

## 食用菌多糖结构与功能研究进展

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**摘要:** 食用菌具有较高的营养价值和功能价值, 多糖作为食用菌最主要的活性成分之一, 不仅能够为机体供给能量, 而且可以参与生物合成反应及细胞的各项生命活动。大多数食用菌多糖是 $\alpha$ -葡聚糖、 $\beta$ -葡聚糖、混合 $\alpha$ 、 $\beta$ -葡聚糖, 以及由果糖、半乳糖、甘露糖等多种单糖组成的杂多糖, 其中, $\beta$ -葡聚糖是食用菌中最具生物活性的多糖。食用菌多糖具有多种生物活性。为了为食用菌多糖在功能性食品中的应用提供理论基础, 综述了食用菌多糖的结构及其抗氧化、抗衰老、调节免疫、抗炎、抗肿瘤、降血糖、降血脂、抗病毒、抗辐射、抗突变、抑菌、抗疲劳、抗凝血等方面的功能及机理, 并对其进行了展望。

**关键词:** 食用菌; 多糖; 结构; 生理功能

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## Research Progress on Structure and Function of Polysaccharides from Edible Fungi

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**Abstract:** Edible fungi have high nutritional value and functional value. Polysaccharide, as one of the most important active components of edible fungi, can not only supply energy for the body, but also participate in biosynthesis reaction and various life activities of cells. Most edible fungi polysaccharides are  $\alpha$ -glucan,  $\beta$ -glucan or mixture of  $\alpha$ ,  $\beta$ -glucan, and heteropolysaccharides composed of fructose, galactose, mannose and other monosaccharides, among which  $\beta$ -glucan is the most bioactive polysaccharide in edible fungi. A large number of studies have shown that edible fungi polysaccharides have a variety of biological activities. Therefore, this paper reviewed the structure of polysaccharides from edible fungi and their functions and mechanisms in antioxidant, anti-aging, immune regulation, anti-inflammatory, anti-tumor, hypoglycemic, hypolipidemic, anti-viral, anti-radiation, anti-mutation, anti-bacterial, anti-fatigue, anti-coagulation and other aspects, providing a theoretical basis for their application in functional foods.

**Key words:** edible fungi; polysaccharides; structure; physiological function

食用菌是可供食用的大型真菌, 通称为蘑菇, 多属担子菌亚门, 少数属于囊菌亚门, 具有独特的香气和口感, 是被公认的功能性食品。我国是最早栽培和利用食用菌的国家, 食用菌资源十分丰富<sup>[1]</sup>, 有很多关于食用菌的记载, 如《吕氏春秋·本味篇》中将香菇的美味描述为“味之美者, 越骆之菌”; 《齐民要术》、《唐本草注》、《种芝经》、《四时纂要》中均记载了一些食用菌的栽培方法; 《菌谱》、《广菌谱》、《吴藻谱》、《神农本草经》记述了许多种食用菌的形态及其生长特征。

多糖被认为是地球上形成的第一种生物聚合物, 由糖苷键聚合而成, 结构复杂且分子量庞大, 来源于植物、微生物细胞壁和动物细胞膜, 在生物体中发挥着信号传导、免疫调控和物质运输等作用, 影响机体物质代谢和能量代谢, 维持人体健康<sup>[2]</sup>。食用菌中含有丰富的多糖, 可从子实体、菌丝体、菌糠或发酵液中分离, 由醛基和酮基通过糖苷键连接, 是具有天然生物活性的高分子聚合物<sup>[3]</sup>。常见的食用菌多糖有香菇多糖、灵芝多糖、杏鲍菇多糖、姬松茸多糖、金针菇多糖、猴头菇多糖、蛹虫草多糖

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等,国内外学者通过大量研究,发现食用菌多糖具有抗氧化<sup>[4]</sup>、抗肿瘤<sup>[5]</sup>、抗病毒<sup>[6]</sup>、抗菌<sup>[7]</sup>、抗炎<sup>[8]</sup>、调节免疫<sup>[9]</sup>、降血糖<sup>[10]</sup>、降血脂<sup>[11]</sup>等生理功能。不同食用菌来源的多糖结构和组成不同<sup>[12]</sup>,作为一种生物反应调节剂,食用菌多糖的生物活性与其结构密切相关,如单糖组成、糖苷键类型、分子质量不同,生物活性和作用机制会有一些的差异。

现代社会,人们对功能性食品更加关注,食用菌多糖作为原料,有其不可取代的价值。笔者对常见的食用菌多糖的结构、功能及其作用机理进行综述,旨在为其在功能性食品中的应用提供理论基础。

## 1 食用菌多糖的结构特征

大多数食用菌多糖是 $\alpha$ -葡聚糖、 $\beta$ -葡聚糖或者混合 $\alpha$ 、 $\beta$ -葡聚糖,以及由果糖、半乳糖、甘露糖等多种单糖组成的杂多糖。目前已报道的葡聚糖主要是(1 $\rightarrow$ 3)- $\beta$ -D-葡聚糖、(1 $\rightarrow$ 6)- $\beta$ -D-葡聚糖、混合(1 $\rightarrow$ 3)- $\alpha$ -D-葡聚糖和(1 $\rightarrow$ 6)- $\beta$ -D-葡聚糖,其中, $\beta$ -葡聚糖是食用菌中最广泛存在的功能多糖,其结构多为具有分支的 $\beta$ -(1 $\rightarrow$ 3)-D-葡聚糖。不同食用菌多糖结构不完全相同,不同栽培方法和提取方法也会影响食用菌多糖的结构,目前关于食用菌多糖的结构特征见表1。

表1 食用菌多糖的结构特征  
Tab.1 Structural characteristics of polysaccharides of edible fungi

多糖种类 Polysaccharide species	提取方式 Extraction method	组分名称 Component name	分子质量/ku Molecular mass	结构 Structure	连接方式 Connection type	参考文献 Reference
香菇多糖 Lentinan	微波辅助双水相萃取	PTP	120	Man:Rib:GluA:Glu:Gal:Ara:Fuc=8.22:1.33:1.14:72.50:12.71:0.52:3.60	$\beta$ -葡聚糖苷键	[13]
		PBP	3.906	Man:Rib:Glu:Gal:Ara=10.46:10.31:71.26:3.44:4.54	吡喃糖环	[14]
	超滤膜	LE-UF-1	136	Glu, Gal, Man		[14]
		LE-UF-2	14~61			
		LE-UF-3	14~35			
水提醇沉	PS-I	179	D-Glu:D-Gal:D-Man:L-Fuc=4:4:1:1	主链3个(1 $\rightarrow$ 6)- $\alpha$ -D-吡喃半乳糖残基,2个(1 $\rightarrow$ 6)- $\beta$ -D-吡喃葡萄糖残基,1个(1 $\rightarrow$ 4)- $\alpha$ -D-吡喃甘露糖残基和2个(1 $\rightarrow$ 3)- $\beta$ -D-吡喃葡萄糖残基	[15]	
碱提法	JLNT	605.4		主链(1 $\rightarrow$ 3)- $\beta$ -D-葡萄糖,侧链(1 $\rightarrow$ 6)- $\beta$ -D-葡萄糖	[16]	
杏鲍菇多糖 Pleurotus eryngii polysaccharide	热水浸提法	H		Man:Glu:Gal:Xyl:Fuc=9.36:79.72:8.18:2.60:0.42		[17]
	超声提取法	U		Man:Glu:Gal:Xyl:Fuc=8.60:80.90:7.41:2.68:0.57		
	超声波辅助热水提取法	U+H		Man:Glu:Gal:Xyl:Fuc=6.75:82.66:7.14:2.30:1.12		
	水提醇沉	PEPw	25	Ara:Man:Gal=1.2:2.3:6.2	主链1,6-linked-Galp;1,2,6-linked-Galp;1,4-linked-Manp 偶有端链与1,2,6-linked-Galp 残基O-2相连	[18]
水提醇沉	PEPE-1	208	Man:D-Glu:D-Gal:D-Xyl=8.01:74.82:11.14:1.24		[19]	
	PEPE-2	12	D-Man:D-Glu:D-Gal=5.23:86.74:5.12			
	PEPE-3	413	D-Man:D-Glu:D-Gal=4.08:90.93:2.89			
水提醇沉	WPEP-N-b	21.4	D-Gal:D-Man:3-O-Me-D-Gal:D-Glu=43.8:39.3:11.7:9.20	主链(1 $\rightarrow$ 6)- $\alpha$ -D-Galp和3-O-Me-D-Galp,侧链以单链t- $\beta$ -D-Manp为主	[20]	
水提醇沉	EPA-1	99.7	D-Man:D-Glu:D-Gal=2.20:1.00:3.20	(1 $\rightarrow$ 6)-Gal 残基	[21]	
金针菇多糖 Flammulina polysaccharide	超声提取法	FVRP	335.3	Xyl:Gal:Man:Fuc:Ara:Rha:Glu:GalA:GluA=17.2:17.0:15.8:9.3:5.7:7.4:8.3:16.2:3.3		[22]
水提醇沉	GNP	353	Glu:Man:Xyl=3.5:0.8:1.4	主链(1 $\rightarrow$ 4)- $\alpha$ -糖苷键,支链(1 $\rightarrow$ 6)- $\alpha$ -糖苷键	[23]	

续表 1 食用菌多糖的结构特征  
 Tab.1(Continued) Structural characteristics of polysaccharides of edible fungi

多糖种类 Polysaccharide species	提取方式 Extraction method	组分名称 Component name	分子量/kDa Molecular mass	结构 Structure	连接方式 Connection type	参考文献 Reference
	水提醇沉	FVPB2	15	D-Gal:D-Man:L-Fuc:D-Glu=1.9:1.2:1:2.5	$\alpha$ -D-Manp(1 $\rightarrow$ ; $\rightarrow$ 3,4)- $\alpha$ -D-Galp(1 $\rightarrow$ ; $\rightarrow$ 6)- $\alpha$ -D-Glcp(1 $\rightarrow$ ; $\alpha$ -L-Fucp(1 $\rightarrow$ ; $\rightarrow$ 2)- $\alpha$ -D-Galp(1 $\rightarrow$ ; $\rightarrow$ 3,6)- $\beta$ -D-Glcp(1 $\rightarrow$	[24]
双孢菇多糖 <i>Agaricus bisporus</i> polysaccharide	水提醇沉	ABP Ia	784	Rib:Rha:Ara:Xyl:Man:Glu:Gal=2.08:4.61:2.45:22.25:36.45:89.22:1.55	1 $\rightarrow$ 2和1 $\rightarrow$ 4糖苷键组成 $\alpha$ -吡喃多糖,可能存在1 $\rightarrow$ 3糖苷键	[25]
	碱提	AIAPS	34.7	Fuc,Rib,Xyl,Man,Gal,Glu		[26]
		AIAPS-1	53.2	Fuc:Rib:Xyl:Man:Gal:Glu=16.5:1:7.9:10.5:57:45.1		
		AIAPS-2	25.3	Fuc:Rib:Xyl:Man:Gal:Glu=3.3:1.1:1:16.6:9.9:14.3		
		AIAPS-3	79.6	Rib:Man:Gal:Glu=1:1.7:8.5:24.3		
	水提醇沉	FPS		Glu:Man:Gal:Fuc:Ara:GlcA=70.30:8.70:12.88:0.79:5.04:1.57	1-linked-Glc; 1, 4-linked-Glc; 1, 6-linked-Glc; 1, 3-linked-Gal 和 1, 3, 6-linked-Man糖苷键	[27]
	碱提	<i>A. bisporus</i> Polysaccharide	12.8	Fuc	主链(1 $\rightarrow$ 6)- $\alpha$ -D-Galp	[28]
姬松茸多糖 <i>Agaricus blazei</i> polysaccharide	水提醇沉	WABM-A-a	360	Glu:Gal:GluA:Fuc=69.2:24.3:4.3:2.2		[29]
		WABM-A-b	10	Glu:GluA:Gal:Xyl:Fuc=95.1:3.7:0.9:0.2:0.1	主链(1 $\rightarrow$ 6)- $\beta$ -D-Glcp,侧链(1 $\rightarrow$ 3)-Glc; (1 $\rightarrow$ 4)-Glc; T-Glc 和 (1 $\rightarrow$ 6)-Galp	
	碱提	ABP-AW1	50	Gal:Glu:Fuc:Ara:Man=29:20:6:2:2	主链(1 $\rightarrow$ 6)- $\beta$ -D-半乳糖醛基,(1 $\rightarrow$ 6)- $\beta$ -D-吡喃葡萄糖醛基和(1 $\rightarrow$ 3,6)- $\beta$ -D-吡喃葡萄糖醛基	[30]
木耳多糖 <i>Auricularia</i> polysaccharide	水提醇沉	CEPSN-1	4.6	Glu:Man:Gal:GluA=98.90:0.11:0.38:0.61	主链(1 $\rightarrow$ 4)- $\alpha$ -D-葡萄糖残基(吡喃葡萄糖型)	[31]
		CEPSN-2	6.7	Glu:Man:Gal:Ara:Fuc:GluA:GalA=97.56:0.14:1.04:0.11:0.45:0.50:0.20		
	水提醇沉	RPS	200		以葡萄糖为主的吡喃多糖	[32]
	微波辅助提取	AAP	27.7	Glu:Gal:Man:Ara:Rha=37.53:1:4.32:0.93:0.91	主链(1 $\rightarrow$ 3)糖苷键	[33]
灵芝多糖 Ganoderan	水提醇沉	GLPC2	20.56	Man:GluA:Glu:Gal:Xyl:Fuc=5.9:9.0:80.4:1.8:1.8:0.9	D-Glcp(1 $\rightarrow$ ; $\rightarrow$ 3)-D-Glcp(1 $\rightarrow$ ; $\rightarrow$ 4)-D-Glcp(1 $\rightarrow$ ; $\rightarrow$ 6)-D-Glcp(1 $\rightarrow$ ; $\rightarrow$ 3,6)-D-Glcp(1 $\rightarrow$ 和 $\rightarrow$ 4)-D-GlcpA(1 $\rightarrow$	[34]
	水提醇沉	GLP-1	107		$\rightarrow$ 6)- $\beta$ -D-Glcp(1 $\rightarrow$ ; $\rightarrow$ 6)- $\alpha$ -D-Glcp(1 $\rightarrow$ ; $\rightarrow$ 3)- $\beta$ -D-Glcp(1 $\rightarrow$	[35]
		GLP-2	19.5		$\rightarrow$ 6)- $\beta$ -D-Glcp(1 $\rightarrow$ ; $\rightarrow$ 3)- $\beta$ -D-Glcp(1 $\rightarrow$	
灰树花多糖 <i>Grifola frondosa</i> polysaccharide	硫酸铵/乙醇双水相萃取法	CGFP	11 430	Ara:Man:Glu:Gal=1:1.4:6.0:1.2	吡喃糖环	[36]
		GFPA	2 954	Ara:Man:Glu:Gal=1.3:1.0:5.1:1.0		
	超临界 CO <sub>2</sub> 技术	GFP	967	Glu:GalA:Man=83.65:9.97:6.38	(1 $\rightarrow$ 4)-D-Glcp; (1 $\rightarrow$ 4)-Manp; T-D-Glcp; T-D-Galp 和(1 $\rightarrow$ 6)-Galp	[37]
	碱提	GFPS	5 420	Glu(99.7%)	(1 $\rightarrow$ 3)- $\beta$ -D-葡聚糖每3个残基上有一个(1 $\rightarrow$ 6)- $\beta$ -D-葡聚糖侧支	[38]

续表1 食用菌多糖的结构特征  
 Tab.1(Continued) Structural characteristics of polysaccharides of edible fungi

多糖种类 Polysaccharide species	提取方式 Extraction method	组分名称 Component name	分子量/ku Molecular mass	结构 Structure	连接方式 Connection type	参考文献 Reference
猴头菇多糖 <i>Hericium erinaceus</i> polysaccharide	水提醇沉	HEPW1	5.163	Fuc:Glu:Gal=6.13:72.28:21.59		[39]
	水提醇沉	HEP	43	Glu,Rha,Gal,Man,Fuc,Ara	→6)-β-D-Glcp-(1→;→2)-α-L-Rhap-(1→	[40]
平菇多糖 <i>Pleurotus ostreatus</i> polysaccharide	热水浸提	HEFP-2b	32.52	Fuc:Gal:Glu:Man=11.81:22.82:44.28:21.09	主链 →6)-linked-α-D-Glcp-(1→;→4)-β-D-Galp-(1→;→3,6)-α-D-Manp 侧链(1→,→6)-β-D-Galp;(1→,→4)-α-D-Manp	[41]
		HEP-1	2 120	Fuc:Gal:Glu=0.331:2.884:1	HEP-1,HEP-2,HEP-3以(1→6)-α-D连接的半乳糖为主链,以(1→3)-β-D的葡萄糖重复单位为侧链	[42]
		HEP-2	927		HEP-4以(1→3)-β-D连接的葡萄糖为主链,HEP-5以(1→4)-α连接的葡萄糖为主链,且均以(1→6)-α-D的葡萄糖为侧链	
		HEP-3	110			
		HEP-4	19.9			
平菇多糖 <i>Pleurotus ostreatus</i> polysaccharide	水提醇沉	POP-W	3034	Man:Glu:Gal:Xyl=40.34:47.60:7.97:4.09	主链 α-D-Glcp(1→;→3,4)-α-D-Glcp(1→;→3,4)-α-D-Manp(1→;→3)-α-D-Galp(1→;→4)-α-D-Glcp(1→;→3)-α-D-Glcp(1→;→2)-β-D-Manp(1→;→4)-β-D-Xylp(1→	[43]
		POPw	23	Glu:Gal:Man:Rha:Ara=52.3:25.8:10.0:6.1:5.2		[44]
蛹虫草多糖 <i>Cordyceps</i> polysaccharide	亚临界水萃取法	CMP-w1	366	D-Man:D-Glu:D-Gal=2.84:1:1.29	1→,1→6,1→2,1→2,6糖苷键1→4和1→4,6糖苷键	[45]
		CMP-s1	460	D-Man:D-Glu:D-Gal=2.05:1:1.09	糖残基为1→,1→6,1→2,1→2,6,1→4和1→4,6键合	
羊肚菌多糖 <i>Morchella</i> polysaccharide	酸水解	LCMPs-II	28	Rha:Xyl:Glu=1:2.19:6.73	(1→4)-α-D-Glcp	[46]
	水提醇沉	MEP2	959	Glu:Gal:Man:GluA=90.971:0.16:0.145:0.094	→4)-α-D-Glcp-(1→	[47]
绣球菌多糖 <i>Sparassis crispa</i> polysaccharide	水提醇沉	MSP-1	11.7	Man:Glu=1.00:1.25	主链 →4)-β-D-Manp-(1→;→4)-β-D-Glcp-(1→;→4)-α-D-Glcp-(1→;→4,6)-α-D-Glcp-(1→	[48]
		SCP-1	13.68	Glu:Gal:Fuc:Man=52.10:31.10:15.04:1.76	主链(1→6)-α-D-Galp;(1→6)-β-D-Glcp;(1→3)-β-D-Glcp;(1→2,6)-α-D-Galp;(1→3,6)-β-D-Glcp	[49]
银耳多糖 <i>Tremella</i> polysaccharide	酶法结合湿打法	TFP	5 800	Man:Xyl:Fuc:Glu:GluA=1.91:0.1:2.49:6.23:0.95		[50]

## 2 食用菌多糖功能及其作用机理

### 2.1 食用菌多糖的抗氧化及抗衰老活性

氧化与衰老是人体新陈代谢的结果,随着年龄的增长,人体内累积大量自由基,导致炎症介质产生,从而引发机体衰老、自身免疫性疾病、心血管疾

病和神经退行性疾病等与氧化应激相关的疾病。机体的抗氧化防御系统主要是提高过氧化氢酶(CAT)、谷胱甘肽过氧化物酶(GSH-Px)和超氧化物歧化酶(SOD)活性,进而改善机体氧化应激反应。因此,寻找有效清除自由基和提高抗氧化酶的活性物质来抵抗与氧化应激相关的疾病是食品研

究的趋势之一。天然抗氧化剂主要从植物和菌物源材料中获得,其中食用菌多糖被视为天然抗氧化剂,因其表面具有丰富的抗氧化活性基团,可通过清除自由基和提高抗氧化酶活性来发挥抗氧化功能,以延缓机体内的各种生物膜被氧化,保护细胞免受氧化损伤,达到抗衰老和阻止脂质过氧化反应发生的作用<sup>[51]</sup>。不同来源多糖由于其组成、摩尔质量比以及分子质量等不同对抗氧化活力产生的影响也不同。相关研究表明,银耳多糖具有清除超氧阴离子自由基( $O_2^{\cdot-}$ )和羟基自由基( $HO\cdot$ )的作用<sup>[52]</sup>;蛹虫草多糖对 $HO\cdot$ 、 $O_2^{\cdot-}$ 、 $ABTS^+$ 和 $DPPH\cdot$ 均有良好的清除作用<sup>[53]</sup>;金针菇多糖具有清除 $DPPH\cdot$ 、 $HO\cdot$ 和 $O_2^{\cdot-}$ 的能力<sup>[54]</sup>。本课题组前期研究发现,绣球菌多糖对 $DPPH\cdot$ 、 $HO\cdot$ 和 $O_2^{\cdot-}$ 的清除率可达85.63%、85.36%和40.86%,并且具备一定的还原力<sup>[55]</sup>。灵芝多糖GLPL1(5.2 ku)和GLPL2(15.4 ku)对 $HO\cdot$ 的清除率分别为78.3%和53.6%,GLPL1清除自由基和螯合 $Fe^{2+}$ 的能力更强,认为低分子量多糖可能会提供更多的活性羟基<sup>[56]</sup>。平菇多糖对 $DPPH\cdot$ 和 $ABTS^+$ 清除率得到类似结论,低分子量多糖POPH-2(398 ku)比高分子量多糖POPH-1(512 ku)清除率高20.6%<sup>[57]</sup>。但并不是所有的结论都是如此,比如阿魏菇多糖由2种多糖组分PFLP1和PFLP2构成,分子质量分别为9.9、10.3 ku,组成为L-鼠李糖、D-半乳糖、D-葡萄糖和D-甘露糖(1:3.64:18.6:1.54)和L-鼠李糖、D-葡萄糖、D-半乳糖、D-木糖和D-甘露糖(1:6.76:4.28:1.08:0.65)。PFLP1具有比较高的清除 $DPPH\cdot$ 和 $O_2^{\cdot-}$ 的活性,螯合 $Fe^{2+}$ 的能力则较低;而PFLP2对 $HO\cdot$ 、 $DPPH\cdot$ 和 $ABTS^+$ 清除活性较强<sup>[58]</sup>。

羊肚菌子实体杂多糖对 $HO\cdot$ 、 $DPPH\cdot$ 和 $O_2^{\cdot-}$ 均有清除作用,并且可以降低丙二醛含量,提高SOD、CAT和GSH-Px水平,保护斑马鱼胚胎免受氧化损伤<sup>[59]</sup>;香菇多糖可提高脂多糖(LPS)诱导的牛乳腺上皮细胞SOD和总抗氧化能力(T-AOC)活性<sup>[60]</sup>;杏鲍菇多糖可有效提高血液中SOD、GSH-Px和CAT3种主要抗氧化酶的活性<sup>[61]</sup>,提高脑、肝、肾组织中GSH-Px、SOD和T-AOC酶活性,降低MDA含量<sup>[62]</sup>;黑木耳多糖可降低小鼠血清MDA水平,提高肝脏和海马的SOD、CAT、GSH-Px以及T-AOC能力<sup>[63]</sup>;桦褐孔菌多糖可显著降低MDA含量,抑制脂质过氧化<sup>[64]</sup>;灵芝多糖作用于胃癌大鼠,血清和胃组织SOD、CAT、GSH-Px水平均呈剂量依赖性提高<sup>[65]</sup>。

另有报道,复合多糖的抗氧化活性比单一多糖更好。如大球盖菇、金针菇、香菇多糖复配后,清除 $DPPH\cdot$ 和 $HO\cdot$ 的能力和还原力均优于单一品种的多糖<sup>[66]</sup>。猴头菇、杏鲍菇、香菇、平菇4种菌丝多糖复配后,清除 $DPPH\cdot$ 能力和还原力均高于活性最强的猴头菇多糖,且复配比例不同活性不同<sup>[67]</sup>。香菇、黑木耳、灰树花、姬松茸和蛹虫草等5种食用菌多糖复合对 $O_2^{\cdot-}$ 和 $HO\cdot$ 的清除率比5种单一多糖均高,认为复配后产生了协同增效的作用<sup>[68]</sup>。

JING等<sup>[69]</sup>从茶树菇菌丝体中提取了2种多糖,并对半乳糖(D-Gal)诱导衰老小鼠的抗氧化活性和抗衰老活性进行研究,表明茶树菇多糖能较好地提高肝脏SOD、CAT、GSH-Px和T-AOC活性,抑制肝脏过氧化脂(LPO)和MDA含量,改善低密度脂蛋白胆固醇(LDL-C)、高密度脂蛋白胆固醇(HDL-C)、LDL-C/HDL-C、甘油三酯(TG)和总胆固醇(TC)水平。此外,羟脯氨酸(HYP)检测结果表明,经茶树菇多糖干预后,衰老小鼠的皮肤胶原蛋白可以得到一定维持。LI等<sup>[70]</sup>研究表明,双孢蘑菇子实体多糖可通过提高血清酶活性、生化水平、脂质含量和抗氧化活性保护肝脏和肾脏。DING等<sup>[71]</sup>研究认为,双孢菇多糖可提高人胚胎肺成纤维细胞(HELFL)的细胞活力,减少活性氧(ROS)的产生,抑制叔丁基过氧化氢(t-BHP)诱导的氧化损伤,提高小鼠肝脏和血清SOD和CAT活性,可作为一种有效的膳食补充剂,用于减缓衰老和预防与年龄相关的疾病。

## 2.2 食用菌多糖的免疫调节及抗炎活性

免疫调控是机体免疫系统在免疫应答过程中所做出的生理性反馈,通过调控免疫细胞与受体分子之间的协同或拮抗作用,使免疫细胞处于活化或抑制状态,或者调控免疫系统与其他系统之间的相互作用,保证机体免疫功能的稳定。炎症是机体组织受损时所发生的一系列保护性应答,是机体稳态维持的调控手段之一,适度的炎症对机体有益,但有时候炎症也会影响机体的正常代谢过程,对人体自身组织进行攻击,发生组织炎症,导致免疫系统异常,人体免疫力下降<sup>[72]</sup>。当机体免疫功能低下时,会使机体反复感染病原微生物,导致肿瘤细胞大量繁殖,癌症发病率升高。

近年来,食用菌多糖的免疫调节活性受到了广泛关注,其免疫调节及抗炎机制详见表2。猴头菇多糖、香菇多糖、杏鲍菇多糖等均可以通过多个途径作用于免疫系统,如改善脏器指数,刺激机体各

种免疫活性细胞的分化和增殖、促进各种受体分子的表达及抗体形成等,通过 TLR4/JNK 和 Akt/NF- $\kappa$ B、NKG2D 及其下游 DAP10/PI3K/ERK 等信号通路提高或促进 NK 细胞和巨噬细胞活性。免疫器官和组织作为机体免疫细胞分化、发育并发挥免疫作用的区域,在机体免疫过程中居首要地位。免疫细胞主要组成有淋巴细胞、造血干细胞和抗原提呈细胞等,它们相互协调作用,共同参与机体的固有免疫和适应性免疫。活化的 NK 细胞通过分泌 IFN- $\gamma$ 、TNF- $\alpha$  等细胞因子发挥免疫调节作用。

巨噬细胞能够通过细胞因子的分泌发挥免疫调节功能,参与机体炎症反应,杀伤清除病原体,有效防御由内源性或外源性病原体侵害而引起的组织炎症反应和损伤,成为机体防御病原微生物感染的第一道防线。食用菌多糖的抗炎作用主要是通过抑制趋化因子与粘附因子的表达、抑制关键酶的活性和调节细胞因子的产生来实现,还可以通过刺激 T 细胞增殖、激活巨噬细胞来提高免疫功能和抗感染能力。

表2 食用菌多糖的免疫调节及抗炎机制  
Tab.2 Immunomodulatory and anti-inflammatory mechanisms of polysaccharides of edible fungi

多糖种类 Polysaccharide species	提取方法 Extraction method	作用机制 Action mechanism	参考文献 Reference
猴头菇多糖 <i>Hericium erinaceus</i> polysaccharide	水提醇沉(温度 80 °C, 时间 3 h)	脾脏、胸腺和肾脏器官指数 $\uparrow$ , SOD、GSH-Px、CAT 活性 $\uparrow$ , 病理损伤 $\downarrow$	[73]
	水提醇沉(料液比 1:20, 温度 100 °C, 时间 30 min, 3 次)	NO、IL-6 和 TNF- $\alpha$ 活性 $\uparrow$	[74]
	水提醇沉(料液比 1:16, 温度 100 °C, 时间 4 h, 2 次)	SIgA 分泌 $\uparrow$ , 体液免疫、巨噬细胞吞噬作用和 NK 细胞活性 $\uparrow$	[75]
	水提醇沉(料液比 1:20, 温度 100 °C, 时间 2 h, 2 次)	巨噬细胞的吞噬能力 $\uparrow$ , CD40 和 CD86 表达 $\uparrow$	[76]
香菇多糖 Lentinan	水提醇沉(温度 97 °C, 时间 4 h)	MHC II 和 CD80/86 表面抗原 $\uparrow$ , IL-2、IFN- $\gamma$ 和 IL-10 分泌 $\uparrow$	[77]
	酸水解(温度 120 °C, 时间 4 h)	脾脏、胸腺指数 $\uparrow$ , 淋巴细胞增殖 $\uparrow$ , 调节体内 CD4 <sup>+</sup> T/CD8 <sup>+</sup> T	[78]
	水提醇沉(料液比 1:40, 温度 80 °C, 时间 2 h, 2 次)	巨噬细胞吞噬能力 $\uparrow$ , 使巨噬细胞分泌 NO、TNF- $\alpha$ 、IL-1 $\beta$	[79]
	热水浸提	T 淋巴细胞增殖 $\uparrow$ , IgG、IgM 水平 $\uparrow$ , NK 细胞活性 $\uparrow$	[80]
杏鲍菇多糖 <i>Pleurotus eryngii</i> polysaccharide	水提醇沉(料液比 1:30, 温度 90 °C, 时间 3 h, 3 次)	RAW 264.7 细胞增殖和吞噬 $\uparrow$ , NO、TNF- $\alpha$ 、IL-6 和 IL-1 $\beta$ 分泌 $\uparrow$	[81]
	微波辅助(料液比 1:80, 功率 640 W, 时间 8 min)	脾脏、胸腺质量 $\uparrow$ , RAW 264.7 增殖 $\uparrow$	[82]
	碱提(料液比 1:20, 温度 80 °C, 时间 3 h, 3 次)	脾淋巴细胞增殖 $\uparrow$ , NK 细胞活性 $\uparrow$ , 腹腔吞噬细胞吞噬能力 $\uparrow$ , 调节肠道菌群	[83]
	水提醇沉(料液比 1:25, 温度 70 °C, 时间 140 min)	肝脏、脾脏及胸腺等脏器指数 $\uparrow$ , TNF- $\alpha$ 、IFN- $\gamma$ 、IL-1、IL-2 及 IL-6 $\uparrow$	[84]
灵芝多糖 Ganoderan	水提醇沉(料液比 1:25, 温度 70 °C, 时间 2 h)	NO、PGE2、IL-1 $\beta$ 、TNF- $\alpha$ 和 IL-6 $\downarrow$ , RAW 264.7 巨噬细胞炎症反应 $\downarrow$	[85]
	水提醇沉(料液比 1:40, 温度 90 °C, 时间 2 h)	T、B 淋巴细胞增殖 $\uparrow$ , 呈一定的剂量依赖性	[86]
	水提醇沉(料液比 1:20, 时间 1 h)	抑制 B16-F10 荷瘤小鼠肿瘤生长, ICAM-1 表达 $\uparrow$ , 增强 T 淋巴细胞肿瘤浸润	[87]
	水提醇沉(料液比 1:35, 温度 66 °C, 时间 137 min)	NK92 细胞本身活性 $\uparrow$	[88]
蛹虫草多糖 <i>Cordyceps</i> polysaccharide	水提醇沉(料液比 1:21, 温度 100 °C, 时间 2 h)	溶血素 $\uparrow$ , IFN- $\gamma$ 、IL-2 $\uparrow$ , IgA、IgM 水平 $\uparrow$ , 体外淋巴细胞 IL-6、TNF- $\alpha$ mRNA 表达 $\uparrow$	[89]
	水提醇沉(温度 100 °C, 时间 2 h)	IEC-6 细胞增殖 $\uparrow$ , NO、IL-6 和 IL-1 $\beta$ $\downarrow$	[90]
	水提醇沉(料液比 1:40, 温度 100 °C, 时间 2 h, 2 次)	IL-1 $\beta$ 、TNF- $\alpha$ 和 IL-10 表达 $\downarrow$ , 减轻炎症 $\downarrow$	[91]
	水提醇沉(料液比 1:40, 温度 100 °C, 时间 1 h, 2 次)	IL-6 和 TNF- $\alpha$ $\uparrow$	[92]
羊肚菌多糖 <i>Morchella</i> polysaccharide	水提醇沉(料液比 1:20, 温度 100 °C, 时间 2 h, 3 次)	TLR-2、TLR-4、TLR-6、p-I $\kappa$ B- $\alpha$ 、NF- $\kappa$ B p65 表达 $\uparrow$ , 改善肠道微生物群落多样性	[93]
	水提醇沉(料液比 1:40, 温度 80 °C, 时间 2 h)	RAW 264.7 细胞中 JNK、ERK 和 p38 表达 $\downarrow$	[94]
	水提醇沉(料液比 1:40, 温度 90 °C, 时间 3 h)	巨噬细胞 RAW 264.7 增殖 $\uparrow$ , iNOS 和 NO $\uparrow$	[95]
	水提醇沉(料液比 1:20, 时间 2 h)	RAW 264.7 细胞吞噬能力 $\uparrow$ , NO、TNF- $\alpha$ 和 IL6 分泌 $\uparrow$	[96]

续表 2 食用菌多糖的免疫调节及抗炎机制  
 Tab.2(Continued) Immunomodulatory and anti-inflammatory mechanisms of polysaccharides of edible fungi

多糖种类 Polysaccharide species	提取方法 Extraction method	作用机制 Action mechanism	参考文献 Reference
金针菇多糖 <i>Flammulina polysaccharide</i>	水提醇沉(料液比 1:20, 时间 3 h)	胸腺、脾脏指数 ↑, SOD、CAT 和 T-AOC 活性 ↑, ACP、LDH 活性 ↑, IL-2、IL-4 ↑, TNF-α、IL-6 ↓	[97]
	水提醇沉(料液比 1:20, 温度 90 °C, 时间 1 h, 3 次)	B 细胞增殖 ↑, IgG、IgM 水平 ↑, 激活 B 细胞释放 IL-10 ↑	[98]
	水提醇沉(料液比 1:20, 温度 90 °C, 时间 1 h, 3 次)	IFN-γ 和 TNF-α 分泌 ↑, 巨噬细胞 RAW 264.7 释放 NO ↑, IL-1β、IL-6 和 TNF-α 分泌 ↑	[99]
	超声波辅助(料液比 1:35, 功率 180 W, 时间 40 min)	RAW 264.7 细胞活力和吞噬能力 ↑, ROS 和 NO 含量 ↓	[100]
绣球菌多糖 <i>Sparassis crispa polysaccharide</i>	水提醇沉(温度 65 °C, 时间 2 h)	脾脏和胸腺指数 ↑, 脾脏淋巴细胞活性 ↑, 白细胞总量 ↑, IgG 功能 ↑, TNF-α、IFN-γ 和 IL-1β mRNA 表达 ↑	[101]
	水提醇沉(料液比 1:40, 温度 75 °C, 时间 2 h)	RAW 264.7 增殖 ↑, NO、TNF-α、IL-6 和 IFN-β 分泌 ↑, TLR4 表达 ↑, TRAF6、IRF3、JNK、ERK、p38 以及 p38 mRNA 和蛋白质水平 ↑	[102]
	酶法辅助(料液比 1:40, 温度 40 °C, 时间 3 h)	RAW 264.7 增殖 ↑, 巨噬细胞吞噬能力 ↑, NO 分泌 ↑, TNF-α、IL-1β、IL-6、IL-3、IL-10、IFN-β mRNA 表达 ↑	[103]
	酶法辅助(料液比 1:40, 温度 40 °C, 时间 3 h)	改善肠道粘膜形态, IL-6、IL-10、TNF-α、IFN-γ 含量 ↑, 调节肠道菌群结构, SCFAs 产生菌的相对丰度 ↑, SCFAs 含量 ↑	[104]
	酶法辅助(料液比 1:40, 温度 40 °C, 时间 3 h)	RAW 264.7 增殖 ↑, NO、IL-6、TNF-α、IFN-β 释放 ↑	[105]
	酶法辅助(料液比 1:40, 温度 40 °C, 时间 3 h)	盲肠内乙酸、丙酸和丁酸含量 ↑, GPR41、GPR43 和 GPR109A 表达 ↑, FOXP-3、IL-6、IL-8 和 IL-10 mRNA 表达 ↑	[106]
大球盖菇多糖 <i>Stropharia rugosoannulata polysaccharide</i>	超声波辅助(料液比 1:40, 功率 1200 W, 时间 20 min)	SOD、CAT 和 GAH-Px 活性 ↑, TNF-α、IL-10 和 IL-1β 含量 ↓	[107]
	水提醇沉(料液比 1:30, 温度 80 °C, 时间 3 h, 2 次)	MPO、NO、MDA 含量 ↓, T-SOD 含量 ↑, IFN-γ、TNF-α、IL-1β 和 IL-6 水平 ↓, IL-10 水平 ↑, 恢复肠道屏障完整性	[108]
银耳多糖 <i>Tremella polysaccharide</i>	水提醇沉(料液比 1:50, 温度 95 °C, 时间 4 h, 2 次)	结肠损伤减轻, TNF-α、IL-1β 和 IL-6 水平 ↓, ZO-1、OCLN mRNA 和蛋白表达 ↑	[109]
茯苓多糖 <i>Pachymaran</i>	碱提(料液比 1:2, 温度 25 °C, 时间 12 h)	RAW264.7 细胞 NO 释放 ↑, IL-1β、IL-6 和 TNFα 分泌 ↑	[110]

### 2.3 食用菌多糖的抗肿瘤活性

随着我国老龄化人口逐渐增加,工业化和城镇化进程不断加快,以及慢性感染、不健康生活方式等危险因素的累加,我国恶性肿瘤发病、死亡人数持续上升。人体内都有原癌基因与抑癌基因,其中原癌基因促进细胞分裂增殖,抑癌基因能抑制细胞生长增殖,并且控制细胞分化,相互制约,维持细胞分裂增殖的动态平衡。当抑癌基因因某些诱因,发生突变、缺失或失活时,可引起细胞恶性转化,导致癌细胞的产生。目前,许多食用菌多糖已被证实具有抗癌作用<sup>[111]</sup>。研究发现,香菇多糖对鼠肝癌细胞 H22、鼠肉瘤细胞 S180、人肝癌细胞 HepG2 和 SMMC-7721、人胃癌细胞 MKN45、人红白血病细胞 K562、人乳腺癌细胞 MCF-7 和人结肠癌细胞 HT-29 具有明显体外抑制增殖作用,表明香菇多糖发挥了非免疫途径的体外直接抗肿瘤活性<sup>[112]</sup>。食

用菌多糖可黏附在细胞表面,通过受体激活 T 淋巴细胞、B 淋巴细胞、巨噬细胞(MΦ)、自然杀伤细胞(NK)和树突状细胞(DC)等免疫细胞,还可以促进白细胞介素-1(IL-1)、白细胞介素-2(IL-2)、肿瘤坏死因子(TNF-α)和干扰素-γ(IFN-γ)等细胞因子的表达。食用菌多糖的抗肿瘤机制见表 3,可通过抑制癌细胞增殖、调节细胞因子水平、减缓肿瘤细胞入侵、黏附和转移以及调控细胞凋亡等多种途径抑制肿瘤<sup>[113]</sup>。蛹虫草多糖、灵芝多糖、平菇多糖等均可以抑制部分癌细胞的增殖,降低癌细胞迁移速率。香菇多糖可调节 p53、p-ERK1/2、MDM2 和 TERT 表达;蛹虫草多糖可改善 SMMC-7721、BGC-823 和 MCF-7 表达等。此外,食用菌多糖通过抑制细胞周期蛋白的产生,调节死亡受体以及促凋亡因子与抗凋亡因子比值,导致细胞周期停滞,诱导细胞凋亡。

表 3 食用菌多糖的抗肿瘤机制  
Tab.3 Antitumor mechanism of polysaccharides of edible fungi

多糖种类 Polysaccharide species	提取方法 Extraction method	作用机制 Action mechanism	生物活性 Biological activity	参考文献 Reference
香菇多糖 Lentinan	水提醇沉(温度 120 °C, 时间 30 min, 3次)	p53、p-ERK1/2、PARP1 ↑, MDM2、TERT、NF-κB p65、Bcl-2、ERα、PI3K、p-Akt、mTOR ↓	抗乳腺癌	[114]
		IFN-γ 表达 ↑, 以 T 细胞独立的方式抑制肿瘤血管生成	抗肺癌	[115]
杏鲍菇多糖 <i>Pleurotus eryngii</i> polysaccharide	水提醇沉(料液比 1:40, 温度 80 °C, 时间 3 h)	HepG-2 细胞凋亡 ↑, caspase-3 和 caspase-9 ↑, 诱导细胞周期停滞	抗肝癌	[116]
金针菇多糖 <i>Flammulina</i> polysaccharide	水提醇沉	SOD 活性 ↓, MDA 活性 ↑, NO 和 LDH 水平 ↑, HepG-2 细胞晚期凋亡/坏死 ↑	抗肝癌	[117]
蛹虫草多糖 <i>Cordyceps</i> polysaccharide	水提醇沉(料液比 1:20, 温度 80 °C, 时间 2 h, 3次)	Caspase-3、Caspase-9、p53 蛋白和 mRNA 水平 ↑, PCNA 蛋白和 mRNA 水平 ↓, 诱导肿瘤细胞凋亡	抗肺癌	[118]
	水提醇沉(料液比 1:20, 温度 80 °C, 时间 10 h, 2次)	SMMC-7721、BGC-823 和 MCF-7 细胞增殖 ↓, 阻断 G0/G1 期, DNA 合成 ↓, 诱导细胞凋亡	抗肝癌 抗胃癌 抗乳腺癌	[119]
灵芝多糖 Ganoderan	超声辅助(料液比 1:20, 温度 60 °C, 时间 40 min)	Cyclin E、Cyclin A 和 CDK2 表达 ↓, P53 表达 ↑, 死亡受体以及促凋亡因子/抗凋亡因子比值 ↑, 细胞周期停滞	抗宫颈癌	[120]
	水提醇沉(料液比 1:20)	SK-HEP-1 和 Huh-7 细胞增殖和迁移能力 ↓, 肝癌细胞增殖 ↓	抗肝癌	[121]
平菇多糖 <i>Pleurotus ostreatus</i> polysaccharide	水提醇沉(料液比 1:6.25, 温度 100 °C, 时间 3 h)	改变肿瘤细胞形态和粒度, 肿瘤细胞增殖能力 ↓, CSC、EMT 和 ABC ↓	抗舌鳞癌	[122]
	碱提(料液比 1:15, 温度 100 °C, 3次)	胸腺和脾脏相对指数 ↑, 淋巴细胞增殖 ↑, IL-2、TNF-α 和 IFN-γ 水平 ↑, NK 细胞和 CTL 活性 ↑	抗肿瘤	[123]
牛肝菌多糖 <i>Porcini</i> polysaccharide	水提醇沉(料液比 1:20, 温度 100 °C, 时间 2 h, 3次)	脾指数和胸腺指数 ↑, NK 细胞和 CTL 活性 ↑, IL-2 和 TNF-α 分泌 ↑	抗胃癌	[124]
灰树花多糖 <i>Grifola frondosa</i> polysaccharide	水提醇沉(温度 100 °C, 时间 6 h, 3次)	T 细胞和 B 细胞增殖活性 ↑, IgG、IgE、IgD 和 IgM 分泌 ↑, RAW264.7 细胞增殖和吞噬 ↑	抗肿瘤	[125]
	水提醇沉(料液比 1:34.72, 温度 100 °C, 时间 2.62 h)	胸腺和脾脏相对质量 ↑, TNF-α 和 IL-2 水平 ↑, iNOS 蛋白表达和 iNOS、TNF-α mRNA 表达 ↑	抗肿瘤	[126]
绣球菌多糖 <i>Sparassis crispa</i> polysaccharide	超声辅助(料液比 1:40, 功率 1 200 W, 时间 3 h, 2次)	TNF-α、IL-6、NF-κB、COX-2、IL-1β mRNA 或蛋白水平 ↓, IL-β mRNA 或蛋白表达 ↑	抗结肠癌	[127]

## 2.4 食用菌多糖的降血糖活性

目前,糖尿病以高患病率和低治疗率已经成为人类三大致死疾病之一,其死亡率仅次于心脑血管疾病和癌症。目前,常用降糖药普遍具有血糖降低受控性差,长期服用易引发低血糖、呕吐和腹泻等不良反应,因此,其应用也受到限制。食用菌多糖表现出优异的降血糖活性,可以通过调节相关酶活性,减轻氧化应激反应,改善肠道菌群代谢,促进胰岛素分泌或释放,增加胰岛素敏感性,改善胰岛素抵抗及糖代谢等来达到降血糖的目的。

梭柄松苞菇多糖能够抑制 α-葡萄糖苷酶活性,减缓葡萄糖的转化和吸收,降低餐后血糖水平<sup>[128]</sup>。LI 等<sup>[129]</sup>从红菇中提取的 2 种水溶性多糖可抑制 α-葡萄糖苷酶和 α-淀粉酶活性,显著增强其抗糖活性。灵芝杂多糖可显著降低高脂饮食(HFD)和链脲佐菌素(STZ)诱导的糖尿病小鼠的血糖,修复胰岛细胞,增加胰岛素分泌,促进肝糖原的合成和储存,提

高抗氧化酶活性和胰岛素抵抗,降低糖尿病小鼠血清胰岛素抵抗指数(HOMA-IR),同时可以改善肠道菌群比例,减少内毒素进入肠道,缓解炎症反应<sup>[130]</sup>。CHEN 等<sup>[131]</sup>从灰树花子实体中获得了具有降血糖活性的灰树花多糖,主要是通过提高小鼠肝脏中胰岛素受体的蛋白水平,促进机体对葡萄糖的吸收,修复胰岛素信号传导途径,从而修复受损的胰岛细胞,缓解胰岛素抵抗。PI3K/Akt 胰岛素信号通路在胰岛素抵抗的发生发展中起关键作用,与糖代谢有关<sup>[132]</sup>。AKT 调节葡萄糖和脂质代谢,主要在胰岛素响应组织中表达活化的 AKT2,促进葡萄糖转运蛋白 4(GLUT4)的翻译。黄菇多糖能够有效抑制 α-葡萄糖苷酶,并通过 PI3K/Akt 通路调控 HepG2-IR 细胞的胰岛素抵抗<sup>[133]</sup>。桦褐孔菌多糖可通过提高高脂饮食和 STZ 诱导的 2 型糖尿病小鼠肝脏的抗氧化活性,显著上调 PI3K-p85、p-Akt(ser473)、GLUT4 蛋白表达,从而降低空腹血

糖,改善胰岛素抵抗<sup>[134]</sup>。

## 2.5 食用菌多糖的降血脂活性

高脂血症是由于脂肪的代谢异常,血浆中脂质含量过高引起的,主要表现为高密度脂蛋白水平过低、甘油三酯(TG)水平和血清胆固醇(TC)过高等。高脂血症作为一种慢性疾病,能直接导致动脉粥样硬化、冠状动脉粥样硬化等疾病,严重威胁人类的健康。食用菌中的 $\beta$ -葡聚糖可发酵性和在人体肠道中形成黏性溶液的特性使其在降血脂方面起着至关重要的作用<sup>[135]</sup>。食用菌多糖通过调整低密度脂蛋白胆固醇(LDL-C)和高密度脂蛋白胆固醇(HDL-C)比例、抑制内源性胆固醇的合成、促进胆固醇逆向转运、提高磷脂胆固醇酰基转移酶的活性、促进TG分解、调控脂代谢相关因子、调节肠道菌群以及减轻氧化应激等多种机制发挥降血脂作用<sup>[136]</sup>。

杏鲍菇多糖可显著改善STZ诱导的糖尿病小鼠TC、TG、LDL-C和极低密度脂蛋白(VLDL-C)的升高和HDL-C的降低<sup>[137]</sup>,改变高脂模型小鼠肠道中微生物群落结构,增加胆汁酸的分泌和脂类的排泄,达到抗肥胖和降低胆固醇的作用<sup>[138]</sup>。羧甲基化羊肚菌多糖可通过下调高胆固醇血症大鼠的肝脏3-羟基-3-甲基戊二酰辅酶 $\alpha$ 还原酶,上调胆固醇-7 $\alpha$ -羟基化酶发挥其降胆固醇能力<sup>[139]</sup>。蛹虫草多糖可降低血脂和肝脏脂肪水平,恢复高脂乳剂引起的脂代谢紊乱<sup>[140]</sup>。此外,蛹虫草多糖还可以逆转高脂饮食所致的肠道微生物群失调,改变代谢物水平,可作为一种潜在的益生元制剂<sup>[141]</sup>。山西农业大学食品科学与工程学院食用菌科技创新团队前期对姬松茸多糖、猴头菌多糖和广叶绣球菌多糖的降胆固醇机制进行了研究,结果表明,姬松茸多糖可通过降低小鼠血清TG和TC含量,增加GLUT4、PI3K、AKT1和AKT2基因表达量,缓解脂代谢紊乱<sup>[142]</sup>;珊瑚状猴头菌多糖可降低大鼠TC和LDL-C水平,增加HDL-C水平,降低HMG-CoA还原酶基因表达量,增加LDL受体(LDL-R)、胆汁酸合成限速酶(CYP7 $\alpha$ -1)基因表达量,调节高胆固醇大鼠的血脂水平<sup>[143]</sup>;广叶绣球菌多糖能改善大鼠肠道形态结构和生理指标,降低HMGCR、NPC1L1、ACAT2、MTP、ASBT和IBABP mRNA或蛋白表达,增加ABCG8 mRNA表达,提高有益菌群相对丰度和短链脂肪酸浓度,调节肠道胆固醇代谢<sup>[144]</sup>。此外,GC-MS代谢组学技术分析结果显示,大鼠血清中氨基酸类代谢物质发生明显改变,绣球菌多糖可回调部分氨基酸水平,降低葡萄糖和胆固醇水

平,进一步推测可能是通过调节谷氨酸与谷氨酰胺代谢起到降血脂作用<sup>[145]</sup>。

## 2.6 食用菌多糖的抗病毒活性

食用菌多糖及其衍生物对病原菌和病毒表现出很强的抗生素特性,临床试验研究证明,真菌多糖对流感病毒、肝炎病毒、单纯疱疹病毒等多种病毒有一定的抵抗和抑制作用<sup>[146]</sup>。食用菌多糖的抗病毒作用主要是通过激活或提高网状内皮细胞、巨噬细胞的吞噬能力,以及通过免疫机制调节提高宿主的免疫功能,从而发挥抗病毒作用<sup>[147]</sup>。

香菇多糖对大肠杆菌、枯草芽孢杆菌有明显的抑制作用<sup>[148]</sup>,可以抑制乙型肝炎病毒DNA的复制和病毒受体细胞的增殖,降低抗凋亡相关蛋白(STAT 3, p-STAT 3 and survivin)的表达<sup>[149]</sup>。ZHANG等<sup>[150]</sup>从金针菇中提取了一种新的水溶性多糖FVP1,分子质量为54.78 ku,由甘露糖(7.74%)、葡萄糖(70.41%)和半乳糖(16.38%)组成,通过降低乙型肝炎表面抗原(HBsAg)、乙型肝炎e抗原(HBeAg)和乙型肝炎病毒(HBV)DNA复制的表达,表现出显著的乙型肝炎表面抗体活性。猴头菇多糖可调节番鸭呼肠孤病毒(MDRV)感染诱导RAW 264.7细胞TLR3信号转导通路活化,抑制TLR3信号转导通路下游产物白细胞介素-1 $\beta$ (IL-1 $\beta$ )、白细胞介素-10(IL-10)、IL-6和TNF- $\alpha$ 的过度表达,上调干扰素- $\beta$ (IFN- $\beta$ )的表达,从而抑制MDRV在RAW 264.7细胞中的复制<sup>[151]</sup>。桦树茸多糖、木质素衍生物及提取物具有较强的抗病毒作用,可以抑制猫杯状病毒、猫疱疹病毒1、猫流感病毒、猫传染性腹膜炎病毒和猫泛白细胞减少症病毒的增殖<sup>[152]</sup>。

## 2.7 食用菌多糖的抗辐射抗突变活性

如果身体长期暴露在电离辐射下,可能会对正常组织器官及人体各系统造成严重损害,如造血系统、神经系统、肺组织等,从而导致疾病的发生<sup>[153]</sup>。食用菌多糖具有潜在的辐射防护活性,主要是通过清除自由基,增强免疫力,发挥免疫调节作用,减少辐射对造血系统的损伤,增强DNA损伤修复能力,抑制细胞凋亡来实现的。

灵芝多糖可上调白细胞(WBC)、血小板(PLT)等,血清代谢组学结果表明,磷脂酰胆碱、次黄嘌呤、牛磺酸、L-肉碱、鞘氨醇、磷酸和胆酸等18个潜在生物标志物发生显著变化,与甘油磷脂代谢、牛磺酸和次牛磺酸代谢、鞘脂代谢、花生四烯酸代谢、亚油酸代谢等通路有关,推测灵芝多糖可以通过对多种代谢靶点的干预来缓解电离辐射造成的损

伤<sup>[154]</sup>。黑木耳子实体多糖可通过调节肝脏中的JNK通路以及胰腺中PDX1/GLUT2通路,恢复氧化还原平衡及血糖耐受能力,改善辐射诱导的糖代谢紊乱<sup>[155]</sup>。XU等<sup>[156]</sup>从银耳中分离纯化出的水溶性均质多糖可恢复血红蛋白、白细胞计数和红细胞计数,有效阻止辐射对小鼠染色体的遗传毒性作用。蛹虫草多糖可以改善微波辐射导致的精子相对数量减少,畸形率增加,SOD、GSH-Px水平降低,MDA水平升高,缓减辐射对雄性小鼠生殖系统的影响<sup>[157]</sup>。此外,蛹虫草多糖可降低环磷酰胺诱导小鼠骨髓嗜多染红细胞微核率及染色体畸变率,具有抗突变活性<sup>[158]</sup>。黄灵菇多糖能显著提高小鼠血浆GSH-Px活性及GSH含量,提高骨髓DNA数量,降低小鼠骨髓染色体畸变率和微核率,抑制Bax蛋白的表达,促进Bcl-2蛋白的表达,抑制细胞色素c的释放和Caspase-3的表达,从而阻断<sup>60</sup>Co- $\gamma$ 辐射诱导小鼠脾细胞线粒体凋亡通路,发挥辐射保护作用<sup>[159]</sup>。

## 2.8 食用菌多糖的抑菌活性

具有抑菌活性的食用菌多糖主要通过破坏细菌的细胞壁和细胞膜、调控细菌内酶活性和离子水平、调控能量代谢、影响基因等方面达到抑菌效果。

姬菇精多糖对大肠杆菌的生长有较好的抑制效果,当质量浓度为4.00 mg/mL时,大肠杆菌被完全抑制,且纯度越高,抑菌能力越强<sup>[160]</sup>。灵芝硫酸多糖对大肠杆菌、铜绿假单胞菌、肠炎沙门氏菌、沙门氏菌、单核细胞增生李斯特菌和金黄色葡萄球菌等具有剂量依赖性的抗菌作用<sup>[161]</sup>。微波提取香菇多糖制备出的微胶囊对金黄色葡萄球菌、枯草芽孢杆菌、大肠杆菌有较强的抑制作用<sup>[162]</sup>。从绣球菌中分离得到的多糖SCPs由海藻糖、葡萄糖和半乳糖组成,摩尔比为0.043:0.652:0.305。抑菌试验表明,SCPs对金黄色葡萄球菌的抑制作用较好,代谢组学结果分析表明,SCPs可使果糖1,6-二磷酸、1,3-二磷酸甘油酸、琥珀酸和草酰乙酸的变化显著,并伴随细胞内ATP的降低,因此,认为SCPs抑制作用机理主要是破坏了金黄色葡萄球菌的糖酵解和三羧酸循环途径的代谢<sup>[163]</sup>。郝正祺等<sup>[164]</sup>研究发现,绣球菌多糖对单增李斯特菌、鼠伤寒沙门氏菌、金黄色葡萄球菌、福氏志贺氏菌、大肠埃希氏杆菌有一定抑制作用,其中对单增李斯特菌、鼠伤寒沙门氏菌的抑制作用较强。蛹虫草多糖对大肠杆菌、金黄色葡萄球菌、枯草芽孢杆菌、副伤寒沙门氏菌和铜绿假单胞菌均有较强的抑菌活性,对大肠杆菌的最低抑菌质量浓度为0.10 mg/mL,此外,导电

性、碱性磷酸酶(AKP)和 $\beta$ -半乳糖苷酶活性均有所提高,生长曲线、真菌蛋白、膜蛋白均发生变化,表明蛹虫草多糖可通过破坏细菌细胞壁和细胞膜来发挥杀菌活性,增加细胞通透性,使其结构损伤,细胞成分释放,从而导致细胞死亡<sup>[165]</sup>。

## 2.9 食用菌多糖的抗疲劳活性

疲劳是机体的一种常见亚健康状态,是由机体的活动造成的各种器官中的营养大量消耗,从而引起的暂时性身体机能降低的现象,主要表现为肌肉力量下降和储存能量降低,并经常伴随着中枢神经紧绷和免疫力下降的现象,严重者更会出现精神不济、意识不清、免疫力下降等状况。诸多研究表明,疲劳的产生与体内积累过量的自由基,导致氧化和抗氧化系统失衡密切相关<sup>[166]</sup>。

杏鲍菇多糖能明显延长小鼠爬杆和游泳时间,提高SOD活性、降低乳酸含量,提高肝糖原和肌糖原含量<sup>[167]</sup>。木耳胞外多糖能改善小鼠的身体疲劳,提高肝糖原含量,降低血清尿素氮和乳酸水平,增强抗氧化酶的活性,降低脂质过氧化,延长力疲小鼠游泳时间<sup>[168]</sup>。猴头菌多糖可降低血乳酸(BLA)、血清尿素氮(SUN)和丙二醛(MDA)含量,提高组织糖原含量和抗氧化酶活性,发挥抗疲劳活性<sup>[169]</sup>。在小鼠的抗疲劳模型试验中,CAI等<sup>[170]</sup>和ZHANG等<sup>[171]</sup>均研究发现,添加外源灵芝多糖和滑菇多糖能显著提高小鼠力竭游泳时间和体内抗氧化酶活性。

## 2.10 食用菌多糖的抗凝血活性

天然抗凝血物质常见的有糖类、黄酮类、生物碱等,它们类别多样、结构复杂。在糖类化合物中,真菌类和藻类植物占有很大比例。

平菇多糖可通过内源性和外源性凝血途径,有效抑制血浆凝块形成<sup>[172]</sup>。黑木耳粗多糖能够抑制血小板聚集,延缓血液凝固<sup>[173]</sup>。灵芝多糖可抑制凝血系统的外源性途径和凝血系统上纤维蛋白原向纤维蛋白的转化,发挥抗凝血活性<sup>[174]</sup>。在体外凝血试验中,随着乌金菇多糖浓度的升高,活化部分凝血活酶时间(APTT)和血凝酶时间(TT)呈浓度依赖性发展,阻碍内在的、外在的和凝血酶介导的纤维蛋白产生抑制,达到抗凝血的目的<sup>[175]</sup>。杨庆伟等<sup>[176]</sup>和LI等<sup>[177]</sup>分别利用灰树花硫酸酯化多糖和红菇多糖也得到了相似的结论。

## 3 展望

食用菌作为营养、美味、可口及对健康有益的食物,是生物活性多糖的重要来源,近年来一直是

食品领域的研究热点之一。 $\beta$ -葡聚糖是食用菌中最广泛存在的功能多糖,结构多为(1 $\rightarrow$ 3)、(1 $\rightarrow$ 4)、(1 $\rightarrow$ 6)等。食用菌多糖具有抗氧化、抗衰老、免疫调节、抗炎、抗肿瘤、降血糖、降血脂、抗病毒、抗辐射、抗突变、抑菌、抗疲劳、抗凝血等生物活性,其中抗氧化和免疫调节是最主要的生物活性功能,其他各种生物活性均以此为基础进行研究。

食用菌多糖的组成、分子量及构象等均会影响其生物活性,但食用菌多糖分子量大,结构复杂,多糖的构效关系及机制仍需要进一步研究,为今后食用菌及其多糖应用于功能性食品和免疫调节剂的技术研究和产品开发奠定基础。

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