



植物精油对畜禽肠道健康的调控作用及机制

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摘 要: 肠道既是营养物质消化吸收的场所,又是防御病原体的天然屏障,其健康程度与畜禽生长性能和机体免疫能力密切相关。因此,如何提升畜禽肠道健康水平,已成为学者们关注的热点问题。植物精油(plant essential oil, PEO)是从植物中提取的一种低分子量的次生植物代谢物,近年来研究发现,PEO可增强肠道屏障功能、促进肠道有益菌群定植,对于改善肠道健康具有一定积极作用。本文从肠道形态、肠道屏障功能及肠道菌群等方面系统地综述了PEO对畜禽肠道健康的影响及调控作用,并探讨了其潜在的作用机制,以期PEO的开发利用提供参考。

关键词: 植物精油;畜禽;肠道健康;调控机制

中图分类号: S816.7

文献标志码: A

文章编号: 0366-6964(2026)02-0614-10

The Regulation of Plant Essential Oil on Intestinal Health of Livestock and Poultry and Its Mechanism

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Abstract: The intestinal tract is not only the central site for the digestion and absorption of nutrients, but also a natural barrier against pathogens, and its health is closely related to growth performance and immune capacity of livestock and poultry. Therefore, improving the intestinal health of livestock and poultry has become a research hotspot among scholars. Plant essential oils (PEO), low molecular weight secondary plant metabolites extracted from plants, have been shown to have positive effects on improving intestinal health, such as enhancing intestinal barrier function and promoting the colonization of beneficial gut microbiota. In this paper, the effects of PEO on the intestinal health of livestock and poultry are systematically reviewed from the aspects of intestinal morphology, intestinal barrier function, and intestinal microbiota, and the potential mechanisms are discussed, in order to provide references for the development and application of PEO.

Keywords: plant essential oil; livestock and poultry; intestinal health; regulatory mechanisms

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肠道是畜禽的消化吸收器官和最大的免疫器官,其健康水平与畜禽生长性能和机体免疫能力密切相关。当前,我国畜禽养殖以规模化、集约化为

主要发展趋势,但集约化、高密度的养殖方式容易损害畜禽肠道稳态^[1],阻碍畜禽生长发育和降低养殖效益。近年来,天然植物生物活性物质(如多糖、

收稿日期:2025-01-20

基金项目:内蒙古自治区自然科学基金(青年)项目(2024QN03066)

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黄酮、皂苷和精油等)因其潜在的生物学功能(增强机体免疫能力、缓解氧化应激、调节胃肠道微生物群平衡等)而受到广泛的关注^[2-3]。植物精油(plant essential oil, PEO)是一种具有挥发性和疏水性的低分子量次生植物代谢物的混合物^[4],已有研究表明,PEO能够促进肠道生长和维护肠道健康^[5]。本文从PEO对畜禽肠道形态、肠道屏障和免疫功能以及肠道菌群的影响、调控作用和其潜在作用机制等角度进行综述,以期PEO在生产上的开发利用奠定基础。

1 PEO 概述

PEO是从植物组织(花、芽、种子、叶、细枝、树皮、果实和根)中提取的一种低分子量的芳香亲脂

性液体,也称为挥发油或芳香油,通常呈无色或淡黄色,具有不溶于水但脂溶性强的特点^[4]。目前已经发现了3 600多种富含精油的芳香植物,多集中于唇型科、菊科、十字花科、伞型科、芸香科、豆科、姜科、蔷薇科和鸢尾科^[6]。根据化学结构,PEO被分为萜烯类化合物(大部分为单萜和倍半萜)、芳香族化合物(主要为萜源衍生物和苯丙烷类衍生物)、脂肪族化合物(主要为烯类、烷烃类和醇类)和含氮含硫化合物(具有刺激气味)^[7],其中萜烯类化合物被广泛应用于制药科学、医学、生物学和农学等领域^[8]。由于PEO来源广泛、提取方法多样,其活性成分和含量往往存在较大差异,表1中列出了常见的精油种类及其主要活性成分。

表1 常见 PEO 及其主要活性成分

Table 1 Common PEO and their main active components

植物精油 PEO	提取方法 Extraction method	主要活性成分(含量) Main active components (Content)	参考文献 Reference
百里香 Thyme	有机溶剂萃取法 (石油醚、甲醇)	百里香酚(21.5%)、对-聚伞花素(14.6%)、钆樟醇(5.4%)	[9]
牛至 Oregano	水蒸气蒸馏法	3-环己烯-1-醇(27.1%)、1,4-环己二烯(11.9%)、2-环己烯-1-醇(5.6%)	[10]
	同时蒸馏萃取法	环己烯-1-醇(39.1%)、环己二烯(18.4%)、3-环己烯-甲醇(5.73%)	
	微波辅助水蒸气提取法	2-环己烯-1-醇(34.8%)、1,4-环己二烯(10.2%)、1,6-辛三烯-3-醇(6.1%)	
丁香 Clove	水蒸气蒸馏法	丁子香酚(89.5%)	[11]
香蜂草 Lemon balm	水蒸气蒸馏法	橙花醇(30.4%)、柠檬醛(27.0%)、异戊二醇(22.0%)	[12]
柠檬草 Lemongrass	水蒸气蒸馏法	香叶醛(50.7%)、橙花醛(33.8%)	[13]
马郁兰 Marjoram	超临界流体萃取法	水合桉烯(37.0%)、4-萜烯醇(12.8%)、 α -松油醇(8.1%)	[14]
鼠尾草 Sage	水蒸气蒸馏法	顺式侧柏酮(26.8%)、樟脑(16.4%)、反式侧柏酮(14.1%)、1,8-桉树脑(10.8%)	[15]
迷迭香 Rosemary	水蒸气蒸馏法	1,8-桉树脑(10.8%)、 α -蒎烯(10.8%)、樟脑(9.2%)	[16]
茴香 Fennel	水蒸气蒸馏法	反式茴香脑(81.1%)、茴香酮(9.7%)	[17]
薄荷 Peppermint	水蒸气蒸馏法	左旋香芹酮(64.4%)、(+)-柠檬烯(11.5%)	[18]
柚皮 Pomelo peel	水蒸气蒸馏法	D-柠檬烯(64.3%)、(-)- β -蒎烯(16.1%)、邻苯二甲酸二异丁酯(9.6%)	[18]
肉桂 Cinnamon	无溶剂微波萃取法	(E)-肉桂醛(67.7%)、丁香酚(11.4%)、芳樟醇(4.3%)、柠檬烯(2.4%)	[19]
	水蒸气蒸馏法	(E)-肉桂醛(59.1%)、丁香酚(14.1%)、芳樟醇(5.4%)、柠檬烯(1.8%)	
大蒜 Garlic	水蒸气蒸馏法	二烯丙基三硫醚(29.3%)、烯丙基二硫(19.9%)、甲基烯丙基三硫醚(12.6)	[20]
茶树 Tea tree	水蒸气蒸馏法	松油烯-4-醇(32.1%)、 γ -松油烯(16.8%)、2-萜烯(10.5%)	[18]

2 PEO 的生理作用

PEO通常含有2~3种主要的萜类或类萜(醇、酸、酚、酮、醛等)化合物,占其成分的30%左右^[8]。

PEO中化合物的种类、含量以及化学键的连接方式使其具有不同的生理作用和芳香气味^[21]。在抗氧化方面,萜烯类化合物与醇类、醛类和酮类等化合物形成共轭碳-碳双键以及羟基官能团,为PEO的

抗氧化活性提供了结构基础^[22]。在抗炎方面,PEO能减少促炎细胞因子分泌及炎症介质的合成,并抑制参与炎症反应的细胞成熟,如树突状细胞、单核细胞和肥大细胞,并调节细胞在炎症反应中的功能^[23]。在免疫调节方面,PEO可在细胞和分子水平上对免疫系统的各个部分产生影响,包括在细胞免

疫中调节 T 细胞和其他免疫效应细胞活性、在体液免疫中促进抗炎细胞因子和抗体的产生等^[7]。此外,PEO 还具有一定的抗菌活性,根据其活性成分,抗菌活性大小顺序为:酚>醛>酮>醇>醚>羟基^[24]。PEO 的生理作用如表 2 所示。

表 2 PEO 的生理作用

Table 2 The physiological effects of PEO

植物精油 PEO	动物 Animal	生理作用 Physiological effect	效果 Outcomes	参考文献 Reference
牛至精油 Oregano EO	荷斯坦犍牛	促生长作用	DMI、ADG ↑	[25]
	肉羊	改善肉品质	改善肌肉脂肪酸组成和肉色;抑制脂质过氧化	[26]
	哺乳期母羊	抗氧化作用	血清中 GSH-Px、SOD ↑;乳中 CAT ↑	[27]
大蒜精油 Garlic EO	肉仔鸡	抗氧化作用	血清中 GSH-Px ↑、MDA ↓	[28]
柠檬精油 Lemon EO				
百里香酚 Thymol	断奶仔猪	抗氧化作用	十二指肠和回肠黏膜 GSH ↑;空肠黏膜 SOD ↑、MDA ↓	[29]
肉桂醛 Cinnamaldehyde				
茶树油 Tea tree EO	山羊	抗炎作用	瘤胃上皮细胞 <i>IL-1β</i> 、 <i>IL-6</i> 、 <i>TNF-α</i> 、 <i>TLR2</i> mRNA 表达水平 ↓	[30]
胡椒精油 Piper nigrum EO	小鼠	抗炎作用	抑制 TLR4 和 MAPK 活性,使 <i>TNF-α</i> 、 <i>IL-1β</i> 、 <i>IL-6</i> mRNA 表达水平 ↓	[31]
百里香酚 Thymol	仔猪	免疫调节作用	血清中 IgG、IgA、IgM、C3、C4 含量和淋巴细胞增殖率、吞噬率 ↑	[7]
肉桂醛 Cinnamaldehyde				
香芹酚 Carvacrol	肉鸭	免疫调节作用	血清中 <i>TNF-α</i> 、 <i>IL-1β</i> 、 <i>IL-6</i> 含量 ↓; IgG、IgA、IgM 含量 ↑	[7]

DMI. 干物质采食量;ADG. 平均日增重;GSH-Px. 谷胱甘肽过氧化物酶;SOD. 超氧化物歧化酶;CAT. 过氧化氢酶;MDA. 丙二醛;GSH. 谷胱甘肽;IL-1β. 白介素-1β;IL-6. 白介素-6;TNF-α. 肿瘤坏死因子-α;TLR2. Toll样受体 2;TLR4. Toll样受体 4;MAPK. 丝裂原活化蛋白激酶;IgG. 免疫球蛋白 G;IgA. 免疫球蛋白 A;IgM. 免疫球蛋白 M。“↑”代表上调,“↓”代表下调

DMI. Dry matter intake; ADG. Average daily gain; GSH-Px. Glutathione peroxidase; SOD. Superoxide dismutase; CAT. Catalase; MDA. Malondialdehyde; GSH. Glutathione; IL-1β. Interleukin-1β; IL-6. Interleukin-6; TNF-α. Tumor necrosis factor- α; TLR2. Toll-like receptor 2; TLR4. Toll-like receptor 4; MAPK. Mitogen-activated protein kinase; IgG. Immunoglobulin G; IgA. Immunoglobulin A; IgM. Immunoglobulin M. “↑” mean up-regulate; “↓” mean down-regulate

3 PEO 对畜禽肠道健康的调控作用及机制

3.1 PEO 改善肠道形态

健康的肠道形态结构是动物抵御疾病风险和吸收营养物质的重要前提。肠道绒毛长度、隐窝深度及其比值是衡量肠道形态的重要指标^[32]。较长的绒毛高度(villus height, VH)可为营养物质的吸收提供更大的表面积,较浅的隐窝深度(crypt depth, CD)意味着肠细胞成熟度高、组织更新快,分泌功能好,而两者的比值(V/C)则反映了小肠的净吸收能力,比值越高,肠上皮细胞的吸收和转运能力越强^[33]。Liu 等^[34]报道,50、100、200 mg·kg⁻¹ 茶树油

均可显著增加肉鸡十二指肠、空肠和回肠绒毛高度,显著降低隐窝深度,并使 V/C 显著增加。Dong 等^[35]同样报道了 100 mg·kg⁻¹ 茶树油可增加断奶仔猪空肠绒毛高度,降低十二指肠隐窝深度,增加十二指肠、空肠和回肠的 V/C 比值。Sun 等^[36]研究发现,300 mg·kg⁻¹ 牛至精油可显著增加 Sewa 肉羊十二指肠、空肠和回肠绒毛高度,并显著增加十二指肠、空肠和回肠 V/C 值。然而,精油的水溶性低、挥发性高和耐热性差等特性限制了其应用。Adil 等^[37]使用纳米胶囊化技术包被迷迭香精油,结果发现,与未被精油相比,包被精油显著增加白羽肉鸡十二指肠、回肠绒毛高度和 V/C 比值,显著降低十二指肠隐窝深度。

3.2 PEO促进肠道消化吸收

动物肠道中营养物质转运蛋白表达提高和内源性消化酶分泌增加对营养物质消化吸收同样具有积极作用,如上皮细胞基底侧膜的转运蛋白-葡萄糖转运蛋白2(glucose transporter type 2, *GLUT2*)和葡萄糖转运蛋白5(glucose transporter type 5, *GLUT5*)允许糖以果糖、半乳糖和葡萄糖的形式进入体循环^[38];肠道中的溶质载体家族1成员1(solute carrier family 1 member 1, *SLC1A1*)促进谷氨酸和天冬氨酸吸收,而小肽转运载体1(peptide transporter 1, *PepT1*)负责运输二肽和三肽^[39-40]。Zhao等^[41]研究发现,三组饲料分别添加肉桂醛($100\text{ mg}\cdot\text{kg}^{-1}$)或香芹酚($100\text{ mg}\cdot\text{kg}^{-1}$)或肉桂醛($50\text{ mg}\cdot\text{kg}^{-1}$)和香芹酚($50\text{ mg}\cdot\text{kg}^{-1}$),均可显著提高断奶仔猪空肠和回肠中 *SLC1A1*、*GLUT2*、*GLUT5*、B(0,+)-型氨基酸转运蛋白B(B(0,+)-type amino acid transport protein, *RBAT*)、钠偶联中性氨基酸转运蛋白2(sodium-coupled neutral amino acid transporter 2, *SNAT2*)、*PepT1*的基因表达水平和溶质载体家族5成员1(solute carrier family 5 member 1, *SLC5A1*)、*GLUT2*、*GLUT5*的蛋白表达水平。*SLC5A1*以跨膜 Na^+ 梯度为驱动因子,将单糖转运通过小肠上皮细胞的刷状边界膜,随后, Na^+ - K^+ -ATP酶产生膜电位,并通过*GLUT2*穿过基底侧膜离开肠上皮细胞^[41]。Zhang等^[42]在小尾寒羊饲料中添加 $10\text{ mL}\cdot\text{kg}^{-1}$ 的花椒精油,发现瘤胃内果胶酶和脂肪酶活性显著提高。上述研究结果表明,PEO可改善动物肠道形态,提高营养转运蛋白表达水平和消化酶活性,促进营养物质的消化吸收,进而提高动物生长性能。

3.3 PEO增强肠道屏障和免疫功能

肠道屏障主要由肠道外黏液层(生物屏障)、内黏液层(化学屏障)、肠道上皮层(机械屏障)和肠道固有层(免疫屏障)通过相互连接或相互依存的方式组成,该屏障具有选择渗透性,允许饲料中的营养素如氨基酸、脂肪酸、葡萄糖、水、电解质和微生物代谢物从肠腔进入体循环,同时对外源致病菌、病毒、食物抗原和环境毒素起到防御作用^[43]。肠道上皮层由单层上皮细胞组成,其中分布着功能特化的分化细胞,它们共同形成的一个连续的、极化的单层,使管腔从固有层分离^[44]。紧密连接(tight junctions, TJs)蛋白,如封闭蛋白(Claudin)、闭合蛋白(Occludin)、闭锁小带蛋白(ZO),将单层上皮细

胞相互连接,是细胞旁通透性的重要调节因子^[45]。Zhao等^[46]研究发现,饲料添加0.1%的混合精油(5%肉桂醛+5%香芹酚+0.8%百里香酚+预混载体)可显著提高断奶仔猪十二指肠、回肠中*ZO-1*、*Claudin-1*、*Claudin-5*和空肠中*Occludin*、E-钙黏蛋白(*E-cadherin*)的mRNA表达水平。Ma等^[47]报道,每天在10月龄荷斯坦公牛饲料中添加 $20\text{ g}\cdot\text{只}^{-1}$ 牛至精油可显著增加结肠中*Claudin-1*、*Claudin-4*、*Occludin*、*ZO-1*、黏蛋白(mucin, *MUC*)-1和*MUC-2*的mRNA表达水平。*MUC*由杯状细胞分泌,能够润滑肠道表面、解毒重金属结合,并与肠道免疫系统相互作用^[48]。此外,有研究发现,肉桂醛和香芹酚可显著提高仔猪空肠中溶菌酶(lysozyme, *Lyz*)和回肠中富含亮氨酸重复序列G蛋白偶联受体5(leucine-rich repeat-containing G-protein coupled receptor 5, *Lgr5*)的表达^[41]。*Lyz*由潘氏细胞分泌,通过使细胞壁内容物逃逸的方式来溶解细菌,从而减少攻击上皮细胞的内源性细菌及其毒素数量^[49],而*Lgr5*是肠道干细胞的标志物,其表达程度反映了肠道维持肠上皮稳态和周转率的能力^[50]。

大量研究表明,细胞因子除在免疫方面的作用外,对于肠道屏障完整性也具有重要的生理和病理作用,如促炎性细胞因子肿瘤坏死因子- α (*TNF- α*)和白介素1 β (*IL-1 β*)可诱导内质网应激,影响Caco-2细胞(肠上皮细胞),并改变肠顶端和基底外膜的关键蛋白(如*E-cadherin*)破坏肠上皮细胞的连接和紧密性^[51];而抗炎细胞因子白介素10(*IL-10*)能增强B细胞的存活、增殖和抗体产生,阻断核转录因子- κ B(nuclear factor-kappa B, *NF- κ B*),降低细胞旁通透性^[52]。Ma等^[47]研究发现,每天剂量为 $20\text{ g}\cdot\text{只}^{-1}$ 的牛至精油可显著降低荷斯坦公牛结肠中*TNF- α* 、Toll样受体(Toll-like receptor, *TLR*)4、*IL-1 β* 的mRNA表达水平,同时显著提高*IL-10*的mRNA表达水平。Yan等^[53]报道,0.4 $\text{g}\cdot\text{kg}^{-1}$ 混合精油(17%肉桂醛和7%百里香酚)对于感染肠产毒素性大肠杆菌的断奶仔猪,可显著抑制其空肠黏膜中*TLR4*、*NF- κ B*、*IL-1 β* 、*TNF- α* 等基因的表达水平,减少干扰素- γ (*INF- γ*)、*TNF- α* 、*IL-6*和分泌型免疫球蛋白A(sIgA)含量。*TLR*除识别和区分多种病原体相关的分子模式外,如脂多糖(LPS)(由*TLR4*识别)和脂肽(由*TLR2*识别),还可诱导上皮细胞增殖,向管腔分泌sIgA,从而促进肠道屏障功能^[54]。Dong等^[35]发现,100 $\text{mg}\cdot\text{kg}^{-1}$ 茶树油可显著上调断奶仔猪

空肠和回肠 *Occludin* 的 mRNA 表达水平,同时显著增加空肠中热休克蛋白(heat shock protein, *Hsp*) 60、*Hsp*70、*Hsp*90 和回肠中 *Hsp*70、*Hsp*90 的基因表达量。*Hsp* 是小肠中具有保护和修复功能的重要应激相关蛋白,其家族成员 *Hsp*60 可保护小肠上皮细胞免受细胞毒性物质的侵害;*Hsp*70 可通过稳定肠上皮细胞之间的 TJs 来维持屏障功能;*Hsp*90 在小肠上皮细胞中过表达具有缓解氧化应激和细胞损伤的保护功能^[55]。由此可见,PEO 可通过调控炎症和 TJs 蛋白相关基因表达水平,促进肠道干细胞分化,来增强肠道屏障功能,维持肠道稳态。

3.4 PEO 调控肠道菌群

哺乳动物胃肠道中蕴藏着大量的微生物群,它们与宿主共同进化,形成具有稳定肠道微环境的微生物群,为宿主提供广泛的生物功能,如营养物质吸收、免疫调节、维持肠道屏障功能等^[56]。目前,越来越多的证据表明,PEO 可以直接影响肠道微生物的丰度和多样性,还可以被肠道菌群转化为宿主可利用的或具有生物活性的代谢物,受调控的微生物和转化的代谢物都有助于维持肠道健康^[57]。在门水平上,厚壁菌门(Firmicutes)和拟杆菌门(Bacteroidetes)是动物胃肠道中的主要菌门,Firmicutes 成员的主要功能是促进能量代谢,将饲料中的纤维素转化为短链脂肪酸(short chain fatty acids, SCFAs);Bacteroidetes 成员的主要功能是降解饲料中的碳水化合物和蛋白质、参与免疫系统发育和维持肠道菌群平衡;两者的较低比值(F:B)有利于消化富含多糖的饲料和抵抗肠道炎症性疾病^[58-60]。Cheng 等^[61]报道,大蒜精油(基础饲料含 $1.5 \text{ g} \cdot \text{kg}^{-1}$)可显著增加仔猪结肠中 Bacteroidetes 和螺旋体菌门(Spirochaetes)相对丰度,显著降低 Firmicutes 和放线菌门(Actinobacteria)相对丰度,导致 F:B 显著降低。与其相反的是,300 $\text{mg} \cdot \text{kg}^{-1}$ 精油(2.5% 百里香酚和 2.5% 香芹酚)显著降低仔猪结肠中 Bacteroidetes 相对丰度,显著增加放线菌门(Actinobacteria)和古菌门(Euryarchaeota)相对丰度^[62]。山苍子精油(100 $\text{mg} \cdot \text{kg}^{-1}$)虽然没有显著改变仔猪盲肠中 Firmicutes 和 Bacteroidetes 的相对丰度,但 F:B 被显著降低,且成剂量依赖性^[63],这可能与仔猪品种、日龄、肠段不同或精油中所含的活性成分不同有关。

在属水平上,牛至精油可提高荷斯坦公牛结肠中拟杆菌属(*Bacteroides*)、粪芽孢菌属(*Coprobacillus*)、

毛螺菌属 *_UCG_001* (*Lachnospiraceae_UCG_001*) 和粪杆菌(*Faecalitalea*)的相对丰度^[47];还可以显著提高绵羊(小尾寒羊×湖羊)回肠中双歧杆菌(*Bifidobacterium*)、瘤胃球菌(*Ruminococcus*)和肠球菌(*Enterococcus*)等有益菌的相对丰度^[64]。*Bacteroides* 成员是维持肠道微生物食物网的主要参与者,能与病原体竞争宿主来源的氨基酸和单糖,并由此产生 SCFAs 直接对抗病原体^[65]。*Faecalitalea* 是一种产丁酸菌,属丹毒丝菌科(*Erysipelotrichaceae*),被认为是一种益生菌,可以保护消化系统免受肠道病原体的侵害^[66]。*Enterococcus* 可促进动物机体生长发育和维护肠道内稳态^[67],*Bifidobacterium* 可通过刺激肠道黏液层生长来增强肠黏膜免疫屏障功能^[68],而 *Ruminococcus* 可通过促进次级胆汁酸(bile acids, BAs)分泌来维持肠道内稳态^[69]。肠杆菌(*Enterobacteria*)、链球菌(*Streptococcus*)和弯曲杆菌(*Campylobacter*)等病原体与腹泻、黏膜损伤、肠道炎症和炎症性肠病有关,常见于断奶仔猪肠道中^[70-71]。Zhao 等^[41]研究发现,香芹酚、肉桂醛可显著降低仔猪结肠中 *Streptococcus* 和 *Campylobacter* 的相对丰度。香芹酚和肉桂醛作为细菌膜渗透剂的杀菌活性已被广泛研究,特别是香芹酚,会减弱质子原动力,改变细胞膜的通透性和消耗 ATP,并通过阻止鞭毛蛋白的合成来抑制细菌运动^[72]。在仔猪饲料中添加丁香酚和百里香酚也得到了相似的结果,肠道中 *Campylobacter* 和大肠埃希菌属-志贺菌属(*Escherichia-Shigella*)相对丰度显著降低^[73]。这些研究结果充分证明,PEO 可选择性地激活益生菌或抑制致病菌的生长能力来发挥促进宿主健康生长的作用。

此外,肠道微生物及代谢物还是肠-器官轴联系的纽带,如肠-肝轴、肠-脑轴、肠-肺轴、肠-心轴等,不同的微生物通过产生生物活性化合物(如 BAs、SCFAs、色氨酸等)向肠道周围器官发出信号与内分泌系统和免疫系统连接,调节多种器官的生理代谢反应^[74]。肠-肝轴是肠道与肝之间存在的一种双向关系,两器官通过胆道、门静脉和体循环相互联系^[75]。肠道静脉血通过门静脉流入肝脏,为其提供 2/3 的血液来源。肝脏处理从肠道吸收的营养物质和微生物代谢物,合成 BAs 并通过胆管进入肠道,这些 BAs 中的绝大多数(>95%)从回肠被重吸收,再由门静脉回到肝,这一过程被称为肠肝循环^[76]。

BAs是该循环中的重要信号分子,在肠道中可促进脂溶性营养物质的消化和吸收,并通过直接抑制特定细菌的生长和间接刺激肠道中抗菌剂的产生,来调节肠道微生物区系,进而在肠道微生物群落形成过程中起到关键作用^[77-78]。据报道,肠-心轴与心血管疾病密切相关^[79]。当肠道屏障功能受损时,肠道通透性增加导致LPS进入血液,激活宿主的TLR4等模式识别受体,引发系统性炎症反应、低度内毒素血症,并促使白细胞、血小板和内皮细胞等多种细胞转化为促凝表型,诱导血栓形成,进而促进动脉粥样硬化和心血管疾病^[80]。肠道微生物代谢物则是肠道微生物影响心血管健康的关键媒介。例如,SCFAs(乙酸、丙酸、丁酸)具有抗炎和调节血压的作用,可以通过调控宿主的代谢过程和免疫反应改善心血管健康,而肠道中的三甲胺随血液循环进入肝后被氧化为氧化三甲胺,激活NF- κ B、MAPK等信号通路促进动脉粥样硬化、血栓性血管炎及相关肾损伤,增加心血管疾病风险^[81]。肠道微生物及代谢物与脑神经形成的双向信号传递机制被称为肠-脑轴。肠道微生物产生的生物活性化合物通过盲肠迷走神经和小肠背根神经节经肠神经系统传递到小肠交感神经节和副交感神经进入循环系统并向大脑发出信号^[82]。反之,大脑通过传入神经感应微生物代谢物,将肠道信息传递给中枢神经系统,从而抑制外周炎症,降低肠道通透性^[83]。所以,肠道受损不仅会影响动物机体健康还会增加疾病发生的风险。肠-器官轴可很好地解释肠道微生物及代谢物对宿主代谢的调控作用,但关于PEO是否通过此途径改善动物机体健康还鲜有报道。

4 小结与展望

PEO因来源广泛、生物学功能丰富,而在畜禽生产中得到了积极应用,但关于PEO调控肠道健康方面的研究多集中于猪、鸡等单胃动物上,而在反刍动物上的调控作用及机理仍有较大的研究空间。目前,已有大量研究表明,PEO可调控动物肠道微生物及其代谢物组成,但针对肠道微生物-代谢物-器官轴互作关系的调控作用和相关机制还有待进一步阐明。此外,PEO气味独特、挥发性强、提取工艺多元导致活性成分差异大等问题限制了其在实际生产中的推广。因此,PEO加工工艺还需进一步完善,提升包被技术,规范提取工艺,以便在畜牧生

产中最有效地优化PEO的使用。

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- (编辑 范子娟)