乳酸菌产共轭亚油酸研究现状

马青雯, 黄艾祥*

(云南农业大学食品科学技术学院, 昆明 650201)

摘 要: 共轭亚油酸(conjugated linoleic acid, CLA)是十八碳二烯酸的异构体。通过食物摄入的 CLA 不能达到每日推荐摄入量, 而 CLA 又具有减肥、抗癌、抗Ⅱ型糖尿病等多种生理功能, 故 CLA 逐渐成为研究热点。与化学合成 CLA 相比, 微生物合成 CLA 更具有优势。乳酸菌(lactic acid bacteria, LAB)具有安全性和益生功能, 利用乳酸菌合成 CLA 是一个理想的途径。目前已发现多种产 CLA 乳酸菌, 人们使用乳酸菌发酵油酸、牛乳、植物油合成 CLA, 并取得了良好的效果。亚油酸异构酶(linoleate isomerase, LAI)对乳酸菌合成 CLA 起重要作用, 但其对乳酸菌合成 CLA 的作用机理还不明确。一些学者对乳酸菌合成 CLA 的中间产物进行了研究, 发现乳酸菌合成 CLA 有多种中间产物。乳酸菌合成 CLA 的代谢机制目前尚不清楚。乳酸菌合成 CLA 对食品工业有重要意义, 也为功能性食品的开发提供了新机遇。本文主要对 CLA 的生理功能、产 CLA 乳酸菌、乳酸菌合成 CLA 的底物、乳酸菌合成 CLA 的途径进行了概述。

关键词: 乳酸菌; 共轭亚油酸; 发酵底物; 亚油酸异构酶; 功能性食品

Research progress on conjugated linoleic acid produced by *Lactobacillus*

MA Qing-Wen, HUANG Ai-Xiang*

(*College of Food Science and Technology*, *Yunnan Agricultural University*, *Kunming* 650201, *China*)

ABSTRACT: Conjugated linoleic acid (CLA) is an isomer of octadecadienoic acid. CLA intaken through food cannot reach the recommended daily intake, and there are many physiological functions about CLA, such as weight loss, anti-cancer, anti-type 2 diabetes, *etc*., so the CLA has gradually become a hot research topic. Compared with chemically synthesized CLA, CLA of microbial synthesis has more advantages. Lactic acid bacteria has safety and probiotic functions. The use of lactic acid bacteria to synthesize CLA is an ideal method. A variety of CLA-producing lactic acid bacteria have been found, people use lactic acid bacteria to ferment oleic acid, milk, and vegetable oil to produce CLA, and have achieved good results. Linoleic acid isomerase is important for synthesis of CLA by lactic acid bacteria, but its mechanism for the synthesis of CLA by lactic acid bacteria is not clear. Some scholars have studied the intermediate products of lactic acid bacteria to produce CLA, and found that there were many intermediate products of lactic acid bacteria to produce CLA. The metabolic mechanism of lactic acid bacteria to produce CLA is unclear. The produce of CLA by lactic acid bacteria is significance to the food industry and also provides new opportunities for the development of functional foods. This article provided an overview of the physiological functions of CLA, CLA-producing lactic acid bacteria, substrates for lactic acid bacteria to synthesize

基金项目: 云岭产业技术领军人才(云发改人事[2014]1782 号)、云南优质益生菌菌种选育及高原特色乳制品产业(2014ZA001)

Fund: Supported by the Yunling Mountains's Industrial and Technical Leaders ([2014] No.1782) and the High-Quality Probiotic Strain Selection and the Plateau Characteristics Dairy Industry of Yunnan (2014ZA001)

***通讯作者:** 黄艾祥, 博士, 教授, 主要研究方向为乳品科学及功能性食品。E-mail: 2979543745@qq.com

***Corresponding author:** HUANG Ai-Xiang, Ph.D, Professor, College of Food Science and Technology, Yunnan Agricultural University, Kunming 650201, China. E-mail: 2979543745@qq.com

CLA, and the ways for lactic acid bacteria to synthesize CLA.

KEY WORDS: lactic acid bacteria; conjugated linoleic acid; fermentation substrate; linoleic acid isomerase; functional food

1　引　言

共轭亚油酸(conjugated linoleic acid, CLA)是含有共轭双键的亚油酸(linoleic acid, LA)异构体[1]。天然的CLA主要存在于乳、乳制品[2]和反刍动物的肉中[3], 在菜籽油[4]、玉米胚芽油[5]、棉籽油[6]等植物油中也存在。每克乳脂肪中约含 5.5 mg 的 CLA[7], 每日通过食物摄入的CLA 远达不到成人的推荐摄入量(3 g/d)[8]。

乳酸菌(lactic acid bacteria, LAB)是动物肠道菌群的重要组成部分[9], 是公认的安全(generally recognized as safe, GRAS)微生物[10]。筛选可合成 CLA 的乳酸菌, 并利用乳酸菌合成 CLA 是一个良好的途径。本文主要对 CLA 的生理功能、产 CLA 乳酸菌、乳酸菌合成 CLA 的底物、乳酸菌合成 CLA 的途径进行概述, 以期对产 CLA 乳酸菌的筛选和 CLA 产品的开发提供理论依据。

2　共轭亚油酸的生理功能

2.1　减　肥

自 1997 年 Park 等[11]首次报道了 CLA 的减肥作用后, 目前已有较多研究证实了该观点。Qi 等[12]用 CLA 饲喂长白猪后, 发现 CLA 能显著降低猪背部和腹部脂肪沉积。Martins 等[13]在脂肪细胞分化 11 d后向细胞中分别添加t10, c12 或 t8, c10 CLA, 发现 t8, c10 CLA 可降低细胞内三酰基甘油(triacylglycerol, TAG)量, t10, c12 CLA 降低了与脂肪生成有关的基因表达水平。Yeganeh 等[14]用 CLA 对肥胖小鼠进行饮食干预后得到: CLA 可减少肥胖小鼠的内脏脂肪、腹股沟脂肪和肩胛间脂肪。由于 CLA 在减肥方面的显著效果, 目前已有较多的 CLA 减肥产品问世, CLA 减肥产品在国外发展迅速, 其中以美国的 CLA 减肥产品居多, 表 1 所示是我国常见的 CLA 减肥产品。

表 1　在我国常见的共轭亚油酸减肥产品统计
Table 1　Statistics of common conjugated linoleic acid weight loss products in China

产地	品牌
美国	MRM、GNC、Sports Research、PSP、Puritan's Pride、Nutrex、NOW
英国	MYPROTEIN、PhD
德国	Medicura、iRonMaxx
加拿大	Webber

2.2　抗　癌

Mccarty 等[15]提出过氧化物酶增殖物激活受体(peroxisome proliferators-activated receptors, PPARγ)可加速癌细胞凋亡并阻碍它们在体外和体内的扩增, 而 CLA 可以激活大鼠脂肪细胞中的 PPARγ, 从而起到广谱抗癌作用。宋琳亮[16]以 CLA 长期处理肝癌细胞模型, 发现 CLA 可以诱导肝癌细胞凋亡。张静姝等[17]探究了 CLA 对体外培养的胃腺癌细胞抑制作用, 结果显示 CLA 可通过调节 Δ6-脱氢酶和环氧合酶的表达, 进而抑制肿瘤细胞的增殖。Shahzad 等[18]研究了 CLA 对癌细胞的影响, 发现 CLA 可抑制卵巢癌细胞的增殖, 其中 165 个与促进癌细胞增值、迁移和侵袭基因的转录被显著抑制, 28 个抑制癌细胞增值的基因被上调。由于 CLA 的广谱抗癌性, CLA 有望在抗癌药中得到应用。

2.3　抗II型糖尿

近年来许多研究发现 CLA 在抗II型糖尿病有显著的作用, 有人提出 CLA 可作为治疗II型糖尿病的药物[19]。Nagao 等[20]使用添加了 CLA 的膳食饲喂糖尿病性脂肪(ZDF)大鼠 8 周后, ZDF 大鼠体内积累的血浆胰岛素和葡萄糖含量降低, 而血浆脂联素水平升高。Song 等[21]研究了含有 CLA 的发酵乳(FM)对 II 型糖尿病小鼠的抗糖尿病作用, 得到了与抗糖尿病药相似的结果: 与对照组相比, FM 喂养小鼠的体重、空腹血糖、血清胰岛素含量显著降低; 此外, FM 喂养小鼠的口服葡萄糖耐量和胰岛素耐受性显著改善。Garibay 等[22]将肥胖儿童和青少年随机分为二甲双胍、CLA 和安慰剂组, 发现干预对各组的体重、身高、身体质量指数(body mass index, BMI)、腰围、健康状况均有积极影响; CLA 组的胰岛素敏感性显著增加, 且高胰岛素血症和胰岛素抵抗明显改善; 此外, CLA 组儿童肌肉活检发现胰岛素受体底物 2(IRS-2)的表达上调。

2.4　其他生理功能

除了以上所述功能外, CLA 还具有抗炎[23]、降血压[24]、抗动脉粥样硬化[25]、增加骨骼密度[26]、抗氧化[27]、抗过敏[28]等生理功能。由此可见, CLA 的开发与应用将给人们带来很大的好处。

3　产 CLA 乳酸菌

目前的 CLA 产品均由化学合成。化学合成 CLA 的反应条件苛刻, 且伴有多种副产物[29]。相对于化学合成 CLA, 微生物合成 CLA 反应条件温和、且副产物较少。最早报道

的可合成 CLA 的微生物是溶纤维丁酸弧菌(*Butuivibrio fibrisolvens*)[30], 后来陆续有报道指出双歧杆菌(*Bifidobacterium*)[31]、乳酸菌(lactic acid bacteria, LAB)、丙酸杆菌(*Propionibacteria*)等也具有合成 CLA 的能力[24]。由于乳酸菌自身具备安全性和益生特性[32], 故许多学者对乳酸菌合成 CLA 进行了研究。张中义等[33]以 LA 为发酵底物, 从酸菜汁中筛选出一株产 CLA 的植物乳杆菌(*Lactobacillus plantarum*), CLA 产量可达到 267.5 μg/mL。刘春晓等[34]以 LA 为发酵底物, 从内蒙古酸油中得到一株产 CLA 的副干酪乳杆菌(*Lactobacillus paracasei*), CLA 产量达 23.586 μg/mL。Dahiya 等[35]从健康婴儿的粪便中分离出了能产(t11, c9)、(t10, c12)和(t9, c11)的 3 种 CLA 异构体的发酵乳杆菌(*Lactobacillus fermentum*)DDHI27, 经过优化发酵条件, 该菌的 CLA 产量达 500 μg/mL。Pandit 等[4]从奶酪和水牛乳中分离得到 7 株 CLA 产生菌, 分别为: 植物乳杆菌、布氏乳杆菌(*Lactobacillus buchneri*)、罗伊氏乳杆菌(*Lactobacillus reuteri*)、短乳杆菌(*Lactobacillus brevis*)、干酪乳杆菌(*Lactobacillus casei*)、瑞氏乳杆菌(*Lactobacillus helveticus*)。除以上提到的乳酸菌外, 保加利亚乳杆菌(*Lactobacillus bulgaricus*) [36]、费氏丙酸杆菌(*Propionibacterium faecalis*)[37]也具有产生 CLA 的能力。

4 乳酸菌合成 CLA 的底物

除 LA、牛乳外, 也可以使用乳酸菌发酵其他底物生产 CLA。Akinori 等[38]使用 *Lactobacillus plantarum* 于 37 ℃下发酵培养液初始 pH 值为 6.0 的蓖麻油 99 h, 发现该菌株能将蓖麻油转化成 CLA。Oezer 等[39]用 23 株 *Lactobacillus plantarum* 发酵水解葵花籽油, 发现经 *Lactobacillus plantarum*AA1-2 和 *Lactobacillus plantarum*AB20-961 发酵后, 发酵液中 CLA 含量升高; 该研究还发现: 葵花籽油添加量为 2%, 培养液初始 pH 值为 6.0 时, CLA 的生成量最高。菜籽油及其脚料也可作为乳酸菌生产 CLA 的底物: 李垚等[40]发现当培养液 pH 值为 6.5、脂肪酶添加量为 2 mg/30 mL 时, 以 40 mg/mL 嗜酸乳杆菌(*Lactobacillus acidophilus*)静息细胞于 36 ℃下发酵 7.5 mg/mL 菜籽油 25 h, CLA 产量可达到(230.12±7.52) μg/mL; 胡冰彬等[41]提出当摇床转速为 120 r/min, 培养基 pH 值为 8.0, 固定化乳酸菌浓度为 0.5 g/mL 时, 于 40 ℃下发酵菜籽油脚料 17 h, CLA 的产量达(261.65±3.21) μg/mL。此外, 也可利用乳酸菌发酵大豆油[42]、芝麻油[43]、红花籽油[44]、苜蓿籽油[45]生产 CLA。

5 乳酸菌转化 CLA 的途径

5.1 亚油酸异构酶

1971 年 Kepler 等[46]发现了亚油酸异构酶(linoleate isomerase, LAI), 这种酶可将亚油酸异构为 CLA。Zhang 等[47]将 *Lactobacillus reuteri*PYR8 的 LAI 基因克隆到毕赤酵母(*Pichia pastoris*)中, 气相色谱分析表明基因重组 *Pichia pastoris* 可将 LA 转化为 CLA。Irmak 等[48]将 *Lactobacillus acidophilu*ATCC 55739 的 LAI 粗酶与 LA 进行发酵后, LA 可被异构成 CLA。He 等[49]将痤疮丙酸杆菌(*Propionibacterium acnes*)的 LAI 基因成功克隆到酵母菌(*Yeast*)中并得到表达后, 使用重组 *Yeast* 发酵 LA 后可在发酵液中检测到 CLA。

虽然 LAI 被发现至今已有 49 年, 但是关于 LAI 的数据还较少。通过搜索美国国立生物技术信息中心(National Center for Biotechnology Information, NCBI)数据库中关于的 LAI 信息可得到: 数据库中收录的 LAI 有 13 种, 这 13 种 LAI 来自 13 种不同的菌株。表 2 所示是 NCBI 数据库中这 13 种 LAI 和分别对应菌株的基本信息。从表 2 可知这 13 种菌株中, 乳杆菌属的菌株最多(6 种), 占其中的 46.15%; 其次是双歧杆菌属(2 种)和链球菌属(2 种); 肉食杆菌属、乳球菌属、曲霉属的菌株各有 1 种。虽然 LAI 在形成 CLA 的过程中起重要作用, 但其在乳酸菌中产 CLA 的机制还不明确[41]。

5.2 乳酸菌转化 CLA 的中间产物

一些学者对乳酸菌产 CLA 的中间产物进行了研究。Ogawa 等[50]使用 *Lactobacillus acidophilus* 发酵 LA, 随着发酵时间的延长, 十八碳羟基脂肪酸的含量呈先上升后下降的趋势; 随着十八碳羟基脂肪酸含量的下降, 发酵液中 CLA 含量逐渐上升; 该研究指出, 十八碳羟基脂肪酸是 LA 转换为 CLA 的中间产物。Ortega 等[51]发现: *Lactobacillus plantarum* 的 *α*-烯醇化酶可使 LA 的羟基衍生物转换成 CLA。Yang 等[52]通过气相色谱-质谱联用仪测定得到: *Lactobacillus plantarum*ZS2058 将 LA 转化为 CLA 过程中有 3 种中间产物: 10-羟基-顺-12-十八碳烯酸、10-氧-顺-12-十八碳烯酸、10-氧-反-11-十八碳烯酸。该研究将 *Lactobacillus plantarum* ZS2058 的 LAI 基因在大肠杆菌(*E.coli*)中成功表达后, 以 LA 为底物, 重组 *E.coli* 发酵液中得到了 CLA 和 3 种与 *Lactobacillus plantarum* ZS2058 一致的中间产物。Kishino 等[53]认为 LAI 是一种由 CLA-HY、CLA-DH 和 CLA-DC 构成的多组分酶系, 该研究使用从 *Lactobacillus plantarum* 中发现的这 3 种酶构建了 3 个表达 CLA-HY, CLA-DH 和 CLA-DC 的大肠杆菌转化子, 当这 3 种转化子同时用作时, 发酵液中才会有 CLA 和中间产物。虽然目前的研究证明了乳酸菌合成 CLA 的过程中伴有中间产物, 但是其 CLA 合成机制有待于进一步研究。

6 展 望

我国居民对食物营养和食物功能的要求逐步提高, 非化学合成的功能性食品也越来越受到人们的喜爱。乳酸

菌由于其自身具有安全性和益生功能, 乳酸菌发酵生产的富含 CLA 的发酵食品, 为发酵食品迎来了新的发展机遇。在今后的研究中除了筛选高产 CLA 的乳酸菌, 将乳酸菌与发酵食品相结合, 提高乳酸菌在发酵食品中的 CLA 产量, 开发 CLA 含量高的发酵食品也是一个重要的研究方向。

表 2　NCBI 数据库中的亚油酸异构酶信息
Table2　Information of linoleic isomerase in NCBI database

序号	蛋白 ID 号	菌株名称	菌株分类
1	AEF13381.1	植物乳杆菌(*Lactobacillus plantarum*)ZS2058	乳杆菌目、乳杆菌科、乳杆菌属
2	CCC77580.1	植物乳杆菌(*Lactobacillus plantarum*)WCFS1	
3	ABB04107.1	嗜酸乳杆菌(*Lactobacillus acidophilus*)H42	
4	AEY68243.1	嗜酸乳杆菌(*Lactobacillus acidophilus*)H42	
5	ABB43157.1	嗜酸乳杆菌(*Lactobacillus acidophilus*)AS1.1854	
6	EIW15098.1	戊糖乳杆菌(*Lactobacillus pentose*)KCA1	
7	CCO09485.2	麦芽香肉杆菌(*Carnobacterium maltaromaticum*)LMA28	乳杆菌目、肉食杆菌科、肉食杆菌属
8	ADA63850.1	乳酸乳球菌亚种(*Lactococcus lactis subsp*)KF147	乳杆菌目、链球菌科、乳球菌属
9	CCB92366.1	唾液链球菌(*Streptococcus salivarius*)CCHSS3	乳杆菌目、链球菌科、链球菌属
10	AFV37144.1	化脓链球菌(*Streptococcus pyogenes*)A20	
11	CDL70825.1	动物双歧杆菌(*Bifidobacterium animalis subsp*)CECT 8145	双歧杆菌目、双歧杆菌科、双歧杆菌属
12	CCK35269.1	长双歧杆菌(*Bifidobacterium longum subsp*)CECT 7347	
13	CAK47170.1	黑曲霉(*Aspergillus niger*)CBS 513.88	散子囊菌目、曲霉科、曲霉属

参考文献

[1] Harvatine KJ, Boisclair YR, Bauman DE. Time-dependent effect of trans-10, cis-12 conjugated linoleic acid on gene expression of lipogenic enzymes and regulators in mammary tissue of dairy cows [J]. J Dairy Sci, 2018, 101(8): 7585–7592.

[2] Cicognini FM, Rossi F, Sigolo S, *et al*. Contents of conjugated linoleic acid isomers cis9, trans11 and trans10, cis12 in ruminant and non-ruminant meats available in the Italian market [J]. Ital J Anim Sci, 2016, 13(2): 124–124.

[3] Pimentel LL, Fontes AL, Salsinha AS, *et al*. Microbiological in vivo production of clna as a tool in the regulation of host microbiota in obesity control [J]. Hist Stud Nat Chem, 2018, 369–394.

[4] Tarling EJ, Ryan KJP, Bennett AJ, *et al*. Effect of dietary conjugated linoleic acid isomers on lipid metabolism in hamsters fed high-carbohydrate and high-fat diets [J]. Brit J Nutr, 2009, 101(11): 1630–1638.

[5] Zamaninour N, Ansar H, Djazayery A, *et al*. Black grapes can change the physiology of adipose tissue in high-fat diets containing flaxseed oil or corn oil in c57bl/6j Mice [J]. Curr Top Nutraceut R, 2016, 14(4): 265–272.

[6] Liu S, Yu B, Wang Z, *et al*. Highly selective isomerization of cottonseed oil into conjugated linoleic acid catalyzed by multiwalled carbon nanotube supported ruthenium [J]. RSC Adv, 2019, 9(36): 20698–20705.

[7] Benbrook CM, Davis DR, Heins BJ, *et al*. Enhancing the fatty acid profile of milk through forage-based rations, with nutrition modeling of diet outcomes [J]. Food Sci Nutr, 2018, 6(3): 681–700.

[8] Pandit A, Anand S, Kalscheur K, *et al*. Production of conjugated linoleic acid by lactic acid bacteria in milk without any additional substrate [J]. Int J Dairy Technol, 2012, 65(4): 603–608.

[9] Natalia Catalán, Villasante A, Wacyk J, *et al*. Fermented Soybean meal increases *Lactic acid bacteria* in gut microbiota of atlantic salmon (*Salmo salar*) [J]. Probiotics Antimicro, 2018, 10(3): 566–576.

[10] Marcello, Tagliavia, Aldo, *et al*. Advanced Strategies for food-grade protein production: A New *E. coli*/lactic acid bacteria shuttle vector for improved cloning and food-grade expression [J]. Microorganisms, 2019, 7(5):116–126.

[11] Park Y, Albright KJ, Liu W, *et al*. Effect of conjugated linoleic acid on body composition in mice [J]. Lipids, 1997, 32(8): 853–858.

[12] Qi RL, Chen Y, Huang JX, *et al*. Effects of conjugated linoleic acid on the expression levels of mir-27 and mir-143 in pig adipose tissue [J]. Genet Mol Res, 2015, 14(2): 6985–6992.

[13] Martins SV, Virgínia MRP, Madeira AP, *et al*. Novel anti-adipogenic properties of the individual trans 8, cis 10 conjugated linoleic acid (CLA) isomer in 3t3-l1 adipocytes [J]. Eur J Lipid Sci Technol, 2016, 119(2): 254–259.

[14] Yeganeh A, Zahradka P, Taylor CG. Trans-10, cis-12 conjugated linoleic acid (t10-c12 CLA) treatment and caloric restriction differentially affect adipocyte cell turnover in obese and lean mice [J]. J Nutr Biochem, 2017, 49: 123–126.

[15] Mccarty MF. Activation of ppargamma may mediate a portion of the

anticancer activity of conjugated linoleic acid [J]. Med Hypotheses, 2000, 55(3): 187–188.

[16] 宋琳亮. 共轭亚油酸对癌细胞 cox-2 和 pparγ 表达及调控的研究[D]. 北京: 中国农业大学, 2005.
Song LL. conjugated linoleic acid on the expression and regulation of cox-2 and pparγ in cancer cells [D]. Beijing: China Agricultural University, 2005.

[17] 张静姝, 陈炳卿, 高彦辉, 等. 共轭亚油酸对肿瘤细胞亚油酸代谢途径中限速酶的影响[J]. 中华预防医学杂志, 2005, 39(3): 195–198.
Zhang JS, Chen BQ, Gao YH, *et al*. Effects of conjugated linoleic acid on the expression of critical enzymes of linoleic acid metabolism in tumor cell [J]. Chin J Prev Med, 2005, 39(3): 195–198.

[18] Shahzad MMK, Felder M, Ludwig K, *et al*. Trans10,cis12 conjugated linoleic acid inhibits proliferation and migration of ovarian cancer cells by inducing er stress, autophagy, and modulation of src [J]. PLoS ONE, 2018, 13(1): e0189524.

[19] Pariza MW. Conjugated linoleic acid may be useful in treating diabetes by controlling body fat and weight gain [J]. Diabet Technol, 2002, 4(3): 335–338.

[20] Nagao K, Inoue N, Wang YM, *et al*. Conjugated linoleic acid enhances plasma adiponectin level and alleviates hyperinsulinemia and hypertension in Zucker diabetic fatty rats [J]. Biochem Bioph Res Co, 2003, 310(2): 561–566.

[21] Song K, Song IB, Gu HJ, *et al*. Anti-diabetic effect of fermented milk containing conjugated linoleic acid on type ii diabetes mellitus [J]. Korean J Food Sci An, 2016, 36(2): 170–177.

[22] Garibay NN, Queipo GG, Alvarez HF, *et al*. Conjugated linoleic acid and metformin on insulin sensitivity in obese children: randomized clinical trial [J]. J Clin Endocr Metab, 2016, 102(1): jc20162701.

[23] Viladomiu M, Hontecillas R, Bassaganya-riera J. Modulation of inflammation and immunity by dietary conjugated linoleic acid [J]. Eur J Pharmacol, 2016, 785(15): 87–95.

[24] 王武, 章立新, 潘见. 共轭亚油酸高产菌株的分离与鉴定[J]. 现代食品科技, 2016, (8): 128–133.
Wu W, Zhang LX, Jian P. Isolation and identification of conjugated linoleic acid-producing lactobacillus strains from fermented pickle brines [J]. Mod Food Sci Technol, 2016, (8): 128–133.

[25] Robyn B, Stephen F, Orina B. Atheroprotective effects of conjugated linoleic acid [J]. Brit J Clin Pharmaco, 2016, 83(1): 46–53.

[26] Deguire JR, Mak IL, Lavery P, *et al*. Orchidectomy-induced alterations in volumetric bone density, cortical porosity and strength of femur are attenuated by dietary conjugated linoleic acid in aged guinea pigs [J]. Bone, 2015, 73: 42–50.

[27] Qi X, Wang J, Yue H, *et al*. Trans10, cis12-conjugated linoleic acid exhibits a stronger antioxidant capacity than cis9, trans11-conjugated linoleic acid in primary cultures of laying hen hepatocytes [J]. Poultry Sci, 2018, 97(12): 4415–4424.

[28] Nakanishi T, Tokunaga Y, Yamasaki M, *et al*. Orally administered conjugated linoleic acid ameliorates allergic dermatitis induced by repeated applications of oxazolone in mice [J]. Anim Sci J, 2016, 87(12): 1554–1561.

[29] Yang B, Gao H, Stanton C, *et al*. Bacterial conjugated linoleic acid production and their applications [J]. Prog Lipid Res, 2017, 68: 26–36.

[30] Kepler CR, Hirons KP, Mcneill JJ, *et al*. Intermediates and products of the biohydrogenation of linoleic acid by butyrinvibrio fibrisolvens [J]. J Biol Chem. 1966, 241: 1350–1354.

[31] Neeru J, Sachin K, Prasanta KC, *et al*. Isolation, characterization and conjugated linoleic acid production potential of bifidobacterial isolates from ruminal fluid samples of murrah buffaloes [J]. Anaerobe, 2019, 56: 40–45.

[32] Sosa-Castañeda J, Hernández-Mendoza A, Astiazarán-García H, *et al*. Screening of *Lactobacillus* strains for their ability to produce conjugated linoleic acid in milk and to adhere to the intestinal tract [J]. J Dairy Sci, 2015, 98(10): 6651–6659.

[33] 张中义, 胡锦蓉, 刘萍, 等. 产共轭亚油酸乳酸菌的筛选及产物分析[J]. 中国农业大学学报, 2004, 9(3): 5–8.
Zhang ZY, Hu JR, Liu P, *et al*. Screening of conjugated linoleic acid producing lactic acid bacteria and its product analysis [J]. J Chin Agric Univ, 2004, 9(3): 5–8.

[34] 刘春晓, 李佳宇, 刘乃齐, 等. 内蒙古锡林郭勒盟地区传统奶油制品中产共轭亚油酸乳酸菌的分离筛选与鉴定[J]. 食品科学, 2016, 37(9): 186–191.
Liu CX, Li JN, Liu NQ, *et al*. Isolation, screening and identification of lactic acid bacteria with conjugated linoleic acid-producing from traditional cream products in Xilingol league of Inner Mongolia [J]. Food Sci, 2016, 37(9): 186–191.

[35] Dahiya DK, Puniya AK. Optimisation of fermentation variables for conjugated linoleic acid bioconversion by *Lactobacillus fermentum* ddhi27 in modified skim milk [J]. Int J Dairy Technol, 2017, 71(1): 46–55.

[36] Lin TY, Hung TH, Cheng T. Conjugated linoleic acid production by immobilized cells of *Lactobacillus delbrueckii* ssp. bulgaricus and lactobacillus acidophilus [J]. Food Chem, 2005, 92(1): 23–28.

[37] Wang LM, Lv JP, Chu ZQ, *et al*. Production of conjugated linoleic acid by propionibacterium freudenreichii [J]. Food Chem, 2007, 103(2): 313–318.

[38] Akinori A, Jun O, Shigenobu K, *et al*. Conjugated linoleic acid production from castor oil by *Lactobacillus plantarum* jcm 1551 [J]. Enzyme Microb Technol, 2004, 35(1): 40–45.

[39] Oezer CO, Kilic B, Kilic GB. *In-vitro* microbial production of conjugated linoleic acid by probiotic l. plantarum strains: Utilization as a functional starter culture in sucuk fermentation [J]. Meat Sci, 2016, 114: 24–31.

[40] 李垚, 徐尔尼, 杨欣, 等. 嗜酸乳杆菌转化菜籽油生成共轭亚油酸条件的优化[J]. 食品与发酵工业, 2013, (3): 38–43.
Li Y, Xu EN, Yang X, *et al*. Optimization of the conditions for conversion of colza oil into conjugated linoleic acid by *Lactobacillus acidophilus* [J]. Food Ferment Ind, 2013, (3): 38–43.

[41] 胡冰彬, 徐颖宣, 范相振, 等. 固定化乳酸菌 3-9 转化菜油脚生成共轭亚油酸研究[J]. 安徽农业大学学报, 2015, 42(3): 398–404.
Hu BB, Xu YX, Fan XZ, *et al*. Immobilized lactic acid bacteria 3-9 for a conversion of rapeseed oil sediment into conjugated linoleic acid [J]. J Anhui Agric Univ, 2015, 42(3): 398–404.

[42] 侯俊财, 刘艳平, 桂仕林, 等. 大豆油对瘤胃培养液中共轭亚油酸及氢化中间产物累积规律的影响[J]. 畜牧兽医学报, 2008, 39(4): 449–454.
Hou JC, Liu YP, Gui SL, *et al*. Effects of soybean oil on concentrations of conjugated linoleic acid and accumulation of intermediates of ruminal biohydrogenation *in vitro* [J]. J Anim Sci Veter Med, 2008, 39(4): 449–454.

[43] 张中洲, 曹健, 罗宇, 等. 费氏丙酸杆菌谢氏亚种转化芝麻油生成共轭亚油酸的研究[J]. 食品科技, 2010, (1): 34–37.
Zhang ZZ, Cao J, Luo Y, *et al*. Study on cla production from sesame oil by *Propionibacterium shermanii* [J]. Food Sci Technol, 2010, (1): 34–37.

[44] 丁晨旭, 张秋龙, 刘斌, 等. 一种嗜酸乳酸杆菌连续多批次转化红花籽油合成共轭亚油酸的方法: 中国, CN 105154482a [P]. 2015-12–16.
Ding CX, Zhang QL, Liu B, *et al*. Method for synthesizing conjugated linoleic acid by continuously transforming safflower seed oil of *Lactobacillus acidophilus* in multiple batches: China, CN105154482a [P]. 2015-12-16.

[45] 董明, 齐树亭. 乳酸菌发酵生产共轭亚油酸[J]. 中国油脂, 2007, (7): 61–63.
Dong M, Qi ST. Production of conjugated linoleic acid by fermentation with *Lactobacillus* [J]. China Oils Fats, 2007, (7): 61–63.

[46] Kepler CR, Tucker WP, Tove SB. Biohydrogenation of unsaturated fatty acids. stereospecificity of proton addition and mechanism of action of linoleic acid Δ12-cis, Δ11-trans-isomerase from *Butyrivibrio fibrisolvens* [J]. J Biol Chem, 1971, 246(9): 2765–2771.

[47] Zhang YH , Zhang LW , Hu S, *et al*. Expression of linoleate isomerase gene from *Lactobacillus reuteri* pyr8 in pichia pastoris [J]. J Zhejiang Univ-SCA, 2006, 505–510.

[48] Irmak S, Dunford NT, Gilliland SE, *et al*. Biocatalysis of linoleic acid to conjugated linoleic acid [J]. Lipids, 2006, 41(8): 771–776.

[49] He X, Shang J, Li F, *et al*. Yeast cell surface display of linoleic acid isomerase from *Propionibacterium acnes* and its application for the production of trans-10, cis-12 conjugated linoleic acid [J]. Biotechnol Appl Bioc, 2015, 62(1): 1–8.

[50] Ogawa J, Kishino S, Ando A, *et al*. Production of conjugated fatty acids by lactic acid bacteria [J]. J Biosci Bioeng, 2005, 100(4): 355–364.

[51] Ortega AJ, Hernández SA. Production of bioactive conjugated linoleic acid by the multifunctional enolase from *Lactobacillus plantarum* [J]. Int J Biol Macromol, 2016, 91: 524–535.

[52] Yang B, Chen H, Gu Z, *et al*. Synthesis of conjugated linoleic acid by the linoleate isomerase complex in food-derived lactobacilli [J]. J Appl Microbiol , 2014, 117(2): 430–439.

[53] Kishino S, Park SB, Takeuchi M, *et al*. Novel multi-component enzyme machinery in lactic acid bacteria catalyzing cc double bond migration useful for conjugated fatty acid synthesis [J]. Biochem Bioph Res Co, 2011, 416(1-2): 188–193.

(责任编辑: 于梦娇)

作者简介

马青雯, 硕士, 主要研究方向为食品微生物。
E-mail: 1289280605@qq.com

黄艾祥, 博士, 教授, 主要研究方向为乳品科学及功能性食品。
E-mail: 2979543745@qq.com