

岩藻黄素的药理作用及药物设计研究进展^Δ

张育新^{1*}, 邓子洋², 王 灿¹, 曾 丹³ (1. 重庆大学材料科学与工程学院, 重庆 400043; 2. 四川大学华西药学院, 成都 610207; 3. 重庆大学附属人民医院/重庆市人民医院过敏反应科, 重庆 401121)

中图分类号 R965 文献标志码 A 文章编号 1001-0408(2025)17-2216-05
DOI 10.6039/j.issn.1001-0408.2025.17.23



摘 要 岩藻黄素是一种广泛存在于藻类、海洋浮游生物和水生贝壳等动植物中的类胡萝卜素,在医药领域具有巨大的开发潜力。本文综述了岩藻黄素在抗炎、抗氧化、抗肿瘤和抗肥胖方面的药理作用及其在药物设计方面的研究进展,发现其可通过激活AMP活化的蛋白质激酶等相关信号通路、调控炎症因子表达、改善菌群稳态等发挥抗炎、抗氧化作用,从而改善代谢相关脂肪性肝病、结肠炎等;可通过多靶点协同作用发挥选择性抗肿瘤效应;可通过调控肠道菌群等发挥抗肥胖作用;其特征性官能团(如羟基、环氧基团等)具有靶点选择性与可逆抑制活性,可作为优化模板指导新型药物设计开发,为突破传统药物设计局限提供了新思路。

关键词 岩藻黄素;药理作用;药物设计;官能团;研究进展

Pharmacological effects and drug design research progress of fucoxanthin

ZHANG Yuxin¹, DENG Ziyang², WANG Can¹, ZENG Dan³ (1. College of Materials Science and Engineering, Chongqing University, Chongqing 400043, China; 2. West China School of Pharmacy, Sichuan University, Chengdu 610207, China; 3. Allergy Department, Chongqing People's Hospital Affiliated to Chongqing University/Chongqing General Hospital, Chongqing 401121, China)

ABSTRACT Fucoxanthin is a pigment found in plants and animals such as algae, marine plankton and aquatic shellfish, and holds significant potential for development in the pharmaceutical field. This review introduces the anti-inflammatory, antioxidant, anticancer, anti-obesity, and other pharmacological effects of fucoxanthin, as well as recent advances in drug design research. It was found that fucoxanthin can exert anti-inflammatory and antioxidant effects through mechanisms such as activating AMP-activated protein kinase related signaling pathways, regulating the expression of inflammatory factors, altering microbial stability, thereby improving conditions such as metabolic associated fatty liver disease and colitis. It can exert selective antitumor effects through multi-target synergistic actions; and it was also found that it can exert anti-obesity effects by regulating the intestinal microbiota. Its characteristic functional groups (such as hydroxyl and epoxy groups) possess target specificity and reversible inhibitory properties, making it a suitable template for guiding the design and development of novel drugs, thereby providing new insights for breaking through the limitations of traditional drug design.

KEYWORDS fucoxanthin; pharmacological effects; drug design; functional groups; research progress

岩藻黄素(fucoxanthin)属类胡萝卜素中叶黄素类天然色素,也被称为岩藻黄质、褐藻黄素,占天然类胡萝卜素的10%以上^[1]。岩藻黄素广泛存在于各种藻类、海洋浮游生物、水生贝壳等动植物中,尤其是在褐藻、硅藻、金藻以及黄绿藻中的含量最为丰富^[1]。岩藻黄素的化学结构式如图1所示,其中的酯基能够减少其细胞毒性,羟基和共轭双键可使其展现出抗氧化特性,这提示岩藻黄素可能具有多种药理作用,有望将其开发成一种低毒性、高选择性的理想药物。基于此,本文从抗炎、抗氧

化、抗肿瘤、抗肥胖等方面综述岩藻黄素的药理作用,并简要概述其在未来药物设计中的研究潜能,以期岩藻黄素的开发及应用提供参考。

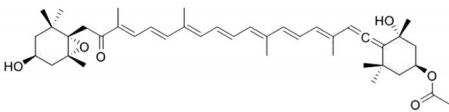


图1 岩藻黄素的化学结构式

1 岩藻黄素的药理作用

1.1 抗炎与抗氧化作用

目前尚无治疗代谢相关脂肪性肝病(metabolic associated fatty liver disease, MAFLD)的特效药物,因此寻找

^Δ基金项目 国家自然科学基金项目(No.52378217)
*第一作者 教授,博士生导师,博士。研究方向:岩藻黄素提取及医工交叉。E-mail: zhangyuxin@cqu.edu.cn

MAFLD的潜在治疗药物至关重要。研究发现,岩藻黄素可通过升高MAFLD小鼠体内超氧化物歧化酶、谷胱甘肽过氧化物酶和肉碱乙酰转移酶水平,降低丙二醛和炎症因子白细胞介素 1β (interleukin- 1β , IL- 1β)、IL-6和肿瘤坏死因子 α (tumor necrosis factor α , TNF- α)水平,从而降低MAFLD小鼠的氧化应激水平,并发挥良好的抗炎作用^[2]。有研究团队通过构建脂肪积累的HepG2细胞与肥胖ob/ob小鼠模型发现,岩藻黄素可通过激活AMP活化的蛋白质激酶(AMP-activated protein kinase, AMPK)信号通路,促进糖酵解和脂肪酸氧化;可通过激活AMPK/Kelch样ECH相关蛋白1/核转录因子红系2相关因子2(nuclear factor-erythroid 2-related factor 2, Nrf2)信号通路,清除过量的活性氧(reactive oxygen species, ROS),改善肝脏脂质代谢;可通过激活AMPK/过氧化物酶体增殖物激活受体 γ 辅激活因子 1α (peroxisome proliferator-activated receptor γ coactivator 1α , PGC 1α)信号通路,促进脂肪酸进入线粒体发生氧化分解^[3-4]。

岩藻黄素可通过强化氧化应激防御系统、抑制促炎细胞因子表达、诱导免疫调节反应以及重塑肠道菌群稳态,改善结肠炎病理进程^[5]。体内研究表明,岩藻黄素可降低肥胖小鼠血清脂多糖水平以及回肠组织中IL-6、TNF- α 表达水平,从而减轻炎症反应^[6]。另有研究发现,岩藻黄素可通过抑制Janus激酶2(Janus kinase 2, JAK2)/信号转导及转录活化因子3(signal transducer and activator of transcription 3, STAT3)信号通路,显著下调结肠上皮细胞NCM460中磷酸化JAK2、磷酸化STAT3、诱导型一氧化氮合酶、环氧合酶2、IL- 1β 、IL-6的表达,抑制促凋亡蛋白——B细胞淋巴瘤2相关X蛋白分泌,从而减轻结肠炎症;同时,该研究还发现,岩藻黄素与JAK2结构域存在稳定结合位点,这为岩藻黄素靶向干预结肠炎提供了生物学证据^[7]。

在卵清蛋白诱导的哮喘小鼠模型中,岩藻黄素可显著降低模型小鼠体内ROS水平,并增强相关抗氧化酶活性^[8]。在代谢综合征大鼠模型中,岩藻黄素可逆转模型大鼠高血压/糖尿病相关器官(如肝、胰、肾)的抗氧化剂耗竭状态,恢复内源性抗氧化物质的生物水平,从而减轻氧化应激^[9]。另外,岩藻黄素还可通过与Nrf2系统中的Kelch相关蛋白发生反应,促进小鼠胚胎肝细胞BNL CL2中相关抗氧化剂的表达,进而发挥抗氧化协同效应^[10]。岩藻黄素还可上调RAW 264.7巨噬细胞中 γ -谷氨酰半胱氨酸和瓜氨酸表达水平,促进谷胱甘肽生物合成,增强 γ -谷氨酰循环,从而抑制炎症反应,改善急性肺损伤^[11]。

综上,岩藻黄素可通过激活AMPK等相关信号通

路、调控炎症因子表达、改善菌群稳态等,发挥抗炎、抗氧化作用,从而改善MAFLD、结肠炎、急性肺损伤等。

1.2 抗肿瘤作用

癌症治疗中,天然产物的多靶点调控优势逐渐受到关注^[12]。岩藻黄素可直接通过调控细胞周期,诱导肿瘤细胞凋亡,从而特异性杀伤肿瘤细胞以保证正常细胞的存活,极大地提升了治疗的安全性和有效性^[13]。岩藻黄素能够治疗神经胶质瘤、宫颈癌、鼻咽癌、胃癌等多种癌症。Salami等^[14]研究发现,岩藻黄素对人胶质瘤细胞U87、U251表现出明显的细胞毒作用,其作用机制与上调促凋亡蛋白表达,抑制磷脂酰肌醇3激酶/蛋白激酶B/哺乳动物雷帕霉素靶蛋白(phosphoinositide 3-kinase/protein kinase B/mammalian target of rapamycin, PI3K/Akt/mTOR)信号通路有关。还有研究发现,在宫颈癌细胞HeLa、SiHa、CaSki中,岩藻黄素可通过调控PI3K/Akt/核因子 κ B(nuclear factor κ B, NF- κ B)信号通路,上调肿瘤坏死因子相关凋亡诱导配体的表达,从而选择性杀伤宫颈癌细胞^[15]。Long等^[16]研究证实,岩藻黄素可通过诱导自噬,抑制鼻咽癌细胞C666-1增殖。Yu等^[17]研究发现,岩藻黄素可通过抑制STAT3信号通路,诱导胃癌细胞SGC-7901、BGC-823的细胞周期阻滞,进而促进细胞凋亡。有研究表明,岩藻黄素可通过调节胃癌细胞HGC-27中血管内皮生长因子C(vascular endothelial growth factor C, VEGF-C)的分泌,抑制淋巴内皮细胞的成管能力;动物实验结果显示,岩藻黄素可通过下调淋巴内皮细胞中透明质酸受体1、VEGF-C及其受体的表达,抑制胃癌淋巴管生成,从而切断胃癌细胞的营养供给与转移路径^[18]。

综上,岩藻黄素可通过多靶点协同作用发挥选择性抗肿瘤效应,并且具有高选择性。

1.3 抗肥胖作用

相关研究发现,岩藻黄素的复方制剂Xanthigen在151例肥胖女性(体重指数 $>30\text{ kg/m}^2$)的临床治疗中展现出显著减重效果^[19]。Hitoe等^[20]也证实,连续4周给予岩藻黄素胶囊制剂治疗后,超重人群(体重指数 $>25\text{ kg/m}^2$)的体重、内脏脂肪水平均显著下降。在Kawee-Ai等^[21]构建的脂肪细胞模型中,5、10、20 $\mu\text{mol/L}$ 的岩藻黄素可浓度依赖性地抑制细胞的脂质沉积(脂质含量分别下降90.27%、88.05%、77.43%)。

岩藻黄素可通过激活产热通路直接干预能量代谢。有研究证明,岩藻黄素可通过上调棕色脂肪组织中解偶联蛋白1(uncoupling protein 1, UCP-1)的表达,促进 β_3 -肾上腺素受体(β_3 -adrenoceptor, β_3 ADR)合成,从而促进线粒体的解偶联作用,增强能量消耗,进而阻止肥胖

进展^[22-23]。

此外,岩藻黄素还可以通过重塑肠道菌群稳态、调控产热方式等间接发挥抗肥胖作用。在肥胖小鼠模型中,0.05%~0.1%的岩藻黄素可逆转厚壁菌门的过度增殖及拟杆菌门相对丰度的减少,增加双歧杆菌属、乳杆菌属的相对丰度,改善肠道菌群失调,进而改善小鼠肥胖症状^[6]。Hao等^[24]研究发现,岩藻黄素可升高高脂饮食喂养小鼠肠道菌群的Chao1、ACE指数,促进小鼠体重逐渐恢复至正常水平。拟杆菌门可促进初级胆汁酸向次级胆汁酸转化,后者通过激活法尼醇X受体和G蛋白偶联受体5介导的环磷酸腺苷(cyclic adenosine monophosphate, cAMP)信号通路,调控葡萄糖-脂质代谢^[25]。由此可见,岩藻黄素可能是通过改变肠道菌群功能,增强初级胆汁酸转化,从而介导cAMP信号通路发挥调控代谢的作用。岩藻黄素还可通过多层级分子调控网络实现抗肥胖疗效。例如,岩藻黄素可抑制脂肪生成关键转录因子过氧化物酶体增殖物激活受体 γ (peroxisome proliferator-activated receptor γ , PPAR γ)、PGC1 α 、CCAAT/增强子结合蛋白 α 及固醇调节元件结合蛋白1c的表达,上调UCP-1蛋白的表达,从而改善肥胖小鼠的代谢综合征^[22]。岩藻黄素还可通过调控肠道菌群代谢产物短链脂肪酸水平来激活AMPK信号通路,从而增强胰岛素敏感性,进一步诱导UCP-1介导的产热效应^[26-27]。值得注意的是,长期补充岩藻黄素,可调控糖尿病小鼠PPAR γ 、PGC1 α 等蛋白的表达,进而抑制脂肪细胞的分化^[28]。

综上,岩藻黄素可通过调控肠道菌群、 β_3 ADR/UCP-1信号通路等发挥抗肥胖作用,是一种具有开发潜力的减肥药物。

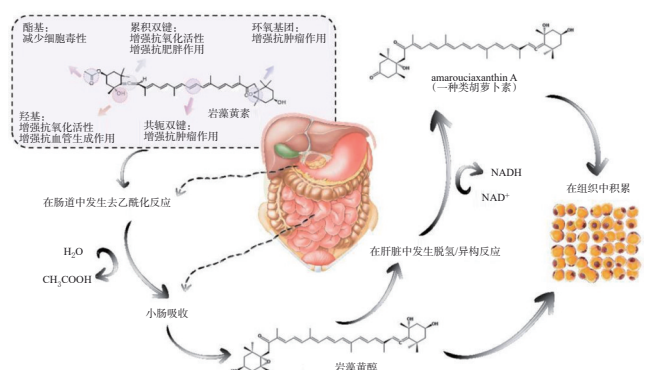
1.4 其他作用

岩藻黄素在保护视网膜、抗焦虑等领域也展现出独特的作用潜力。研究表明,岩藻黄素可促进视网膜色素上皮(retinal pigment epithelium, RPE)细胞中ROS水平恢复正常^[29],还可通过修复RPE细胞的吞噬功能,上调C-Mer原癌基因酪氨酸激酶、整合素 α V β 5的表达,激活L型钙离子通道,从而显著改善RPE细胞的吞噬指数,进而发挥视网膜保护作用^[30]。Jiang等^[31]研究表明,岩藻黄素可显著下调焦虑小鼠海马、前额叶皮层及下丘脑组织中IL-1 β 、IL-6及环氧合酶2蛋白表达,升高AMPK磷酸化水平,抑制NF- κ B p65核转位,从而显著缓解小鼠的焦虑样行为。

2 岩藻黄素的药物设计研究潜能

岩藻黄素的药理活性与其独特的分子结构密不可分。岩藻黄素结构中的羟基、共轭双键及环氧基团构成

了其独特的结构功能域,这些特征性官能团不仅可直接参与清除自由基、调控信号通路等生物学过程,还能为岩藻黄素的药物设计提供天然模板。岩藻黄素及其衍生物(岩藻黄醇等)的分子结构和特性,以及其在人体中的转化过程如图2所示。



NADH: 烟酰胺腺嘌呤二核苷酸(还原型); NAD⁺: 烟酰胺腺嘌呤二核苷酸(氧化型)。

图2 岩藻黄素及其衍生物的分子结构和特性以及其在人体中的转化过程示意图

研究发现,岩藻黄素可通过不受p53状态限制的空间位阻效应,阻断Mortalin蛋白与p53蛋白的相互作用,下调Mortalin蛋白表达,阻碍其下游信号通路转导,从而发挥对肿瘤细胞的选择性杀伤作用^[32]。还有研究发现,岩藻黄素的环氧基团可作为微管蛋白抑制剂稳定地结合在秋水仙碱结合位点上,从而通过阻滞G₂/M期进程,实现对细胞周期的调控^[33]。岩藻黄素还可通过氢键靶向结合单胺氧化酶(monoamine oxidase, MAO)活性位点,从而发挥治疗帕金森病的作用;另外,MAO氨基酸残基的疏水性作用还可进一步促进MAO与岩藻黄素的结合,从而发挥可逆性抑制效应^[34-35]。

此外,岩藻黄素递送系统的设计也取得了一定进展。例如,利用益生菌囊泡包封技术可实现岩藻黄素的肠道靶向富集,并显著增强其抗炎活性^[5];利用细胞外囊泡载体技术可实现岩藻黄素的器官特异性递送,并提高其生物利用率^[36];利用高内相凝胶技术可提高岩藻黄素的口服利用率,并延长其半衰期^[37];利用纳米技术将岩藻黄素与姜黄素联合构建多层结构的纳米粒,可实现药物的智能序贯释放体系等^[38]。

综上,岩藻黄素的特征性官能团展现出靶点选择性与可逆性抑制特性,可作为优化模板指导新型药物设计开发,为突破传统药物设计局限提供了新思路。

3 总结与展望

岩藻黄素可通过激活AMPK等相关信号通路、调控炎症因子表达、改善菌群稳态等发挥抗炎、抗氧化作用,从而改善MAFLD、结肠炎、急性肺损伤等疾病病理状

态;可通过多靶点协同作用发挥选择性抗肿瘤效应;可通过调控肠道菌群、 β_3 ADR/UCP-1 信号通路等发挥抗肥胖作用。另外,岩藻黄素的特征性官能团具有良好的靶点选择性和可逆抑制活性,是新型药物设计开发的模板。

目前,岩藻黄素在药理学、毒理学和药剂学领域已有相关研究文献发表,然而该成分的产业化、商业化开发仍处于起步阶段^[39],这可能与岩藻黄素的性能研究不足以及生产工艺开发中遇到的难题(如生产工艺成本高、绿色可持续性低)有关。已有研究在硅藻中探索岩藻黄素的合成路径^[40],未来或可通过生物合成技术,解决岩藻黄素的生产难题。

参考文献

- [1] HOSOKAWA M. Molecular nutritional research for effective utilization of marine lipid-soluble components[J]. *J Oleo Sci*, 2025, 74(4): 329-340.
- [2] 任祥雨,郑佳文,田笑笑,等. 岩藻黄素对小鼠非酒精性脂肪性肝病的修复作用[J]. *食品科学*, 2024, 45(3): 42-52.
- [3] YANG S, LI J, YAN L, et al. Molecular mechanisms of fucoxanthin in alleviating lipid deposition in metabolic associated fatty liver disease[J]. *J Agric Food Chem*, 2024, 72(18): 10391-10405.
- [4] KIM M B, BAE M, LEE Y, et al. Consumption of low dose fucoxanthin does not prevent hepatic and adipose inflammation and fibrosis in mouse models of diet-induced obesity[J]. *Nutrients*, 2022, 14(11): 2280.
- [5] LIANG D, LIU C Y, LI Y, et al. Engineering fucoxanthin-loaded probiotics' membrane vesicles for the dietary intervention of colitis[J]. *Biomaterials*, 2023, 297: 122107.
- [6] SUN X W, ZHAO H L, LIU Z L, et al. Modulation of gut microbiota by fucoxanthin during alleviation of obesity in high-fat diet-fed mice[J]. *J Agric Food Chem*, 2020, 68(18): 5118-5128.
- [7] MA J J, YUE S M, LIU Y H, et al. Fucoxanthin ameliorates ulcerative colitis by maintaining the epithelial barrier via blocking JAK2/STAT3 signaling pathway[J]. *Toxicol Appl Pharmacol*, 2025, 495: 117213.
- [8] YANG X J, GUO G, DANG M Y, et al. Assessment of the therapeutic effects of fucoxanthin by attenuating inflammation in ovalbumin-induced asthma in an experimental animal model[J]. *J Environ Pathol Toxicol Oncol*, 2019, 38(3): 229-238.
- [9] RAJI V, LOGANATHAN C, RAMESH T, et al. Dual anti-diabetic and antihypertensive activity of fucoxanthin isolated from *Sargassum wightii* Greville in vivo rat model[J]. *Food Sci Hum Wellness*, 2023, 12(5): 1693-1700.
- [10] LIU C L, CHIU Y T, HU M L. Fucoxanthin enhances HO-1 and NQO1 expression in murine hepatic BNL CL.2 cells through activation of the Nrf2/ARE system partially by its pro-oxidant activity[J]. *J Agric Food Chem*, 2011, 59(20): 11344-11351.
- [11] DING R, ZHONG S Y, DENG L Y, et al. Fucoxanthin prevents lipopolysaccharide-induced acute lung injury by inhibiting ferroptosis via Nrf2/STAT3 and glutathione pathways[J]. *Am J Chin Med*, 2024, 52(6): 1773-1794.
- [12] FILHO A M, LAVERSANNE M, FERLAY J, et al. The GLOBOCAN 2022 cancer estimates: data sources, methods, and a snapshot of the cancer burden worldwide[J]. *Int J Cancer*, 2025, 156(7): 1336-1346.
- [13] MÉRESSE S, FODIL M, FLEURY F, et al. Fucoxanthin, a marine-derived carotenoid from brown seaweeds and microalgae: a promising bioactive compound for cancer therapy[J]. *Int J Mol Sci*, 2020, 21(23): 9273.
- [14] SALAMI M, SALAMI R, AARABI M H, et al. Targeting glioma cells with nutraceuticals: therapeutic effects based on molecular mechanisms, new evidence and perspectives [J]. *Mini Rev Med Chem*, 2023, 23(11): 1167-1192.
- [15] JIN Y, QIU S, SHAO N, et al. Fucoxanthin and tumor necrosis factor-related apoptosis-inducing ligand (TRAIL) synergistically promotes apoptosis of human cervical cancer cells by targeting PI3K/Akt/NF- κ B signaling pathway [J]. *Med Sci Monit*, 2018, 24: 11-18.
- [16] LONG Y, CAO X B, ZHAO R Q, et al. Fucoxanthin treatment inhibits nasopharyngeal carcinoma cell proliferation through induction of autophagy mechanism[J]. *Environ Toxicol*, 2020, 35(10): 1082-1090.
- [17] YU R X, YU R T, LIU Z. Inhibition of two gastric cancer cell lines induced by fucoxanthin involves downregulation of Mcl-1 and STAT3[J]. *Hum Cell*, 2018, 31(1): 50-63.
- [18] WANG J, DONG X, LI D, et al. Fucoxanthin inhibits gastric cancer lymphangiogenesis and metastasis by regulating Ran expression[J]. *Phytomedicine*, 2023, 118: 154926.
- [19] ABIDOV M, RAMAZANOV Z, SEIFULLA R, et al. The effects of Xanthigen in the weight management of obese premenopausal women with non-alcoholic fatty liver disease and normal liver fat[J]. *Diabetes Obes Metab*, 2010, 12(1): 72-81.
- [20] HITOE S, SHIMODA H. Seaweed fucoxanthin supplementation improves obesity parameters in mild obese Japanese subjects[J]. *Funct Foods Health Dis*, 2017, 7(4): 246.
- [21] KAWEE-AI A, KIM A T, KIM S M. Inhibitory activities of microalgal fucoxanthin against α -amylase, α -glucosi-

- dase, and glucose oxidase in 3T3-L1 cells linked to type 2 diabetes[J]. *J Oceanol Limnol*, 2019, 37(3):928-937.
- [22] DENG Z Z, WANG J, WU N, et al. Co-activating the AMPK signaling axis by low molecular weight fucoidan LF2 and fucoxanthin improves the HFD-induced metabolic syndrome in mice[J]. *J Funct Foods*, 2022, 94: 105119.
- [23] SHARMA P P, BASKARAN V. Polysaccharide (laminaran and fucoidan), fucoxanthin and lipids as functional components from brown algae (*Padina tetrastomatica*) modulates adipogenesis and thermogenesis in diet-induced obesity in C57BL/6 mice[J]. *Algal Res*, 2021, 54: 102187.
- [24] HAO J Y, ZHANG J X, WU T. Fucoxanthin extract ameliorates obesity associated with modulation of bile acid metabolism and gut microbiota in high-fat-diet fed mice [J]. *Eur J Nutr*, 2024, 63(1):231-242.
- [25] PERINO A, DEMAGNY H, VELAZQUEZ-VILLEGAS L, et al. Molecular physiology of bile acid signaling in health, disease, and aging[J]. *Physiol Rev*, 2021, 101(2): 683-731.
- [26] ZHU L Y, WEI Y H, WANG Y H, et al. Protective efficacy of Shenge san on mitochondria in H9c2 cardiomyocytes[J]. *J Tradit Chin Med*, 2022, 42(6):892-899.
- [27] FERREIRA Y A M, JAMAR G, ESTADELLA D, et al. Role of carotenoids in adipose tissue through the AMPK-mediated pathway[J]. *Food Funct*, 2023, 14(8): 3454-3462.
- [28] LIN H V, TSOU Y C, CHEN Y T, et al. Effects of low-molecular-weight fucoidan and high stability fucoxanthin on glucose homeostasis, lipid metabolism, and liver function in a mouse model of type II diabetes[J]. *Mar Drugs*, 2017, 15(4):113.
- [29] LIU Y X, LIU M, ZHANG X C, et al. Protective effect of fucoxanthin isolated from *Laminaria japonica* against visible light-induced retinal damage both *in vitro* and *in vivo* [J]. *J Agric Food Chem*, 2016, 64(2):416-424.
- [30] 郭紫欣, 刘芸君, 刘翼翔, 等. 岩藻黄素改善视网膜色素上皮细胞吞噬功能的非抗氧化途径[J]. *食品科学*, 2022, 43(23):168-173.
- [31] JIANG X, WANG G K, LIN Q, et al. Fucoxanthin prevents lipopolysaccharide-induced depressive-like behavior in mice via AMPK-NF- κ B pathway[J]. *Metab Brain Dis*, 2019, 34(2):431-442.
- [32] GARG S, AFZAL S, ELWAKEEL A, et al. Marine carotenoid fucoxanthin possesses anti-metastasis activity: molecular evidence[J]. *Mar Drugs*, 2019, 17(6):338.
- [33] JANUAR H I, DEWI A S, MARRASKURANTO E, et al. In silico study of fucoxanthin as a tumor cytotoxic agent [J]. *J Pharm Bioallied Sci*, 2012, 4(1):56-59.
- [34] CACABELOS R. Parkinson's disease: from pathogenesis to pharmacogenomics[J]. *Int J Mol Sci*, 2017, 18(3): E551.
- [35] JUNG H A, ROY A, CHOI J S. *In vitro* monoamine oxidase A and B inhibitory activity and molecular docking simulations of fucoxanthin[J]. *Fish Sci*, 2017, 83(1): 123-132.
- [36] WU C, XIANG S, WANG H, et al. Orally deliverable sequence-targeted fucoxanthin-loaded biomimetic extracellular vesicles for alleviation of nonalcoholic fatty liver disease[J]. *ACS Appl Mater Interfaces*, 2024, 16(8):9854-9867.
- [37] SHANG W B, SUN Y D, SONG J, et al. Novel high internal phase oleogels-in-water Pickering emulsions stabilized solely by whey protein isolate for 3D printing and fucoxanthin delivery[J]. *Food Hydrocoll*, 2023, 140:108609.
- [38] WANG L H, WEI Z H, XUE C H, et al. Co-delivery system based on multilayer structural nanoparticles for programmed sequential release of fucoxanthin and curcumin [J]. *Food Hydrocoll*, 2023, 141:108729.
- [39] KHAW Y S, YUSOFF F M, TAN H T, et al. The critical studies of fucoxanthin research trends from 1928 to June 2021: a bibliometric review[J]. *Mar Drugs*, 2021, 19(11):606.
- [40] CAO T J, BAI Y, BUSCHBECK P, et al. An unexpected hydratase synthesizes the green light-absorbing pigment fucoxanthin[J]. *Plant Cell*, 2023, 35(8):3053-3072.

(收稿日期:2025-03-09 修回日期:2025-07-26)

(编辑:唐晓莲)