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植物精油对畜禽肠道健康、免疫调节和肉品质的研究进展

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摘　要: 近年来抗生素在畜禽养殖业中的滥用加重了病原菌的耐药性,增加了抗生素在农副产品中残留以及环境污染等问题。植物精油(PEO)是从植物中提取纯化的天然挥发性芳香物质,已经有大量研究证明其具有良好的抗菌、抗寄生虫、抗氧化和增强免疫的作用,并且毒性小、在动物体内几乎无残留。因此,使用 PEO 作为抗生素替代品引起了人们的关注。本文归纳了多种 PEO 的主要成分,总结了 PEO 对畜禽肠道健康、免疫调节和肉品质的影响及其作用机理,为 PEO 在畜牧业中的应用提供参考。

关键词: 植物精油;肠道健康;免疫调节;肉品质;应用前景

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中国是世界上最大的抗生素生产和使用国,同时也是抗生素滥用和细菌耐药性的重灾区。在畜禽生产中,抗生素可以改善动物生长性能、保障动物健康、减少疾病的发生和降低饲养成本。然而,抗生素的滥用导致大量抗生素被排放到了水土环境中,致使环境中细菌耐药性的日益严重。环境中的抗生素及耐药细菌一旦进入人体的肠道,将会破坏人体肠道的正常菌群稳态,对人体的肠道健康造成了严重的威胁;而残存于环境中的污染物,则加剧了细菌耐药对人体健康的影响。因此,欧盟、日本、韩国等国家或组织分别于 2006 年、2008 年和 2011 年禁止在饲料中使用抗生素作为促生长类药物饲料添加剂;我国农业农村部于 2019 年发布的 194 号公告称"自 2020 年 7 月 1 日起,饲料生产企业停止生产含有促生长类药物饲料添加剂(中药类除外)的商品饲料"[1]。因此,寻找新的更加安全、有效的抗生素替代品成为了畜牧业当前的研究热点。

植物精油(PEO)是从植物的各个部分,包括种子、根、茎、叶和果实[2-3],通过蒸汽蒸馏或溶剂萃取等方法获得的挥发性芳香物质[4-5]。目前,PEO 广泛应用在香料、化妆品、肥皂和药品中。同时,许多草本植物和香料精油也是受欢迎的食品调味品,如从大蒜、辣椒、肉桂和小茴香中提取的 PEO,具有增强食品风味、激发人们的进食欲望的作用。实际上,PEO 也是良好的抗生素替代品[6],因为 PEO 及其成分具有良好的抗菌[7-8]、降血脂[9]、抗氧化[10]、抗病毒[11-12]、抗虫[13-14]和抗炎作用[15],这些特性与抗生素在畜禽养殖业的作用相似。一些研究人员发现,在畜禽生产中,许多草本植物和 PEO 能够有效抑制有害病原微生物的生长繁殖、保护动物呼吸道及肠道健康、促进动物生长和减少应激[16-17]。PEO 与抗生素相比,具有安全性高、副作用小、成本低廉且资源丰富的优势[18]。因此,使用 PEO 作为新的抗生素替代品引起了人们的关注[19]。本文阐述了 PEO 对畜禽肠

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道健康、免疫调节和肉品质的作用,并提出了 PEO 未来的研究方向。

1 PEO 的生物活性成分

目前用于提取 PEO 的植物主要包括牛至、薰衣草、生姜、薄荷、丁香、肉桂、小茴香、迷迭香、鼠尾草、猫爪草和桉树等,提取方法主要包括蒸馏提取法、溶剂萃取法、过饱和法、树脂萃取法、蜡包埋法和冷压法[20]等。PEO 主要成分通常利用色谱分离,借助质谱进行鉴定,其组成成分主要包括萜烯类化合物(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(具有刺激性气味,含量较少)。PEO 组成成分中的大多数物质具有芳香气味,其中萜类化合物是中草药中的有效成分,具有多种药理活性,如祛痰、止咳、镇痛、消炎等[16-17],同时也是一类重要的天然香料,在畜禽养殖中发挥着替代抗生素促生长的作用。PEO 的各种成分含量受多种因素的影响,包括品种、环境条件、栽培方法、采摘季节时间、储存、加工工艺、提取方法和条件等[21-23]。几种常见 PEO 的主要成分可见表 1。

表 1 常见 PEO 及其主要成分

Table 1 Common PEO and main components

植物精油 PEO	主要成分 Main composition	含量 Content/%	参考文献 Reference
当归 Angelica root	α-蒎烯	24.7	[24]
	δ-3-胡萝卜素	10.5	
	α-水芹烯+月桂烯	10.8	
	柠檬烯	12.9	
	β-水芹烯	10.4	
	ρ-伞花烃	7.7	
佛手柑 Bergamot	β-蒎烯	7.7	[25]
	柠檬烯+β-水芹烯	39.4	
	γ-萜品烯	8.6	
	芳樟醇	11.1	
	乙酸芳樟酯	28.0	
柴胡 Cajuput	1,8-桉叶素	41.1	[26]
	对伞花烃	6.8	
	萜品油烯	5.9	
	α-松油醇	8.7	
豆蔻 Cardamon	1,8-桉叶素	33.7	[27]
	α-乙酸松油酯	44.8	
雪松木 Cedarwood	α-雪松烯	15.7	[28]
	β-雪松烯	43.7	
	γ-雪松烯	10.6	
香菜 Coriander	ρ-伞花烃	6.1	[29]
	芳樟醇	72.0	
小茴香 Dill	柠檬烯	50.9	[30]
	反式二氢香芹酮	10.4	
	香芹酮	20.3	
	莳萝油脑	36.3	
柠檬桉 Eucalyptus citriodora	香茅醛	72.8	[29]
	香茅醇	14.5	
天竺葵 Geranium	异薄荷酮	6.4	[31]
	香茅醇	42.0	
	香茅醛	5.5	
	香叶醇	14.2	
生姜 Ginger	香茅基甲酸酯	14.1	[32]
	柠檬醛	4.9	
	香叶醛+乙酸冰片酯	8.1	
	β-异丁烯二烯	22.1	
	芳基姜黄烯	14.5	
	β-桉叶醇	5.4	
杜松子 Juniperberry	α-蒎烯	33.7	[33]
	桧萜	27.6	
	月桂烯	5.5	
青柠 Lime	香叶醛	6.0	[34]
	柠檬烯	55.5	
	β-蒎烯	11.0	
	γ-松油烯	14.5	
柑桔 Mandarin	柠檬烯	79.5	[34]
	γ-松油烯	9.7	
肉豆蔻 Nutmeg	α-蒎烯	26.0	[29]
	β-蒎烯	15.0	
	桧萜	27.1	
	肉豆蔻醚	5.9	
胡椒 Pepper	α-蒎烯	9.0	[34]
	β-蒎烯	10.4	
	桧萜	19.4	
	δ-3-胡萝卜素	5.4	
	柠檬烯	17.5	
	β-石竹烯	14.7	
松树 Pinus	α-蒎烯	9.0	[34]
	β-蒎烯	10.4	
	桧萜	21.6	

续表 1

植物精油 PEO	主要成分 Main composition	含量 Content/%	参考文献 Reference
迷迭香 Rosemary	α-蒎烯	7.4	[30]
	β-蒎烯	5.0	
	1,8-桉叶素	43.6	
	樟脑	12.3	
鼠尾草 Sage	1,8-桉叶素	8.4	[35]
	α-侧柏酮	31.8	
	β-侧柏酮	33.2	
龙蒿 Tarragon	(Z)-β-罗勒烯	7.3	[35]
	(E)-β-罗勒烯	6.9	
	甲基胡椒酚	77.6	
尤加利桉树 Eucalyptus radiata	α-松油醇	14.0	[36]
	1,8-桉叶素	62~72	
鼠尾草 Clary Sage	芳樟醇	8.0	[29]
	乙酸芳樟酯	75.0	

2　PEO 对肠道健康的调控方式

肠道菌群的基因数量约是宿主基因的 100 倍,在宿主的整个生长阶段发挥着至关重要的作用,因此有报道将其描述为“被遗忘的器官”[37]。肠道菌群的类型和数量始终处于动态变化中,饮食是影响肠道菌群组成和活性最重要的因素之一[38]。PEO 中含有大量的酚、萜烯、醛和酮类物质,具有良好的抗菌活性,能够抑制革兰氏阴性菌、阳性菌和部分真菌的生长,尤其对革兰氏阳性菌的抑制效果更佳[39-41],而 PEO 的选择性抗菌会调节肠道菌群的平衡,改变肠道菌群多样性和相对丰度。目前有关 PEO 的抗菌机理尚不明确,不同类型的 PEO 可能通过不同途径来抑制微生物的生长。大蒜精油能够降低金黄色葡萄球菌生物膜的厚度,进而破坏细菌生物膜完整性,并导致细胞膜通透性增加,使细胞中 ATP 浓度和 pH 降低,细胞成分流失,最终导致细菌死亡,从而发挥抗菌作用[42]。而茶树精油则通过干扰遗传信息处理相关的基因表达,包括 DNA 复制、转录和修复,破坏这些基本功能,最终抑制细菌生长[43]。

PEO 可通过介导肠道菌群的平衡进而调节肠道菌群的代谢物,而肠道菌群的代谢物与肠道健康之间有着密切的联系[44-45]。肠道菌群能将未消化的食物转化为功能性代谢产物,如短链脂肪酸和吲哚类物质,帮助宿主消化吸收;或者产生有害代谢产物,如细菌外毒素,抑制肠道上皮细胞的增殖,影响宿主健康[46-47]。短链脂肪酸是主要的细菌代谢产物之一,可以作为能量直接被肠道上皮细胞利用,并改善肠道免疫功能[48],动物流行病学研究显示,细菌代谢产物短链脂肪酸能够减轻各种顽固性疾病症状,例如自闭症、溃疡性结肠炎和克罗恩病[49-51],尤其是丁酸脂,具有免疫调节、诱导细胞凋亡和抗癌等作用。从肉鸡盲肠中提取微生物并进行了培养,发现牛至精油能够增加粪肠球菌和乳酸杆菌的比例,并减少链球菌属相对丰度,菌群的改变增加了有益短链脂肪酸(尤其是乙酸和丁酸)的含量,进而改善肠道健康[52]。PEO 对动物肠道微生物及代谢产物的影响见表 2。

表 2　PEO 对动物肠道微生物及代谢产物的影响

Table 2　Effects of PEO on intestinal microflora and metabolites in animals

植物精油 PEO	动物 Animals	微生物及代谢产物 Microflora and metabolites	结果 Results	参考文献 Reference
甜橙精油 Sweet orange essential oil	高脂饮食小鼠	放线菌门(Actinobacteria)和拟杆菌门(Bacteroidetes)的相对丰度显著提高,而厚壁菌门(Fimicutes)的相对丰度显著降低,反映肠道炎症状态的内毒素含量显著降低	有维持肠道的屏障作用	[53]
肉桂醛精油 Cinnamon essential oil	炎症性肠病小鼠	肠道菌群的多样性和丰富性得到改善,其中螺杆菌属(*Helicobacter*)和拟杆菌属(*Bacteroides*)的数量减少,拟杆菌属 S24-7 家族(Bacteroides_S24-7)和产生短链脂肪酸的细菌数量增多,包括拟普雷沃菌属(*Alloprevotella*)和毛螺菌科 NK4A136 组(Lachnospiraceae NK4A136)	有效缓解炎症性肠病的症状	[54]

续表 2

植物精油 PEO	动物 Animals	微生物及代谢产物 Microflora and metabolites	结果 Results	参考文献 Reference
大蒜精油 Alicia	酒精性脂肪肝小鼠	改善肠道菌群组成,其中副杆菌属(*Parabacteroides*)、克罗诺杆菌属(*Cronobacter*)数量增多,厌氧棍状菌属(*Anaerotruncus*)、瘤胃球菌科(Ruminococcaceae)的数量减少	抑制了三酰甘油的产生,改善了肝炎相关指标	[55]
广藿香精油 Patchouli essential oil	小鼠	产生乳酸的细菌明显增加,如约翰逊乳杆菌(*Lactobacillus johnsoni*)、罗伊氏乳杆菌(*Lactobacillus reuteri*)、乳酸乳杆菌(*Lactococcus lactis*)和普拉梭菌(*Faecalibacterium prausnitzii*),同时乳杆菌属(*Lactobacillus*)和普拉梭菌属(*Faecalibacterium*)的相对丰度也显著增加,此外,双歧杆菌属(*Bifidobacterium*)的相对丰度增加了约 10 倍;显著降低病原菌,如萨特菌属(*Sutterlla* spp.)、死亡梭杆菌(*Fusobacterium mortiferum*)和幽门螺杆菌(*Helicobacter* spp.)的相对丰度	增加有益菌在菌群中的比例,维持肠道 pH 平衡,帮助宿主消化和保护肠黏膜	[56-57]
复合精油(八角茴香精油和百里香精油) Compound plant essential oils (*Illicium verum* essential oil and thymus mongolicus essential oils)	蛋鸡	在门水平上,盲肠中拟杆菌门的相对丰度升高,而厚壁菌门和梭杆菌门(Fusobacteria)的相对丰度降低,疣微菌科 UCG-005(Ruminococcaceae_UCG-005)、厌氧球菌属(*Anaerotruncus*)的相对丰度降低	帮助宿主的消化吸收,提高宿主对多糖物质的消化能力,有利于减轻肠道炎症	[58]
75%百里酚+25%肉桂醛 75% thymol + 25% cinnamaldehyde	肉鸡	盲肠菌群中乳酸杆菌和大肠杆菌的比例增加,盲肠乙酸和丁酸盐的比例增加,而丙酸和异戊酸的比例降低,此外,盲肠中精胺的比例增加	可以调节肠道菌群,改善菌群代谢产物,帮助宿主消化吸收,并提高生长性能	[59]
大蒜精油 Garlic essential oil	蛋鸡	盲肠中别样杆菌属、考拉杆菌属的相对丰度增加	有助于改善蛋鸡肠道组织形态,增加有益菌的定植,并提高产蛋性能	[60]

PEO 影响肠道黏膜免疫反应、上皮屏障功能、氧化应激和炎症反应,这可能是直接或间接地通过肠道菌群代谢物的差异表达来保护肠道屏障[61-62]。广藿香精油的添加会明显增加小鼠肠道中产短链脂肪酸细菌的丰度,如丁酸厌氧菌(*Anaerostipes butyraticus*)和乳杆菌(*Lactobacillus lactis*)等,明显降低病原菌丰度,如萨特菌属(*Sutterlla* spp.)、死亡梭杆菌(*Fusobacterium mortiferum*)和幽门螺杆菌(*Helicobacter* spp.)。肠道上皮细胞中短链脂肪酸的关键受体 G 蛋白受体(GPR)41、GPR 43 和 GPR 109a 被显著刺激,进一步促使肠道上皮中杯状细胞黏蛋白 2(*Muc* 2)基因表达,并且促进潘氏细胞分泌溶菌酶和防御素,使 E-钙黏蛋白/N-钙黏蛋白的比例升高(在溃疡性结肠炎和克罗恩疾病的患者中通常会检测到 E-钙黏蛋白的下调和 N-钙黏蛋白的上调)[63-64]。此外,紧密连接蛋白-1(*ZO*-1)和闭合蛋白(occludin)的表达量增加;参与炎症反应的Ⅰ型血管细胞黏附蛋白(*VCAM*-1)和细胞间黏附因子-1(*ICAM*-1)的表达均显著下调,*VCAM*-1 和 *ICAM*-1 主要在内皮细胞中表达,并负责聚集白细胞以激活炎症反应,这可能进一步刺激巨噬细胞由 M1 型

转变为 M2 型,进而减少诱导型一氧化氮合酶(iNOS)的活性缓解机体炎症水平,提高机体的抗炎能力[57]。在仔猪肠道组织的研究中,发现 PEO 能够改善肠道形态(绒毛高度升高,绒毛高度和隐窝深度的比值升高),提高蔗糖酶和乳糖酶的活性,促进与营养物质运输相关的关键蛋白的表达,如葡萄糖转运蛋白 2(*GLUT2*)和钠-葡萄糖协同转运蛋白 1(*SGLT1*),以及紧密连接蛋白(occludin)的表达[65-66]。这些结果表明,PEO 可以通过调节紧密连接蛋白的表达,提高消化酶的活性,增强肠道屏障,并改善肠道形态(图 1)。

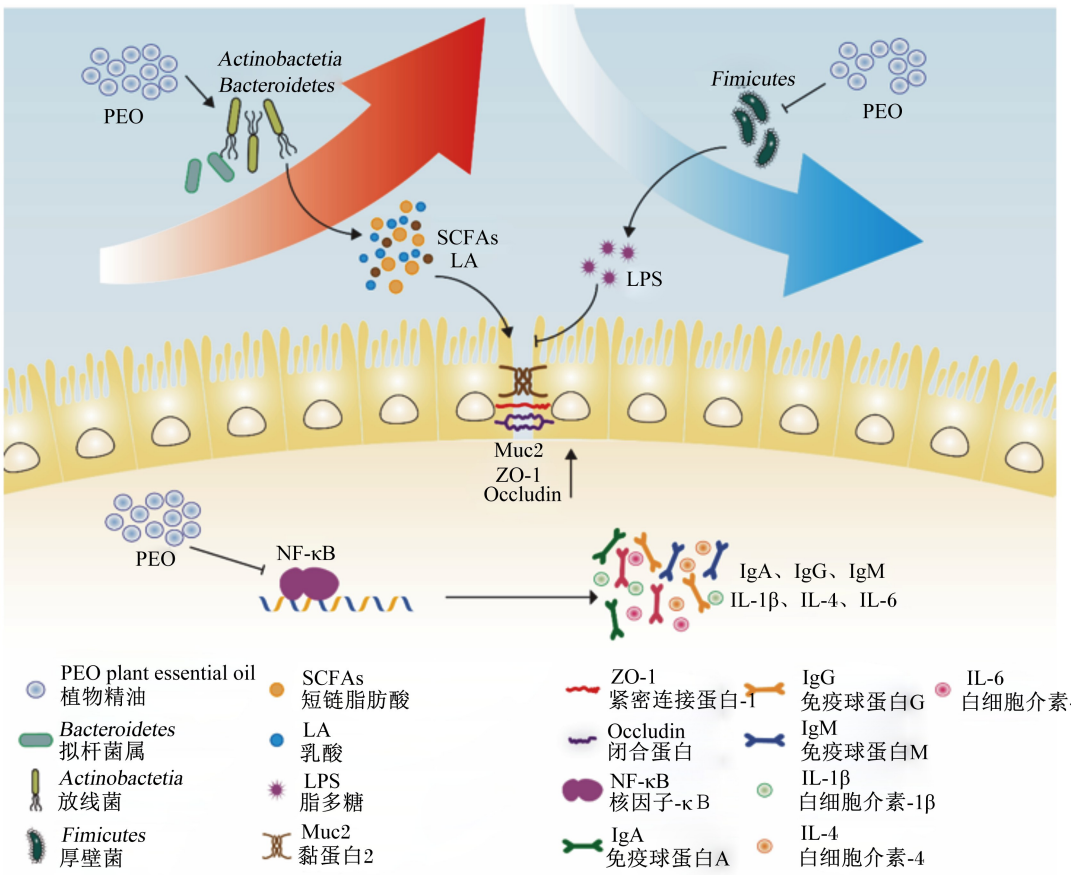

图 1　PEO 对肠道健康和免疫的影响

Fig.1　Effects of PEO on gut health and immunity[46-47,53,57,74]

3　PEO 在动物机体中的免疫调节作用

炎症是机体对不同类型有害因子的复杂免疫过程,包括病原微生物、刺激性化合物和有害物质等,它们会诱导急性炎症反应,反应一般持续时间较短,这对宿主健康是有益的。但是如果炎症持续存在或消退不充分,易引发宿主多种疾病,例如癌症、心血管、神经系统和免疫系统疾病等[67]。动物机体的免疫通常处于动态平衡,当动物机体的免疫系统遭受攻击时,如肠道菌群中过量的病原菌分泌的内毒素(LPS)或应激情况下导致的活性氧(ROS)失衡,会加速抑制蛋白(IκB)与核因子-κB(NF-κB)的解离,刺激 NF-κB 转移至细胞核内,转录因子 NF-κB 诱导大量的促炎蛋白表达,包括参与机体炎症、细胞凋亡和线粒体凋亡的细胞因子、趋化因子和酶等。同时,细菌 LPS 和应激均会传递信号给具有氧化应激感应能力的 Kelch 样环氧氯丙烷相关蛋白 1(Keap1)蛋白,接收信号的 Keap1 蛋白将与核因子 E2 相关因子(Nrf2)解离,并通过活化其下游基因产生抗氧化作用,有助于细胞清除过量的 ROS,抵抗外来有毒物质(图 2)。

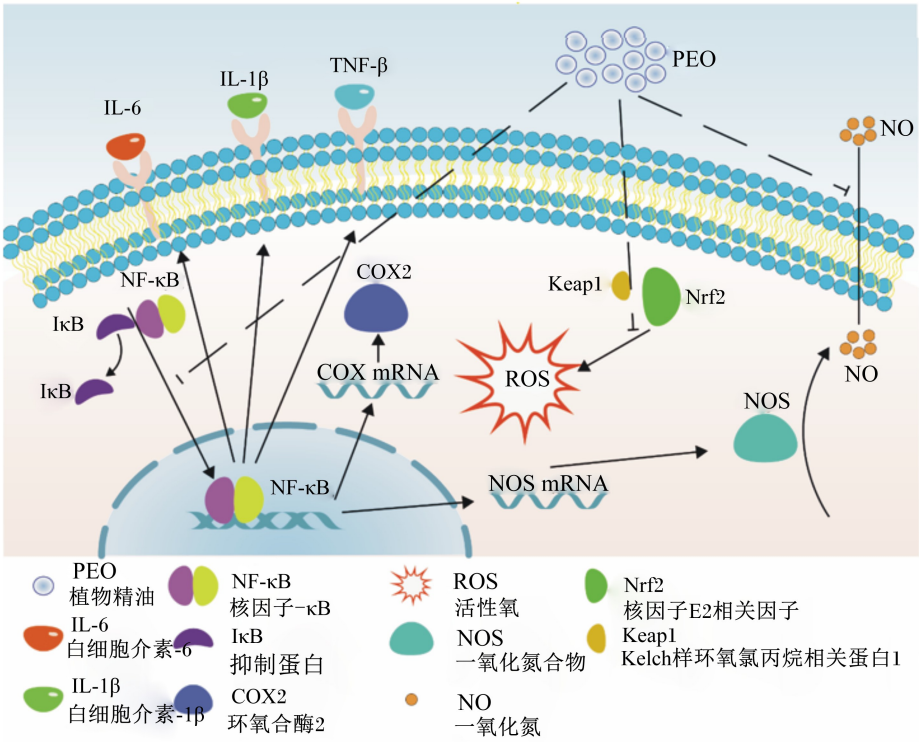

图 2 PEO 对免疫的影响

Fig.2 Effects of PEO on immune[68-69]

近年来,由于抗生素的使用受到了限制,PEO 作为抗生素替代品已成为人们关注的一种可能的天然添加剂。PEO 可促进动物对营养物质的消化吸收,减少肠道中病原菌的数量,调节免疫系统[70-71]。同时 PEO 主要成分中的萜烯类物质具有免疫调节特性,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[72]。当 Aβ 淀粉样蛋白处理 PC12 细胞时,桉树油主要功能性成分 1,8-桉叶素可以通过减缓 NF-κB 通路的激活,减少促炎细胞因子白细胞介素-6(IL-6)和白细胞介素-1β(IL-1β)的分泌,并抑制促炎通路相关的酶如环氧合酶-2(*COX*-2)和一氧化氮合酶(*NOS*)的转录表达,导致一氧化氮(NO)信号强度减弱,进而缓解线粒体损伤和细胞炎症水平[68]。大肠杆菌攻毒肉鸭后补充 PEO,能够缓解机体炎症反应,降低血清总蛋白和球蛋白含量,减少机体器官损伤以及通过减轻大肠杆菌对空肠 Toll 样受体 4(TLR4)的刺激而减少肿瘤坏死因子-α(TNF-α)、炎症细胞因子 IL-1β 和 IL-6 的分泌,增加免疫球蛋白 G(IgG)和免疫球蛋白 M(IgM)的含量,提高机体免疫功能[69]。PEO 对动物免疫系统的影响见表 3。

4 PEO 对肉品质的影响

PEO 的某些挥发性化合物成分具有天然抗氧化剂的潜力[79],由于 PEO 比合成抗氧化剂更容易被人们接受,因此使用 PEO 来改善肉品质成为了新的研究热点。目前有关 PEO 对肉品质影响的研究主要分为 2 个方向:1)通过在畜禽饮食中补充 PEO,改变机体脂质代谢来影响其肉品质[80];2)在肉制品中直接添加 PEO,利用 PEO 的抗氧化性保持肉品质的稳定,如使用 PEO 制作的生物膜包装密封肉制品或在肉制品中使用 PEO 作为抗氧化剂。

脂质是风味物质的重要前体物质,PEO 可能通过调节脂质代谢来影响肉的风味。辣椒素可以激活瞬时受体电位香草酸亚型 1(TRPV1)通道,阻止 3T3-L1 前脂肪细胞和内脏脂肪组织细胞中的脂肪生成[80]。此外,饮食中的姜黄素可以降低肝胆固醇合成,影响脂质代谢过程[81]。Yan 等[82]在仔猪饮食中添加了 0.01%的混合 PEO(包含百里香、迷迭香和牛至精油),发现混合 PEO 能够增

加眼肌面积,并改善猪肉颜色和大理石花纹评分。张云峰[83]发现 PEO 能够显著提高肉鸭肌肉的亮度值,提高系水率,降低剪切力并提高嫩度。然而,Ranucci 等[84]得到了与之矛盾的试验结果,在饲粮中补充迷迭香、大蒜、牛至或生姜的精油(500 mg/kg),结果表明并没有改变猪肉的脂肪酸谱,其他指标如蒸煮损失、滴水损失、剪切力值和化学成分也没有显著变化,但饲喂牛至精油的猪肉却呈现脂质氧化程度减少的趋势。因此,PEO 能否改变畜禽肉中的脂质组成有待进一步的研究证明。

表 3　PEO 对动物免疫系统的影响

Table 3　Effects of PEO on animal immune system

植物精油 PEO	动物 Animals	结果 Results	参考文献 Reference
桉树精油 *Eucalyptus* essential oil	人单核细胞衍生巨噬细胞	显著刺激其吞噬反应,并减少促炎细胞因子的释放,同时桉树精油可能通过补体受体介导的吞噬作用发挥其抗炎功能	[73]
广藿香酮 Pogostone	急性肺损伤小鼠	可抑制 LPS 诱导的促炎细胞因子 IL-1β、IL-6、TNF-α 和 iNOS 的分泌,有效促进了抗炎因子 IL-4 的分泌	[74]
混合精油 Mixture essential oils	小鼠	在健康小鼠中,丁香精油增加了白细胞数量,增强了延迟性超敏反应,而在经环磷酰胺免疫抑制的小鼠中,丁香精油恢复了细胞和体液免疫反应	[75]
百里香酚和肉桂醛的混合精油 Thymol and cinnamaldehyde mixture essential oils	仔猪	改善断奶仔猪的免疫状况,例如,提高淋巴细胞增殖率,吞噬率,并在血清中观察到更高的 IgG、IgA、IgM、C3 和 C4 含量	[65-66]
混合精油 Mixture essential oils	肉鸡	在疫苗接种后,血清中感染性新城疫、支气管炎和法氏囊病病毒的抗体滴度线性增加	[76]
混合精油 Mixture essential oils	大肠杆菌攻毒肉鸭	能够缓解机体炎症反应,降低血清总蛋白和球蛋白含量,减少机体器官损伤以及通过减轻大肠杆菌对空肠 TLR4 的刺激而减少炎症细胞因子 TNF-α、IL-β 和 IL-6 的分泌,提高机体免疫功能,提高抗体 IgG 和 IgM 的含量,提高法氏囊指数	[69]
牛至精油 Oregano essential oils	泌乳期母猪	母乳中 T 淋巴细胞数量增加,但对仔猪的免疫应答(免疫球蛋白浓度、T 淋巴细胞和自然杀伤细胞活性)没有影响	[77]
牛至精油 Oregano essential oils	肉鸡	对免疫反应(血清 IgG、IgM 含量和新城疫病毒抗体滴度)均无显著影响	[78]
1,8-桉叶素 1,8-cineole	Aβ 淀粉样蛋白处理的 PC12 细胞	恢复了细胞活力,降低线粒体膜电位和 ROS 水平,减少 TNF-α 分泌,降低促炎细胞因子 IL-1β 和 IL-6 含量	[68]

人们普遍认为,脂质氧化是造成储存过程中肉品质下降的主要原因,其次蛋白质的氧化也增加了肉的韧性,降低肉品质,因此调控肉制品的氧化过程也是改善肉品质的关键。PEO 常用作天然抗氧化剂用于阻止油脂和脂肪食品中脂质的过氧化过程。有关芳香 PEO 抗氧化活性的研究表明,富含百里香酚和香芹酚的牛至精油对氧化过程具有较大的抑制作用[85-86]。Kulisic 等[87]研究发现,牛至精油的抗氧化能力与 α-生育酚及合成的抗氧化剂丁基化羟基甲苯(BHT)相当,并发现牛至精油与其他抗氧化剂的协同作用也会增强整体抗氧化能力。在活性食品包装中使用 PEO 是未来的趋势,PEO 可以延长储存期间的食品稳定性,抑制腐败或病原微生物的生长,并防止食品氧化[88-90]。

Zhang 等[91]在鲤鱼真空包装袋中加入肉桂精油，发现能够降低肉中巨型球菌的相对丰度，抑制了气单胞菌属的生长，而乳酸菌相对丰度相对较高，其保质期延长了约 2 d。PEO 制成的活性食品包装的生物可降解薄膜，具有较强的防水性，不会对环境造成污染，对食品有很好的保鲜作用，具有广阔的应用前景[89]。

5 小 结

PEO 作为天然安全的抗生素替代品，尽管其抗菌性、抗氧化性和抗炎性已经得到了验证，但是 PEO 中含有复杂的功能性物质，对动物机体产生影响的机制尚未阐释清楚，例如 PEO 如何提高动物生长性能等。在畜牧行业中，为了更加安全有效地使用 PEO，未来 PEO 可能的研究方向集中在以下几个方向：

① 生物活性物质的鉴定和标准化。PEO 复杂的功能性成分存在着协同和拮抗的作用，明确 PEO 整体的功能特性与单一化学成分的研究同样重要。单一化学成分的研究有助于确定发挥关键作用的功能性物质，整体研究有助于明确协同和拮抗的最终结果。由于不同 PEO 的成分及含量差异较大，功能性物质的鉴定和标准化显得尤为重要。

② PEO 和其他添加剂的联合使用。PEO 与其他添加剂或混合精油的联合使用可能存在着相互作用，这种复杂的相互作用制约着精油的发展应用，合理的利用协同作用将 PEO 的抗菌性和抗氧化性最大化，降低有效作用时的最低添加水平，在当下畜牧业发展过程中具有重要生产意义。

③ PEO 对肠道健康的复杂调控机理。PEO 能够改善肠道健康已经被众多学者所证实。然而，PEO 对肠道菌群的调节、肠道菌群与宿主肠道健康的相互关系和潜在的分子机理过于复杂，不同 PEO 的作用机理可能存在差异，这些都有待于进一步研究探索。

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Research Progress of Plant Essential Oil on Intestinal Health, Immune Regulation and Meat Quality of Livestock and Poultry

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Abstract: In recent years, the abuse of antibiotics in livestock and poultry farming industry has aggravated the resistance of pathogens, the residue of antibiotics in agricultural and by-products, and environmental pollution. Plant essential oil (PEO) is a naturally volatile aromatic substance extracted from plants and has been shown to have good antibacterial, anti-parasite, antioxidant and immune-enhancing properties, as well as low toxicity and virtually no residue in animals, so the use of PEO as an antibiotic substitute has attracted attention. This paper summarized the main components of PEO, the effects of PEO on intestinal health, immune system and meat quality of livestock and poultry as well as the mechanism of action. It provided a theoretical basis for the application of PEO in animal husbandry.[***Chinese Journal of Animal Nutrition*, 2021, 33(5):2439-2451**]

Key words: plant essential oil; intestinal health; immune function; meat quality; application prospect

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