多酚的种类和含量各有特点,这与其生物学功能和代谢途径密切相关。大部分多酚,如黄烷醇和阿魏酸,主要集中在谷物的最外层[48],分布于谷物细胞壁中[49],其可有效抑制微生物的生长和氧化反应的发生[50],是谷物抵御外界病原体和环境胁迫的第一道防线。其中,阿魏酸不仅具有抗氧化活性,还可与谷物中的木质素结合,以增强细胞壁的结构稳定性[35]。花青素主要分布在谷物的糊粉层[45]。此外,多酚在谷物中的分布也与其生物合成途径密切相关,如酚酸类物质的生物合成主要发生在谷物的次生代谢过程中,而黄酮类化合物则更多地与谷物的光合作用和抗氧化防御机制相关[51]。这些多酚化合物在抗氧化、抗炎和抗菌等方面表现出显著的生物活性,在食品保鲜和医药领域潜在应用价值较大。

2　谷物多酚含量的影响因素

2.1　谷物品种

不同谷物品种其多酚含量差异显著。例如,西藏野生大麦的多酚含量显著高于栽培大麦[52]。16种不同品种、22种不同样本啤酒大麦中,多酚含量及相关酶活性因品种特性和生长、种植条件的不同而表现出显著差异[53]。西藏野生大麦不仅比栽培大麦具有更高的多酚浓度,还表现出更广泛的遗传多样性[54]。栽培大麦的多酚含量为0.19~0.75 mg/g,其频率分布接近正态分布,而野生大麦中的多酚含量约为栽培大麦平均值的两倍[55]。此外,同一品种谷物的不同部位多酚含量也存在差异。例如,青稞麸皮中的结合多酚种类最多,其次为青稞全谷物,而青稞米中的多酚种类最少[56]。

谷物颜色也会显著影响其多酚含量。例如,裸大麦中多酚的含量因颜色的不同而各异,总酚酸和总黄酮含量分别在黑色和白色样品中达到最高[57]。赵萌萌等[58]研究发现,黑色藜麦的游离酚和结合酚含量最高,其次是红色藜麦,白色藜麦的多酚含量最低。蓝青稞中主要的酚酸类型为肉桂酸多酚,而黑、黄、紫青稞中以苯甲酸多酚为主;黑、蓝青稞中主要的黄酮类化合物分别为查尔酮和黄酮,而黄、紫青稞中以黄酮醇为主[59]。此外,在黑豆芽中,异黄酮和多酚含量最高,黄豆芽次之,绿豆芽最低[60]。综上,谷物的品种、部位和颜色均对其多酚含量和组成具有重要影响。

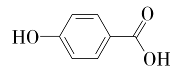
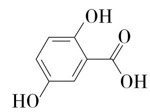
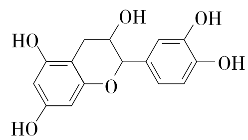
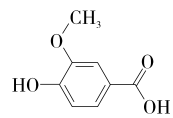
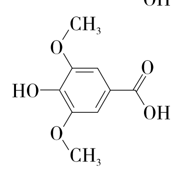
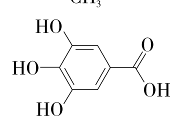
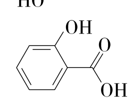
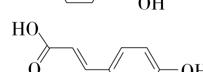
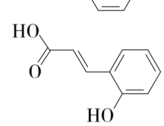
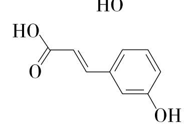
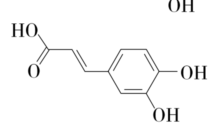
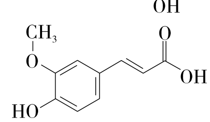
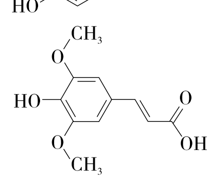
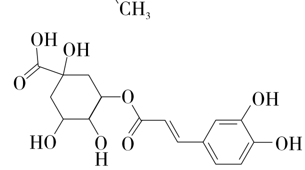
2.2　谷物发芽

萌芽能提高谷物中多酚的含量,同时增加游离酚在总多酚中的占比。例如,啤酒大麦发芽前后,其多酚含量及游离酚和结合酚组分均发生了显著变化,发芽后大麦的多酚含量普遍高于发芽前[61]。此外,发芽还会显著影响大麦粗多酚、单体酚酸的种类和含量,以及其抗氧化活性[62]。Gan等[63]研究表明,黑小麦在发芽3~8 d后,其游离酚和结合酚的抗氧化活性及多酚含量均显著提高。在大麦萌发过程中,酶的代谢活动会导致籽粒和叶柄中黄酮类化合物含量减少,而胚根中黄酮类化合物含量增加[64]。燕麦经发芽处理后,有39种多酚差异代谢物上调,其多酚含量显著高于未发芽的原麦[65],这与萌发能够显著增加燕麦中游离酚、结合酚和总多酚含量的结论一致[66]。

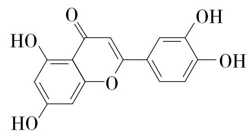
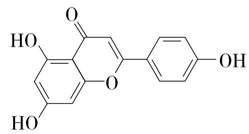
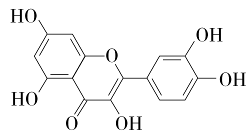
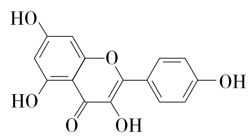
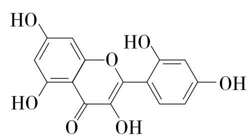
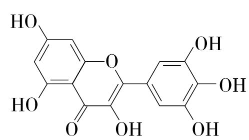
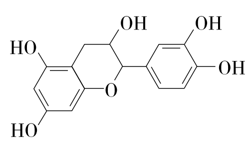
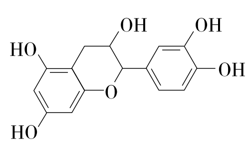
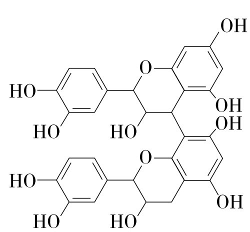
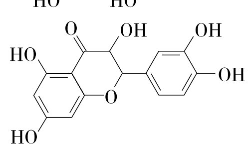
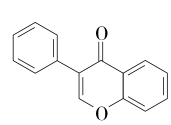
在谷物萌芽过程中,环境胁迫如干旱胁迫、盐胁迫以及超声协同萌发等均会对多酚含量产生影响。例如,干旱胁迫能够不同程度地增加中亚大麦籽粒中多酚的含量[67]。而辐照强度和干旱胁迫对青大麦中多酚含量均有显著影响[68]。同时,萌发处理及超声波协同萌发处理被认为是富集黑青稞多酚及提高抗氧化活性的有效手段[69]。在谷物生长初期,多酚含量呈上升趋势,而在生长后期多酚含量会有所下降。例如,小麦在生长初期多酚含量呈升高趋势,但在12~15 d后显著降低[70]。玉米在鲜食期的多酚含量也高于完熟期[12]。

表 1　谷物多酚的化学分类

Table 1　Chemical classification of grain polyphenols

种类	分类	名称	结构	来源及功能活性	文献
酚酸类	水杨酸衍生物	对羟基苯甲酸		植物、微生物和土壤中常见的有机酸，具有抗菌消炎等生物活性	［24］
		龙胆酸		乙酰水杨酸的代谢产物，对癌症有一定的预防作用	［25－26］
		儿茶酸		从天然植物中提取出来的一类酚类活性物质，具有延缓衰老、控制肥胖、抗菌等作用	［27］
		香草酸		香草醛生物合成途径中的前体物质，可通过诱导自噬，缓解 PA 诱导的 HepG2 细胞脂肪变性	［28］
		丁香酸		木质素降解的副产物，具有潜在的抗糖化、抗高血糖、保护神经和增强记忆的特性	［29－30］
		没食子酸		通常由单宁酸分解制得，具有改善心力衰竭病例中的心脏功能障碍和纤维化等作用	［31］
		水杨酸		植物次生代谢产物，具有抗胆固醇活性	［32］
	肉桂酸衍生物	对香豆酸		一种常见的膳食多酚，以共轭和游离形式存在于水果、蔬菜和谷物中，具有抗高血压、抗炎、抗癌、抗菌、抗糖尿病、抗癌和抗氧化作用等多种药理学活性	［33］
		邻香豆酸			
		间香豆酸			
		咖啡酸		植物代谢过程中产生的苯丙素类化合物，具有预防癌症、糖尿病、动脉粥样硬化、阿尔茨海默病及抗微生物感染等生物活性	［34］
		阿魏酸		作为谷物中常见的酚酸，既具有抗氧化活性，还可与谷物中的木质素结合，增强细胞壁的结构稳定性	［35］
		芥子酸		黑麦、小麦等谷物麸皮中天然存在的酚酸类化合物，具有抗炎、抗癌、保护肝脏、保护心脏等药理学活性	［36］
	其他	绿原酸		植物体内咖啡酸与奎宁酸通过酯化反应形成的次级代谢产物，具有抗氧化、抗菌和调节糖脂代谢等生物活性	［37］

续表1

种类	分类	名称	结构	来源及功能活性	文献
黄酮类	黄酮	木犀草素		谷物表皮中伴随木质素生物合成产生的黄酮类化合物,具有细胞毒性、抗炎、抗氧化和抗菌等多种生物活性	[38]
		芹菜素		在谷物胚芽中通过苯丙烷代谢途径生成,具有预防糖尿病、恶性肿瘤等慢性疾病的作用	[39]
	黄酮醇	槲皮素		由类黄酮代谢途径合成,具有降血糖、抗氧化、抗炎和抗过敏等重要生物活性	[40]
		山奈酚		一种主要的类黄酮苷元,具有抗微生物、抗炎、抗氧化、抗肿瘤、保护心脏、保护神经和抗糖尿病等多种药理学特性	[41]
		桑色素		谷物发酵过程中由黄酮类前体转化的次级代谢产物,可通过调控活性氧生成诱导肿瘤细胞凋亡	[42]
		杨梅素		谷物籽粒中微量存在的黄酮类化合物,具有调节血糖代谢及改善胰岛素抵抗的生理功能	[43]
	黄烷醇	儿茶素		儿茶素和表儿茶素是高粱等谷物中多酚氧化酶催化生成的多酚类物质,可有效抑制蛇毒磷脂酶A2活性	[44]
		表儿茶素			
		原花青素 B_2		花青素类化合物是谷物糊粉层中由苯丙氨酸代谢途径合成的色素成分,兼具抗氧化和抗菌特性	[21, 45]
	二氢黄酮醇	花旗松素		谷物共生微生物代谢产生的黄酮类化合物,对炎症、肿瘤及代谢性疾病具有广泛抑制活性	[46]
	异黄酮类	异黄酮		经异戊二烯途径合成的植物雌激素,在激素相关疾病防治及癌症化学预防中具有应用价值	[47]

2.3 物理加工

剪切作用、煮制、高压、臭氧、紫外线处理以及辐射等物理加工方式均会对谷物中多酚的种类和含量造成影响。例如,挤压处理会对小麦胚芽的多酚含量和抗氧化活性产生影响,随着挤压温度的升高,小麦胚芽中总黄酮、总酚酸和抗氧化能力均呈下降趋势[71]。煮制方式对黑小麦的酚酸组成也有一定影响,煮制后结合酚含量明显增加,但高压煮制与常压煮制之间的差异相对较小[72]。高压放电处理会导致小麦在萌芽过程中多酚含量的变化及其在根茎中的分配发生变化[73]。此外,气态臭氧处理可以通过诱导氧化应激防御机制来提高多酚含量[74]。紫外线处理也能够有效提升青稞中的多酚含量[75],而碳离子辐射对藜麦籽粒中多酚含量的变化具有显著影响[76]。综上,不同的物理加工方式对谷物多酚的影响具有多样性和复杂性。

2.4 化学、生物加工

化学、生物加工技术,如包埋和发酵,能够提升多酚的稳定性和生物有效性[77]。例如,利用β-环糊精对大麦发酵提取物进行直接包埋[78],可增强多酚的稳定性。而经过发酵处理后藜麦的多酚含量显著提高[79],利用红曲霉发酵青稞也能显著提高其多酚含量[80]。在小麦的酒精发酵过程中,副产物酒糟中的多酚含量远高于麸皮[81],通过使用枯草芽孢杆菌和酿酒酵母菌的混合发酵,可以增加游离型和结合型阿魏酸含量,其中结合型阿魏酸为水溶性麸皮多酚的主要形式[82]。刘颖[83]采用酶解和发酵联合处理苦荞,发现其多酚含量高于仅使用菌种发酵的处理组,这可能是因为微生物的生长代谢破坏了结合酚与细胞壁之间的酯键或醚键。后续可进一步探索不同微生物及其发酵条件对谷物多酚含量及其活性的调控影响。

3 谷物多酚的提取方式

3.1 传统提取方式

谷物多酚的提取方法多样,不同的提取方法对多酚提取效率和生物活性影响各异。以甲醇、乙醇等为溶剂可提取谷物中的游离酚[84],但有机溶剂提取法较难直接提取出谷物中的结合酚[85]。谷物结合酚通常以酯键、糖苷键、醚键等与谷物细胞壁连接,或通过氢键与细胞壁上的其他多糖相连[86]。传统提取方法主要包括酸法、碱法和酶解法,这些方法各有优缺点,选择合适的提取方法对于提高多酚的提取效率和保持其生物活性至关重要。

3.1.1 酸法提取 酸法提取是在较高温度下用1%~5%的酸性溶液裂解多酚化合物与细胞壁间的酯键和糖苷键,破坏细胞壁释放结合态多酚[87],其中酸性溶液通常采用无机酸溶液,如HCl、H_2SO_4[88],具有提取方便、操作简单等优点。强酸水解更易释放出谷物麸皮内部和与细胞壁成分如膳食纤维、蛋白质相结合的酚酸[89]。采用酸法提取小米多酚,其得率比碱法更高[90]。高温可降低细胞壁的结构刚性,使酸性溶液更容易渗透到细胞壁内部,加速阿魏酸等结合酚与细胞壁多糖等成分之间的键断裂[91]。但温度过高可能导致阿魏酸、对香豆酸等多酚发生分解[92],从而降低多酚含量。王彩霞等[93]研究发现,采用H_2SO_4提取小麦多酚的水浴温度＞75 ℃后,多酚会发生降解并导致乙醇挥发,使其提取率降低。因此,采用酸法提取谷物多酚需严格控制酸浓度、提取温度和提取时间,以减少多酚的降解。

3.1.2 碱法提取 与酸法提取相似,碱法提取是通过破坏多酚化合物与细胞壁之间的酯键和醚键,从而释放谷物中的多酚[87]。常用的碱法提取溶剂包括NaOH、NH_4OH、$Ca(OH)_2$等[94]。Huang等[95]研究表明,碱法提取对小麦麸皮表面结构的破坏程度高于酸法提取,更有利于多酚的释放。Kim等[96]采用高效液相色谱比较不同提取方法时,碱法提取的麦麸多酚表现出更高的抗氧化活性,与Balli等[90]和Oliveira-Alves等[97]的研究结果有异,这可能与所采用的谷物原料和提取方法及其具体条件不同有关。尽管碱法提取在多酚释放方面具有优势,但也存在多酚降解的风险。例如,随着NaOH浓度的增加,玉米须多酚提取率先升高后降低[98]。多酚通常具有芳香环和多个羟基基团,在较高pH条件下,这些羟基基团会发生去质子化,产生共振或互变异构,导致多酚分子电子密度增加,从而更容易被氧化降解[99]。例如,阿魏酸、儿茶素等多酚化合物中的酚羟基在碱性条件下更容易被氧化,且难以还原成多酚形式[100]。因此,碱法提取需要精确控制pH值和提取条件,以保护多酚的稳定性。

3.1.3 酶解法 纤维素酶或半纤维素酶、果胶酶、淀粉酶等酶类能够水解谷物细胞壁中的纤维素、多糖等结构,从而释放包埋在细胞壁中的结合酚[94]。酶解法可在温和的条件下进行,能够减少多酚的降解,提高提取质量,同时具有高效性、选择性和环保性等优点。常用的酶类包括纤维素酶、果胶酶等,它们能够特异性地分解细胞壁中的纤维素和果胶,释放结合态多酚。陈东方[101]研究表明,采用淀粉酶、蛋白酶和纤维素酶提取燕麦多酚,可以显著提高提取物的体外总抗氧化活性。采用复合酶提取谷物多酚的研究较多,如采用体积比为1∶1的纤维素酶与α-淀粉酶提取荞麦多酚[102],或采用体积比为7∶3的纤维素酶与果胶酶提取小米多酚[103]。尽管酶解法提取效率高,但其成本较高,且需要精确控制酶的种类、用量以及影响酶活性的各项因素。酶解条件中各因素对多酚含量的影响大小依次为酶解时间＞pH＞温度[104]。

3.2 现代提取技术

3.2.1 超临界流体萃取(SFE) 超临界流体萃取是一种利用超临界二氧化碳作为溶剂的提取技术,具有高效、无溶剂残留、对环境友好等优点。超临界二氧化碳具有良好的溶解性和扩散性,可有效提取多酚。但多酚为极性物质,而二氧化碳为非极性物质[105],因此其对多酚的溶解

性有限,通常加入极性助剂如乙醇、甲醇或水来提高SFE对多酚的提取效率[106]。王彩霞等[93]研究表明,与传统有机溶剂提取法相比,SFE能够显著提高多酚的提取效率。例如,SFE将蓝色小麦多酚的提取率提高了51.5%。此外,SFE对小麦全谷物中多酚含量及单个酚酸含量的提取效果比己烷溶剂提取法增加了0.85~2.60倍[107]。尽管SFE的提取效率高,溶剂残留少,但设备成本较高,操作条件较为严格。

3.2.2 超声辅助萃取(UAE) 超声辅助萃取是一种利用超声波产生的空化效应破坏谷物细胞壁,从而释放多酚的高效提取技术[108]。通过将合适的溶剂与样品混合,并在受控温度下进行特定时间的超声处理,可以显著提高多酚提取物的回收率。Melini等[109]研究表明,甲醇和丙酮水溶液为提取黑藜麦多酚的最优溶剂。UAE的提取效率不仅受超声时间、温度和溶剂选择的影响,还与超声波频率、超声波分布、样品粒度以及固液比等因素密切相关[110−111]。UAE可以在静态和动态模式下进行。在静态模式下,样品被放置在密闭容器内进行超声处理,溶剂不会发生连续转移;而在动态模式下,溶剂会不断更新,确保其持续与样品接触,从而提高提取效率并有效转移提取物[112]。动态模式更适用于提取在高温下可能发生降解的多酚。总的来说,UAE提取时间短、提取效率高,且相较于其他方法对多酚的生物活性影响较小。

3.2.3 微波辅助萃取(MAE) 微波辅助萃取是一种通过微波的热效应和非热效应快速提取多酚的技术,具有高效、节能的特点。微波能够迅速加热样品,加速多酚的释放,同时其非热效应可进一步破坏细胞壁结构,从而提高提取效率。Rahman等[113]研究表明,与UAE相比,MAE提取的黑米多酚含量更为丰富。Lu等[114]研究发现,微波可能会诱导小麦粉中的淀粉糊化,从而降低小麦粉中多酚提取率。总体而言,MAE具有提取时间短、效率高的优势,但需要精确控制微波功率和时间,以避免多酚因过度加热而降解。

综上,谷物多酚的提取方法多样,每种方法均有其独特的优点和局限性。选择合适的提取方法对于提高多酚的提取效率和保持其生物活性至关重要。后续研究可进一步优化提取工艺,以提高多酚的提取质量和应用价值。同时,结合现代提取技术和发酵法,有望进一步提高谷物多酚的提取效率和生物活性,为谷物多酚的开发和应用提供更多的可能性。

表2总结了不同谷物多酚的最优提取工艺。

4 谷物多酚的功能及其在水产品保鲜中的应用

4.1 抗氧化作用

水产品在贮藏过程中发生的蛋白质和脂肪氧化等会对其风味、保水性、外观和质地等感官品质产生负面影响[125]。Rodrigues等[126]研究表明,鱼肉肌肉结构中的水分子由蛋白质的亲水性或疏水性决定,其质地特性会在贮藏初期下降30%~60%。而谷物多酚可通过清除自由基和抑制氧化反应等方式,有效保护肉制品中的脂质、蛋白质等不受氧化损失,减少氧化产物的形成,进而延长保质期、提高营养价值、改善感官品质[127]。例如,绿豆中的多酚类化合物可通过抑制脂质氧化和微生物生长,延长食品保质期[128]。谷物多酚和黄酮含量越高,其抗氧化活性越强[129],其中酚酸中黄烷醇的部分结构能与含硫、含氮等发臭化合物结合,具有一定的除臭作用[130],而花色苷可通过清除自由基和抑制氧化反应,延长食品的保质期[131]。将多酚用于鱼糜的制作[132],或与膳食纤维等混合[133]、制作活性包装薄膜[134],可在不影响产品的感官特性和营养价值的基础上增加其抗氧化活性;多酚还可调节鱼类的脂质代谢[135],从而增加其抗氧化,实现水产品的增值;在鱼肉贮藏过程中,鱼肉蛋白质中总巯基含量变化反映了蛋白的氧化程度[136],而谷物中富含的生育酚可阻止鱼肉冻藏过程中二硫键的形成,从而保持肌球蛋白结构的完整性[137]。谷物多酚作为天然抗氧化剂对人体无害,可替代传统的合成抗氧化剂,提高鱼类产品的食品安全性。此外,谷物多酚还可与其他保鲜方法协同作用,进一步提高保鲜效果。

4.2 抗菌作用

谷物多酚对多种细菌和霉菌具有抑制作用。将多酚与壳聚糖制作涂层处理鱼肉,可抑制细菌生长,保持鱼肉品质[138]。藜麦中皂苷和类黄酮物质具有较好的抗菌活性[139],其多酚提取物对蜡样芽孢杆菌具有较好的抑制效果[140];而黄酮提取物对大肠杆菌、金黄色葡萄球菌、枯草芽孢杆菌均具有明显抑制作用,其中对大肠杆菌的抑制作用最为敏感[141];鲜食玉米中的黄酮类化合物如槲皮素,在抗菌方面也表现出显著的效果,可抑制多种病原菌的生长,从而提高食品的安全性和稳定性[142];此外,豌豆中的酚酸类化合物,可抑制多种病原菌的生长,从而延长食品的保质期[143]。图1展示了谷物多酚对水产品保鲜的作用机理。

5 结论与展望

谷物多酚种类繁多,主要包括酚酸类和黄酮类,其分布因谷物种类、品种和生长环境的不同而存在显著差异。多酚在谷物中具有抗氧化、抗炎和抗菌等生物活性,且在食品保鲜和医药领域具有重要应用价值。谷物多酚的提取方式多样,传统提取方法如酸法、碱法和酶解法各有优缺点,现代提取技术如超临界流体萃取、超声辅助萃取和微波辅助萃取等具有更高的提取率和质量。谷物多酚含量受谷物品种、生长情况、物理加工、化学或生物加工等多种因素的影响。在水产品保鲜中,谷物多酚通过抗氧化、抗菌和改善感官品质等作用,展现出良好的保鲜效果

表 2　谷物多酚的最优提取工艺

Table 2　Optimal extraction technology of cereal polyphenols

提取方法	研究对象	工艺条件	提取率/($mg \cdot g^{-1}$)	结论	文献
酸法提取	小麦	10% H_2SO_4,料液比 1∶15(g/mL),温度 78 ℃,时间 60 min	2.17	与传统有机溶剂提取游离酚的方式相比,蓝色小麦多酚提取率提高了 51.5%	[93]
	青稞	11.10% H_2SO_4,水料比 1∶17 (g/mL),温度 75 ℃	3.25	酸法提取液中丁香酸、苯甲酸、没食子酸含量丰富,碱法提取液中柚皮苷、芦丁等黄酮类物质含量丰富	[89]
	小米	1.2 mol/L H_2SO_4、时间 180 min、温度 55 ℃	1.78	阿魏酸甲酯作为结合酚存在于小米中	[90]
碱法提取	小麦	1.2 mol/L NaOH、时间 1.6 h	3.57	小麦的总抗氧化活性为 11.76~13.01 μmol TE/g,结合的原儿茶酸和没食子酸为 HS-490 和 HD-2967 品种小麦中含量最高的主要酚酸	[115]
	玉米须	2.19 mol/L NaOH、时间 2.19 h、料液比 1∶31.99 (g/mL)	1.78	益母草苷和阿魏酸分别为玉米须游离酚和结合酚中的主要多酚化合物	[98]
酶解法	荞麦	1.4% 纤维素酶与 α-淀粉酶质量比为 1∶1;料液比 1∶12(g/mL),pH 4.40,温度 49 ℃,时间 2 h	8.27	纤维素酶能有效酶解麸皮中的纤维素、半纤维素,释放阿魏酸;淀粉酶水解可通过伸展淀粉链破坏其网状结构和水解糖苷键,使咖啡酸、香草醛等单体酚释放	[102]
	小米	1.1% 纤维素酶与果胶酶质量比为 7∶3,pH 3.00,温度 58 ℃,时间 88 min	15.21	相同条件下,小米多酚、叔丁基对苯二酚(TBHQ)、丁基羟基茴香醚(BHA)、2,6-二叔丁基-4-甲基苯酚(BHT)的抗油脂氧化作用排序为 TBHQ>小米多酚>BHA>BHT	[103]
	苦荞	2.5% 纤维素酶、α-淀粉酶、木聚糖酶质量比为 1∶2∶1;料液比 1∶10 (g/mL),温度 50 ℃,时间 5 h	3.36	槲皮素及其代谢产物槲皮素-3-*O*-葡萄糖醛酸为苦荞的主要抗氧化物质,能显著抑制棕榈酸诱导的活性氧的过量生成	[83]
超临界流体萃取	燕麦	CO_2 流体温度 55 ℃、压力 38 MPa	0.019	燕麦中具有 C6-C3 结构的多酚(咖啡酸、芥子酸、香豆酸和阿魏酸)含量高达 1.39 mg/g,其中香豆酸和阿魏酸含量最高	[116]
超声辅助提取	大麦苗	61% 乙醇,料液比 1∶20 (g/mL),功率 70 W,时间 32 min	12.04	大麦苗中的多酚提取物具有抗氧化性和抑制胆碱酯酶活性等功效	[117－118]
	藜麦	40% 乙醇,料液比 1∶25 (g/mL),功率 120 W,时间 35 min,温度 40 ℃	9.23	藜麦多酚的体外抗氧化活性不及抗坏血酸,但仍具有一定的抗氧化能力	[119]
	青稞	80% 丙酮,料液比 1∶25 (g/mL),功率 500 W,时间 30 min,温度 35 ℃	0.636	经超声辅助提取的青稞多酚的 DPPH 自由基清除能力和 FRAP 还原能力分别比未处理组提高了 3.99% 和 1.01%	[120]
	红芸豆	42% 乙醇,料液比 1∶42 (g/mL),功率 308 W,时间 51 min,温度 45 ℃	218.92	芸豆种皮多酚提取物的 DPPH 自由基清除能力为 145.47 μmol Trolox/g DW,$ABTS^+$ 自由基清除能力为 230.34 μmol Trolox/g DW	[121]
	紫皮豇豆	80% 丙酮,料液比 1∶5 (g/mL),时间 5 h,温度 4 ℃	6.14	紫皮豇豆多酚单体含量最高的是芦丁,为(6.479±0.130) mg/100 g	[122]
	蚕豆	45% 乙醇,料液比 1∶25 (g/mL),功率 300 W,时间 20 min,温度 35 ℃,pH 5.00	2.03	蚕豆游离态、结合态多酚对 H_2O_2 诱导的 HepG2 细胞损伤具有一定的抑制作用,且抑制效果随多酚浓度升高明显增强	[123]
微波辅助萃取	黑稻壳	超声时间 10.02 min,超声温度 49.46 ℃,34% 乙醇,微波温度 49.46 ℃,料液比 1∶40.79 (g/mL),微波时间 31.11 s	1.72	通过微波辅助萃取法从黑稻壳中鉴定出没食子酸、对香豆酸、阿魏酸、槲皮素、水杨酸、奎尼酸、芹菜素、丁香酸、绿原酸 9 种酚类物质	[124]

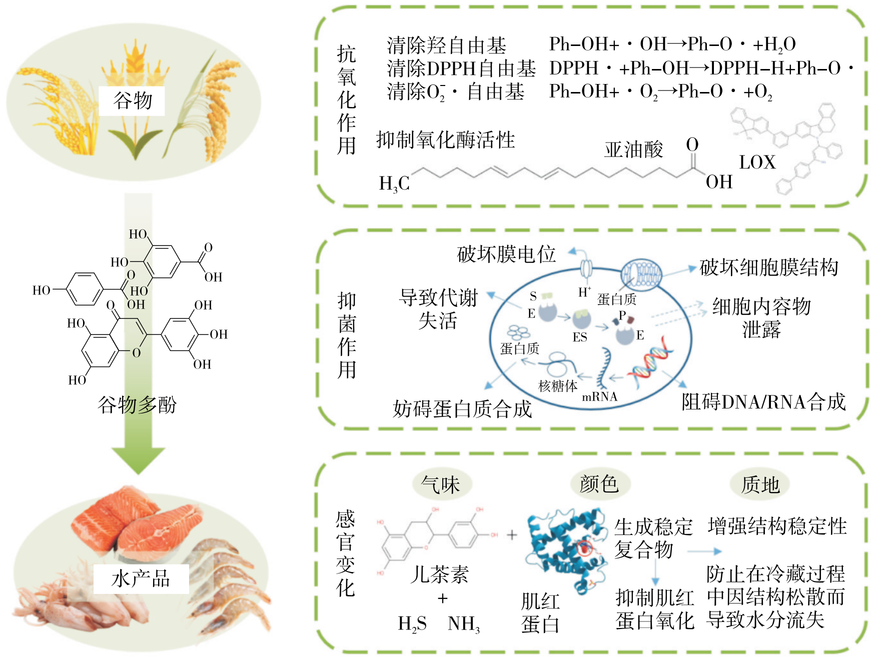


图 1　谷物多酚对水产品保鲜作用机理

Figure 1　Mechanism of grain polyphenols in aquatic product preservation

和应用前景。

未来的研究可以进一步优化传统提取方法和现代提取技术的工艺参数,提高谷物多酚的提取率和生物活性,降低成本,实现工业化生产。深入研究谷物多酚的生物合成途径及其在不同生长环境下的调控机制,揭示其在谷物生长发育中的功能,为培育高多酚含量的谷物品种提供理论依据。结合现代提取技术和发酵法,开发新型谷物多酚提取方法,提高其在食品保鲜、医药和化妆品等领域的应用价值。同时,探索谷物多酚与其他保鲜技术的协同作用机制,开发更高效、安全的保鲜方案。

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