甜菜根关键活性成分及其生物功能研究进展

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摘　要: 甜菜根是我国主要的糖料作物之一, 在农业生产中具有重要的地位。甜菜根中的必需氨基酸、蛋白质、维生素、矿物质和膳食纤维等营养成分丰富, 同时含有高水平的硝酸盐、甜菜色素、甜菜碱、类胡萝卜素、酚类化合物及抗坏血酸等多种生物活性成分。甜菜根在提高运动能力方面的功能作用被广泛证实, 其产品已被初步应用到运动营养领域。此外, 甜菜根及其提取物具有抗氧化应激、抗炎症反应、抑菌等生物活性功能, 在心血管疾病、肥胖、糖尿病、肝脏损伤以及癌症等疾病的干预中具有重要作用。本文对甜菜根中的关键生物活性成分及其生物功能相关的最新研究进行综述, 旨在进一步促进甜菜根资源的综合利用, 为甜菜根在食品、医药及保健产品中的开发应用提供科学依据。

关键词: 甜菜根; 营养成分; 活性成分; 生物功能

Research progress on key bioactive components and bioactivities of *Beta vulgaris* L.

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ABSTRACT: *Beta vulgaris* L. is one of the main sugar-yielding crops in China, and occupies an important position in agricultural production. *Beta vulgaris* L. is rich in nutrients such as essential amino acids, protein, vitamins, minerals and dietary fiber, and contains many bioactive componentssuch as nitrates, betalains, betaine, carotenoids, phenolic compounds and ascorbic acid. The functional role of *Beta vulgaris* L. in improving exercise capacity has been widely confirmed, and its products have been initially applied to the field of sports nutrition. In addition, *Beta vulgaris* L. and its extracts have anti-oxidative stress, anti-inflammatory, antibacterial and other bioactivities, and play an important role in the intervention of cardiovascular diseases, obesity, diabetes, liver damage, cancer and other diseases. This article reviewed the latest research related to the key bioactive components in *Beta vulgaris* L. and their bioactivities, aiming to further promote the comprehensive utilization of *Beta vulgaris* L. resources and provide

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a scientific basis for the development and application of *Beta vulgaris* L. in food, medicine and health products.

KEY WORDS: *Beta vulgaris* L.; nutrients; bioactive components; bioactivities

0　引　言

甜菜根(*Beta vulgaris* L.)是一种藜科甜菜属二年生草本植物，起源于亚洲和欧洲。甜菜根的块根部分为其可食用部分，通常呈圆球状或纺锤状，且根据品种的不同呈现出红紫色、金黄色或红白色[1]。甜菜根具有耐旱、耐寒及耐盐碱等特点，在我国主要分布于北纬40°以北的东北、华北和西北地区。据统计，2020年我国甜菜产量达1198.40万t[2]。作为一种糖料作物，甜菜根在我国农业生产中具有重要地位[3–4]。

甜菜根营养价值高，富含维持人体健康所需的氨基酸、蛋白质、脂肪、维生素、矿物质和膳食纤维等营养成分[1,5]。近年来的研究表明，甜菜根中含有硝酸盐、甜菜色素、甜菜碱、类胡萝卜素、酚类化合物和抗坏血酸等多种生物活性成分，具有提高运动能力[6]、降血压[7]、抑制肿瘤细胞增殖[8]、抗氧化应激和抗炎症[9]等生物活性功能，在多种疾病的预防和辅助治疗中具有重要作用。

本文对甜菜根中的关键活性成分(图1)及其生物功能的最新研究进展进行综述，并对未来的研究方向进行展望，以期促进甜菜根及其提取物在功能食品和生物医药中的进一步应用。

1　高含量的硝酸盐

除莴苣、菠菜和芝麻菜等绿叶类蔬菜以外，根茎类蔬菜甜菜根中的硝酸盐含量也极为丰富(644~1800 mg/kg)，是人类饮食中硝酸盐的主要来源之一[1,10]。

1.1　膳食硝酸盐转化为一氧化氮的途径

膳食硝酸盐是一氧化氮(nitric oxide, NO)的储存形式[11]。人体在消化和吸收富含硝酸盐的食物之后，血浆硝酸盐浓度升高，随后唾液腺对血液中的硝酸盐主动吸收并将其浓缩在唾液中[12]。大约20%的硝酸盐通过唾液腺进入口腔，被舌背部的共性兼性厌氧细菌还原为亚硝酸盐，这些亚硝酸盐占人体总亚硝酸盐的80%[12–13]。亚硝酸盐大部分在胃中转化为NO，一小部分由肠道吸收入血并运输至身体其他部位，再通过各种途径进一步还原为NO和其他氮氧化物[14]。而未在口腔中被还原的硝酸盐则在肠道和其他组织中与还原酶作用，或再次进入血液循环[15]。膳食硝酸盐转化为NO的这种方式称为硝酸盐-亚硝酸盐-NO途径[16]。NO作为细胞生物学上一种重要的气体信号分子，在调节血管张力、神经传递、线粒体呼吸和骨骼肌收缩功能等生理过程中发挥着重要的作用[17]。

1.2　生物功能

1.2.1　降血压

高血压是一种多因素疾病，它的发生在一定程度上与体内NO的产生减少及生物利用度受损有关[18]。大量流行病学研究证实，膳食摄入富含硝酸盐的甜菜根是预防和治疗高血压的潜在策略[19–22]。一项针对健康老年个体的随机交叉实验结果显示[23]，与基线值相比，服用140 mL富含硝酸盐的甜菜根汁(硝酸盐含量为12.9 mmol) 3 h后收缩压(systolic blood pressure, SBP)、舒张压(diastolic blood pressure, DBP)及平均动脉血压(mean arterial blood pressure, MAP)均显著降低，并于服用6 h后恢复至基线水平；以140 mL去除硝酸盐的甜菜根汁(硝酸盐含量小于等于0.04 mmol)作为安慰剂对照组，与基线值相比，服用3 h后的SBP、DBP和MAP均无显著性差异，提示甜菜根中高含量的硝酸盐

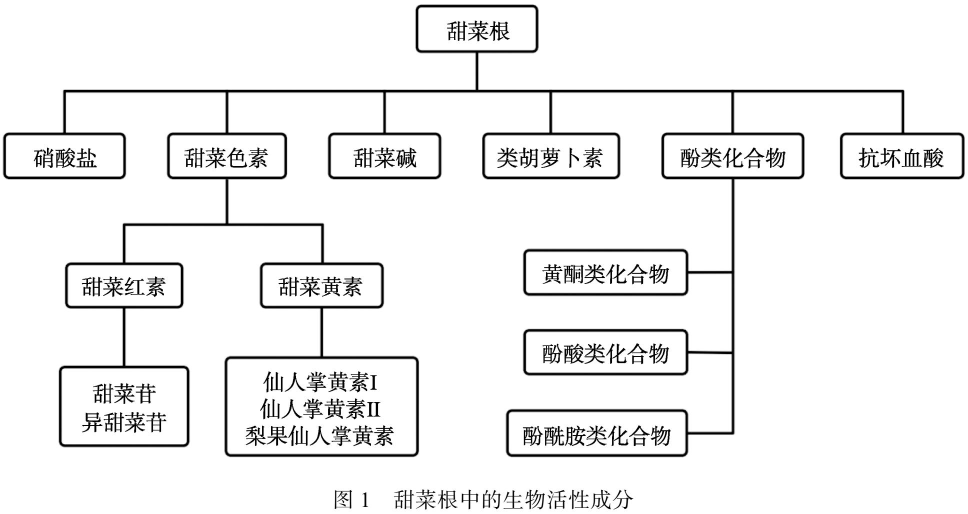


图1　甜菜根中的生物活性成分

Fig.1　Bioactive components in *Beta vulgaris* L.

具有急性的降血压效果。STANAWAY 等[24]的研究结果验证了补充富含硝酸盐的甜菜根汁对血压的急性影响，同时发现这种急性作用在老年个体中比在年轻个体中更优。此外，VANHATALO 等[25]研究发现，口腔微生物群会随着无机 NO^{3-}膳食摄入量的增加而发生变化，从而调节体内 NO 稳态和血压水平，强调了口服微生物群靶向疗法在改善 NO 生物利用度方面的潜力。

1.2.2　提高运动能力

膳食硝酸盐补充剂是一种可用于提高运动能力的科学有效的饮食策略，是过去十年运动营养领域的主要创新成果之一。研究证实，以甜菜根汁的形式补充膳食硝酸盐可以提高运动耐力、肌肉力量和短跑能力，其可能机制包括降低运动耗氧量、提高肌肉效率、增强骨骼肌收缩功能等[26–27]。此外，越来越多的研究结果显示，甜菜根汁补充剂在提高抗阻运动[28]、高强度间歇性运动[29]、30 s 全力冲刺运动[30]等能力方面也具有显著作用。JONES 等[31]对纳入研究的 6 项人体干预实验进行荟萃分析，结果表明以甜菜根汁的形式补充膳食硝酸盐可以加速肌肉功能的恢复并减少剧烈运动后的肌肉酸痛。值得一提的是，WYLIE 等[32]研究发现人体骨骼肌中的硝酸盐浓度远高于血液中的硝酸盐浓度，并在高强度运动后减少，提示骨骼肌在硝酸盐运输、储存和代谢中起着重要作用。然而，也有研究指出，急性或长期补充甜菜根汁对长跑能力的提高没有有效帮助[33–34]。

1.2.3　增强认知功能

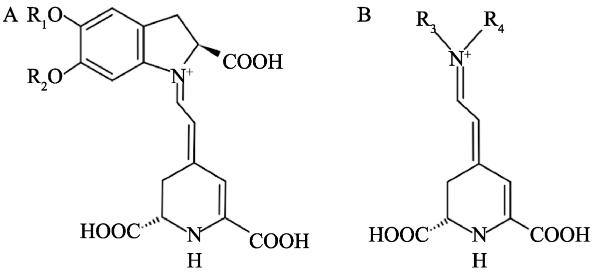
认知功能障碍的发病机制之一是由 NO 活性受损引发的脑灌注不足[35]。研究表明，补充富含硝酸盐的甜菜根汁可增加额叶白质区域脑灌注，并改善 Stroop 测试的反应时间[24,36]。一项随机、双盲、安慰剂对照的临床实验结果显示，40 名健康成年人服用 450 mL 甜菜根汁(硝酸盐含量约 5.5 mmol) 90 min 后，前额叶皮层脑血流量增加，且连续 3 s 减法任务的认知能力得到改善[37]。GILCHRIST 等[38]研究发现，连续两周补充 250 mL 甜菜根汁(硝酸盐含量为 7.5 mmol)可显著改善 2 型糖尿病患者的简单反应时间。

2　甜菜色素

甜菜色素(betalains)是一种最早从甜菜中分离出的含氮水溶性色素，在结构上属于吡啶衍生物[39]。甜菜色素呈现出鲜艳的紫红色或黄色，是甜菜根色泽的主要来源，被食品工业和化妆品行业用作天然着色剂[40]。甜菜色素具有多种生理活性，如抗氧化、抗炎症反应、抗心血管疾病、抗癌等，在保健食品和药品的开发中具有重要作用。

2.1　甜菜色素的种类

甜菜色素的合成前体为酪氨酸，经过多个酶促反应和自发反应，形成甜菜红素(betacyanins)和甜菜黄素(betaxanthins)[41]。在化学结构上(见图 2)，甜菜红素由甜菜醛氨酸和环-3,4-二羟基苯丙氨酸组成，甜菜黄素则由甜菜醛氨酸和氨基酸/胺组成[10,42]。甜菜红素呈紫红色，主要包括甜菜苷(betanin)和异甜菜苷(isobetanin)，在 535~540 nm 处表现出最大吸收；甜菜黄素呈黄色，主要包括仙人掌黄素 I (vulgaxanthin I)、仙人掌黄素 II (vulgaxanthin II)和梨果仙人掌黄素(indicaxanthin)，在 460~480 nm 范围内表现出最大吸收[10,43]。



注：R_1 和 R_2：氢、酰基或糖部分；R_3：胺或氨基酸基团；R_4：通常是氢。

图 2　甜菜红素(A)和甜菜黄素(B)结构式

Fig.2　General structures of betacyanins (A) and betaxanthins (B)

2.2　生物功能

2.2.1　抗氧化作用

甜菜色素具有清除活性氧的抗氧化作用，是一种天然的抗氧化剂[44]。DA SILVA 等[45]以高脂饲料喂养大鼠 60 d 诱导氧化应激模型，后按 20 mg/kg 的剂量连续灌胃给予甜菜苷 20 d，发现短期摄入甜菜苷可减少大鼠肝脏丙二醛(malondialdehyde, MDA)含量，并增加血浆中超氧化物歧化酶、过氧化氢酶和谷胱甘肽过氧化物酶的活性。VIEIRA 等[46]对纯化得到的甜菜苷进行体外模拟消化实验，发现甜菜苷经小肠模拟消化后仍表现出较高的抗氧化能力。甜菜色素还具有羟基自由基(•OH)、2,2-联氮-双-3-乙基苯并噻唑啉-6-磺酸[diammonium 2,2’-azino-bis (3-ethylbenzothiazoline-6-sulfonate), ABTS]、1,1-二苯基-2-三硝基苯肼(1,1-diphenyl-2-picrylhydrazyl, DPPH)清除能力和铁螯合活性，并能够在体外抑制铁非依赖性和铁依赖性脂质过氧化[47]。

2.2.2　抗炎症反应

体外研究表明，从甜菜根中纯化得到的甜菜色素可以抑制脂多糖诱导小胶质细胞肿瘤坏死因子-*α* (tumor necrosis factor-*α*, TNF-*α*)、白细胞介素-6 (interleukin-6, IL-6)和白细胞介素-1*β* (interleukin-1*β*, IL-1*β*)等炎症介质的产生[48]。MARTINEZ 等[49]以甜菜根为原料，采用醇沉法制备出一种富含甜菜色素的染料，并通过动物实验发现按 100 mg/kg 的剂量腹腔注射染料可抑制角叉菜胶诱导的小鼠腹腔液中超氧阴离子、TNF-*α* 和 IL-1*β* 水平升高，对角叉菜胶引起的爪子水肿和腹膜炎具有明显的抗炎症作用。该团队进一步研究发现，甜菜色素处理的骨髓源性巨噬细胞在脂多糖刺激后表现出较低的 TNF-*α* 和 IL-1*β* 细胞因子水平以及核因

子 κB (nuclear factor-κB, NF-κB)活化水平[47]。

2.2.3 抑菌作用

甜菜色素可以通过破坏细菌细胞膜的结构、功能和通透性，抑制细菌的繁殖[42]。CANADANOVIC-BRUNET 等[50]制备了以甜菜色素为主要成分的甜菜根提取物，并通过体外抗菌实验发现甜菜根提取物可以有效抑制金黄色葡萄球菌、鼠伤寒沙门氏菌和蜡状芽孢杆菌的生长。VULIC 等[51]发现，革兰氏阴性菌(鼠伤寒沙门氏菌、弗氏柠檬酸杆菌)和革兰氏阳性菌(金黄色葡萄球菌、蜡状芽孢杆菌)对富含甜菜色素的甜菜根提取物表现出高敏感性，而酵母菌和霉菌则具有抗药性。尽管甜菜色素的抗菌活性在食品行业有重要的应用潜力，但其发挥抑菌作用的确切机制尚不明确，这将是未来研究的重点[52]。

2.2.4 干预慢性疾病

甜菜色素在心血管疾病、癌症等慢性疾病的干预中也具有重要作用。在一项随机交叉实验中，48 名男性心血管疾病患者按照随机顺序接受为期 2 周的富含甜菜色素的仙人掌补充剂和甜菜根补充剂，之间设置 2 周的洗脱期[53]。结果显示，与基线值相比，两种补充剂都显著降低了患者血浆中同型半胱氨酸(homocysteine, Hcy)、葡萄糖、总胆固醇、甘油三酯和低密度脂蛋白的浓度，同时降低了患者的 SBP 和 DBP。LEE 等[54]通过体外实验发现，200 μg/mL 甜菜苷在 37 ℃下处理 48 h，对人肝癌 HepG2 细胞活性的抑制效果最佳，抑制率达 49%。HENAREJOS-ESCUDERO 等[55]采用秀丽隐杆线虫肿瘤模型评估了 3 种富含甜菜碱的提取物和 6 种纯甜菜色素的抗肿瘤潜力，结果表明色氨酸-甜菜黄素的抗肿瘤活性最高，可使肿瘤大小减小 56.4%，并将线虫寿命延长 9.3%，其潜在机制涉及 DAF-16 转录因子和胰岛素信号通路的调节。

3 甜菜碱

甜菜碱(betaine)又称为三甲基甘氨酸(图 3)，是一种最早从甜菜中分离出来的胆碱衍生物，广泛分布于动物、植物和微生物中[56–57]。甜菜根中的甜菜碱含量达 4.8 mg/g 鲜重，是甜菜碱的膳食来源之一[54]。基于其特殊的化学结构，甜菜碱在机体内发挥两种重要的生理作用：细胞渗透压保护剂和一碳单位(甲基)供体[58]。甜菜碱作为一种重要的甲基供体，在 Hcy 甲基化形成甲硫氨酸的生化过程中发挥重要的作用，而血清高 Hcy 则与动脉硬化、心血管疾病、高血压和糖尿病等多种疾病直接或间接相关[59]。甜菜碱的生物活性功能已经成为近年来的研究热点。

3.1 抗氧化作用

线粒体是生物氧化的主要场所，活性氧(reactive oxygen species, ROS)作为该反应的副产物，过量积累会对机体产生潜在危害。研究表明，甜菜碱具有抗氧化活性，能够降低小鼠血液中 MDA 水平，同时增加超氧化物歧化酶(superoxide dismutase, SOD)和谷胱甘肽过氧化物酶水平，从而减少 ROS 的产生[60]。ADJOUMANI 等[61]发现，膳食补充 1.2%甜菜碱可以增加高脂饮食武昌鱼肝脏组织中 SOD、过氧化氢酶和还原型谷胱甘肽水平，同时降低 MDA 水平。

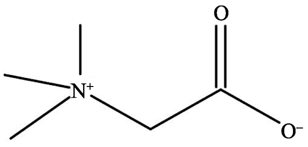


图 3 甜菜碱结构式

Fig.3 General structures of betaine

3.2 抗炎症反应

高脂饮食是诱导机体低度炎症的原因之一，膳食甜菜碱补充可减轻高脂饮食 C57BL/6J 小鼠内脏脂肪中 IL-6 的表达，并增加脂肪组织中的甜菜碱和丁酰甜菜碱水平[62]。SHI 等[63]以脂多糖诱导的小胶质细胞为炎症模型，发现甜菜碱可以抑制小胶质细胞中促炎细胞因子的产生，并促进抗炎细胞因子的释放。越来越多的研究表明，甜菜碱通过抑制 NF-κB 的活性，阻断 IL-1β、环氧化酶-2、诱生型一氧化氮合成酶等炎症因子的表达[64]。

3.3 保护肝脏

VUKICEVIC 等[65]以硫代乙酰胺诱导肝损伤 C57BL/6 小鼠为模型，发现甜菜碱的肝脏保护作用与其抗氧化应激和抗炎症反应活性有关，甜菜碱(2% w:V 溶解于饮用水中)可显著降低小鼠血清谷丙转氨酶、γ-谷氨酰转肽酶、胆红素、MDA、蛋白质氧化产物、C-反应蛋白、IL-6 和 γ-干扰素等水平。VESKOVIC 等[66–67]发现，膳食补充甜菜碱通过降低 C57BL/6 小鼠肝脏氧化应激、炎症和细胞凋亡水平，并增加小鼠肝脏中自噬体的数量，干预蛋氨酸-胆碱缺乏饮食诱导的非酒精性脂肪肝。此外，甜菜碱可以通过改善受损含硫氨基酸代谢增强大鼠肝脏的抗氧化能力，进而预防酒精性肝损伤的发生[68]。

3.4 干预慢性疾病

越来越多的研究表明，甜菜碱在肥胖[69]、糖尿病[70]、癌症[71]和阿尔茨海默病[72]等疾病的干预中具有潜在作用。DU 等[73]研究发现，补充甜菜碱可以通过抑制小鼠白色脂肪组织产生、肌细胞内脂质积累和炎症反应，减轻高脂饮食引起的肥胖并改善胰岛素抵抗。HUANG 等[70]通过链脲佐菌素诱导糖尿病大鼠模型，发现口服 50 mg/kg 和 100 mg/kg 甜菜碱可以改善大鼠葡萄糖代谢，并抑制炎症因子的产生。一项荟萃分析显示，饮食或血液中甜菜碱水平越高，癌症(尤其是结直肠癌)的发病风险越低[71]。阿尔茨海默病是一种神经退行性疾病，与营养不良和高 Hcy 水平有关。

SUN 等[72]发现，甜菜碱干预可使阿尔茨海默病患者血液中的 Hcy 恢复到正常水平，有效抑制炎症因子并增加记忆相关蛋白表达。

4　其他生物活性成分

4.1　类胡萝卜素

类胡萝卜素是一类重要的脂溶性色素，普遍存在于植物、真菌、细菌以及藻类中，是其黄色、橙色或红色色泽的主要来源之一[74]。甜菜根中的类胡萝卜素主要包括β-胡萝卜素和叶黄素，其中β-胡萝卜素的含量约为 1.9 mg/100 g[75]。共轭双键的存在使得类胡萝卜素可以通过电子转移、夺氢和加成反应，中和单分子氧和过氧自由基，表现出抗氧化特性，从而在癌症、心血管疾病、光敏性皮肤病等疾病中具有保护作用[74,76]。大量体外和体内研究表明，类胡萝卜素通过调节氧化应激、主要信号激酶的磷酸化和激活、细胞凋亡、细胞周期进程、细胞间隙连接通讯和血管生成等，抑制癌症的发生和发展[77–78]。AUNE 等[79]对相关的前瞻性研究进行系统回顾和荟萃分析发现，类胡萝卜素作为水果和蔬菜摄入量的标志物，其膳食摄入量和/或血液浓度的增加与心血管疾病的风险降低有关，提示可以通过增加水果和蔬菜摄入量来预防心血管疾病。此外，作为维生素 A 的前体物质，胡萝卜素可以在预防维生素 A 缺乏症方面发挥重要作用[80]。

4.2　酚类化合物

酚类化合物是植物中最丰富的次生代谢产物[81]。甜菜根是酚类化合物的主要膳食来源，其总酚含量达 (3.67±0.61) GAE mg/g，但不同品种的甜菜根以及同一甜菜根的不同部位之间的总酚含量存在一定差异[82]。目前，从甜菜根中分离出的酚类化合物主要包括：甜菜二氢黄酮(betagarin)、5-羟基-6,7-亚甲二氧基黄酮(cochliophilin A)、2’-羟基-5-甲氧基-6,7-亚甲二氧基异黄酮(betavulgarin)等黄酮类化合物；绿原酸(chlorogenic Acid)、咖啡酸(caffeic Acid)、表儿茶素(epicatechin)、芦丁(rutin)等酚酸类化合物；N-转阿魏酰苯胺(N-trans-feruloyltyramine)和N-反式阿魏酰高香草胺(N-trans-feruloylhomovanillylamine)等酚酰胺类化合物[1]。大量流行病学研究和荟萃分析表明，膳食酚类化合物的摄入可以帮助预防慢性疾病的发生，包括神经退行性疾病[83]、癌症[84]、糖尿病[85]、肥胖[86]和心血管疾病[83]。此外，酚类化合物可以参与免疫系统调节的表观遗传机制，在免疫介导的疾病干预中具有重要意义[87]。

4.3　抗坏血酸

抗坏血酸(维生素 C)是植物和动物系统中重要的氧化还原辅助因子，广泛存在于新鲜水果和绿色蔬菜中。甜菜根是膳食补充抗坏血酸的重要来源，其抗坏血酸的含量为 3.6 mg/100 g[1]。抗坏血酸是植物、动物和人类最重要的水溶性抗氧化剂，在 Fe^{3+}还原、缺氧诱导因子 1α 调节、胆固醇代谢等多种生化反应中起着至关重要的作用[88]。此外，流行病学研究表明，膳食补充抗坏血酸对增强免疫力、预防癌症和心血管疾病具有有益作用[89–90]。

5　结束语

甜菜根因其具有高营养价值和药用价值而在世界范围内被广泛种植和食用。甜菜根能够为人体提供维生素、矿质元素和氨基酸等多种营养元素。此外，甜菜根还含有丰富的硝酸盐、甜菜色素、甜菜碱等关键生物活性成分，具有抗氧化应激、抗炎症反应、提高运动能力、增强认知功能、抗菌等生物功能，同时可以干预糖尿病、癌症、心血管疾病等各种氧化应激引起的慢性疾病。这表明甜菜根补充剂有望成为临床中经济、实用的天然饮食干预措施。值得一提的是，甜菜根提高运动能力的功能已被初步应用到体育营养领域。

虽然甜菜根发挥这些有益作用的确切机制尚未完全阐明，但目前已有的研究表明，甜菜根发挥心血管保护、认知功能改善和运动能力提高等作用是由硝酸盐及其转化的 NO 介导的，而其他慢性疾病的改善则是由甜菜碱、甜菜色素以及其他活性成分的抗氧化和抗炎作用介导的。鉴于各种化合物的贡献相对复杂，在机制探究过程中应当认识到甜菜根中多种化合物之间的协同效应。同时，应当充分考虑过量摄入甜菜根及其活性成分(尤其是硝酸盐)对健康造成的潜在不利影响，以及特殊人群(如糖尿病患者)对高含糖量甜菜根汁的不适应性。未来，在进一步阐明甜菜根生物功能机制和评估甜菜根长期食用安全性的基础上，应加快不同类型的甜菜根产品的开发，在提高甜菜根价值的同时为消费者带来健康益处。

参考文献

[1] CHHIKARA N, KUSHWAHA K, SHARMA P, *et al*. Bioactive compounds of beetroot and utilization in food processing industry: A critical review [J]. Food Chem, 2019, 272: 192–200.

[2] 中华人民共和国国家统计局. 2020 中国统计年鉴[J]. 统计理论与实践, 2021, (1): 2.
National Bureau of Statistics of People’s Republic of China. 2020 China statistical yearbook [J]. Stat Theor Pract, 2021, (1): 2.

[3] YASAMINSHIRAZI K, HARTUNG J, FLECK M, *et al*. Bioactive compounds and total sugar contents of different open-pollinated beetroot genotypes grown organically [J]. Molecules, 2020, 25(21): 4884.

[4] 邵科. 甜菜(*Beta vulgaris* L.)块根和含糖率增长与蔗糖代谢酶的关系及其营养调控的生理基础与实践[D]. 呼和浩特: 内蒙古农业大学, 2014.
SHAO K. The relationship among increasing root weight, sugar content and sucrose metabolism related enzymes in sugarbeet (*Beta vulgaris* L.) and its physiological basis and practice of nutritional regulation [D]. Huhehot: Inner Mongolia Agricultural University, 2014.

[5] SOBHY ES, ABDO E, SHALTOUT O, *et al*. Nutritional evaluation of beetroots (*Beta vulgaris* L.) and its potential application in a functional beverage [J]. Plants (Basel), 2020, 9(12). DOI: 10.3390/plants9121752

[6] BALSALOBRE-FERNÁNDEZ C, ROMERO-MORALEDA B, CUPEIRO R, *et al*. The effects of beetroot juice supplementation on exercise economy, rating of perceived exertion and running mechanics in elite distance runners: A double-blinded, randomized study [J]. PLoS One, 2018, 13(7): e0200517.

[7] BAHADORAN Z, MIRMIRAN P, KABIR A, *et al*. The nitrate-independent blood pressure-lowering effect of beetroot juice: A systematic review and meta-analysis [J]. Adv Nutr, 2017, 8(6): 830–838.

[8] TAN ML, HAMID SBS. Beetroot as a potential functional food for cancer chemoprevention, a narrative review [J]. J Cancer Prev, 2021, 26(1): 1–17.

[9] ZIELIŃSKA-PRZYJEMSKA M, OLEJNIK A, DOBROWOLSKA-ZACHWIEJA A, *et al*. *In vitro* effects of beetroot juice and chips on oxidative metabolism and apoptosis in neutrophils from obese individuals [J]. Phytother Res, 2009, 23(1): 49–55.

[10] MILTON-LASKIBAR I, MARTÍNEZ JA, PORTILLO MP. Current knowledge on beetroot bioactive compounds: Role of nitrate and betalains in health and disease [J]. Foods, 2021, 10(6): 1314.

[11] 王逸聪, 陈玮琪, 王昊, 等. 硝酸盐代谢与脑血管病相关性研究进展[J]. 中华医学杂志, 2021, 101(4): 306–310.
WANG YC, CHEN WQ, WANG H, *et al*. Research progress on the relationship between nitrate metabolism and cerebrovascular disease [J]. Nat Med J China, 2021, 101(4): 306–310.

[12] NYAKAYIRU J, LOON L, VERDIJK L. Could intramuscular storage of dietary nitrate contribute to its ergogenic effect? A mini-review [J]. Free Radical Bio Med, 2020, 152: 295–300.

[13] 夏登胜, 王松灵. 唾液硝酸盐、亚硝酸盐代谢及其对人体影响的研究[J]. 北京口腔医学, 2005, (1): 57–59.
XIA DS, WANG SL. Study on the metabolism of nitrate and nitrite in saliva and its influence on the human body [J]. Beijing J Stomatol, 2005, (1): 57–59.

[14] 逄瑗博, 孙丽, 王振国, 等. 硝酸盐和亚硝酸盐转化为NO的方式、途径及其对心血管疾病治疗研究进展[J]. 武警医学, 2020, 31(12): 1076–1079.
PANG AIB, SUN L, WANG ZG, *et al*. The way of converting nitrate and nitrite into NO and the research progress in the treatment of cardiovascular disease [J]. Med J Chin People’s Armed Police Force, 2020, 31(12): 1076–1079.

[15] 韩悦, 范志红, 朱瑞欣. 蔬菜中硝酸盐对心血管健康的改善作用[J]. 中国食物与营养, 2020, 26(2): 85–89.
HAN Y, FAN ZH, ZHU RX. Effects of nitrate in green leafy vegetables on cardiovascular diseases [J]. Food Nutr China, 2020, 26(2): 85–89.

[16] LUNDBERG JO, CARLSTROM M, WEITZBERG E. Metabolic effects of dietary nitrate in health and disease [J]. Cell Metab, 2018, 28(1): 9–22.

[17] JONES AM, VANHATALO A, SEALS DR, *et al*. Dietary nitrate and nitric oxide metabolism: Mouth, circulation, skeletal muscle, and exercise performance [J]. Med Sci Sport Exer, 2021, 53(2): 280–294.

[18] TONG T, WANG YN, ZHANG CM, *et al*. *In vitro* and *in vivo* antihypertensive and antioxidant activities of fermented roots of *Allium hookeri* [J]. Chin Herbal Med, 2021, 13(4): 541–548.

[19] OCAMPO DAB, PAIPILLA AF, MARIN E, *et al*. Dietary nitrate from beetroot juice for hypertension: A systematic review [J]. Biomolecules, 2018, 8(4). DOI: 10.3390/biom8040134

[20] ORMESHER L, MYERS JE, CHMIEL C, *et al*. Effects of dietary nitrate supplementation, from beetroot juice, on blood pressure in hypertensive pregnant women: A randomised, double-blind, placebo-controlled feasibility trial [J]. Nitric Oxide, 2018, 80: 37–44.

[21] JONES T, DUNN EL, MACDONALD JH, *et al*. The effects of beetroot juice on blood pressure, microvascular function and large-vessel endothelial function: A randomized, double-blind, placebo-controlled pilot study in healthy older adults [J]. Nutrients, 2019, 11(8). DOI: 10.3390/nu11081792

[22] KUKADIA S, DEHBI HM, TILLIN T, *et al*. A double-blind placebo-controlled crossover study of the effect of beetroot juice containing dietary nitrate on aortic and brachial blood pressure over 24 h [J]. Front Physiol, 2019, 10: 47.

[23] RAUBENHEIMER K, HICKEY D, LEVERITT M, *et al*. Acute effects of nitrate-rich beetroot juice on blood pressure, hemostasis and vascular inflammation markers in healthy older adults: A randomized, placebo-controlled crossover study [J]. Nutrients, 2017, 9(11): 1270.

[24] STANAWAY L, RUTHERFURD-MARKWICK K, PAGE R, *et al*. Acute supplementation with nitrate-rich beetroot juice causes a greater increase in plasma nitrite and reduction in blood pressure of older compared to younger adults [J]. Nutrients, 2019, 11(7): 1683.

[25] VANHATALO A, BLACKWELL JR, L'HEUREUX JE, *et al*. Nitrate-responsive oral microbiome modulates nitric oxide homeostasis and blood pressure in humans [J]. Free Radical Bio Med, 2018, 124: 21–30.

[26] JONES AM, THOMPSON C, WYLIE LJ, *et al*. Dietary nitrate and physical performance [J]. Annu Rev Nutr, 2018, 38: 303–328.

[27] MCMAHON NF, LEVERITT MD, PAVEY TG. The effect of dietary nitrate supplementation on endurance exercise performance in healthy adults: A systematic review and meta-analysis [J]. Sports Med, 2017, 47(4): 735–756.

[28] SAN JAF, DOMINGUEZ R, LAGO-RODRIGUEZ A, *et al*. Effects of dietary nitrate supplementation on weightlifting exercise performance in healthy adults: A systematic review [J]. Nutrients, 2020, 12(8). DOI: 10.3390/nu12082227

[29] NYAKAYIRU J, JONVIK KL, TROMMELEN J, *et al*. Beetroot juice supplementation improves high-intensity intermittent type exercise performance in trained soccer players [J]. Nutrients, 2017, 9(3). DOI: 10.3390/nu9030314

[30] CUENCA E, JODRA P, PEREZ-LOPEZ A, *et al*. Effects of beetroot juice supplementation on performance and fatigue in a 30-s all-out sprint exercise: A randomized, double-blind cross-over study [J]. Nutrients, 2018, 10(9). DOI: 10.3390/nu10091222

[31] JONES L, BAILEY SJ, ROWLAND SN, *et al*. The effect of nitrate-rich beetroot juice on markers of exercise-induced muscle damage: A systematic review and meta-analysis of human intervention trials [J]. J Diet Suppl, 2021, 21: 1–23.

[32] WYLIE LJ, PARK JW, VANHATALO A, *et al*. Human skeletal muscle nitrate store: Influence of dietary nitrate supplementation and exercise [J]. J Physiol, 2019, 597(23): 5565–5576.

[33] HURST P, SAUNDERS S, COLEMAN D. No differences between beetroot juice and placebo on competitive 5-km running performance: A

double-blind, placebo-controlled trial [J]. Int J Sport Nutr Exe, 2020, 30(4): 295–300.

[34] CASTRO T, MANOEL F, FIGUEIREDO DH, *et al*. Effect of beetroot juice supplementation on 10-km performance in recreational runners [J]. Appl Physiol Nutr Metab, 2019, 44(1): 90–94.

[35] POELS MM, IKRAM MA, VERNOOIJ MW, *et al*. Total cerebral blood flow in relation to cognitive function: The rotterdam scan study [J]. J Cereb Blood Flow Metab, 2008, 28(10): 1652–1655.

[36] PRESLEY TD, MORGAN AR, BECHTOLD E, *et al*. Acute effect of a high nitrate diet on brain perfusion in older adults [J]. Nitric Oxide, 2011, 24(1): 34–42.

[37] WIGHTMAN EL, HASKELL-RAMSAY CF, THOMPSON KG, *et al*. Dietary nitrate modulates cerebral blood flow parameters and cognitive performance in humans: A double-blind, placebo-controlled, crossover investigation [J]. Physiol Behav, 2015, 149: 149–158.

[38] GILCHRIST M, WINYARD PG, FULFORD J, *et al*. Dietary nitrate supplementation improves reaction time in type 2 diabetes: Development and application of a novel nitrate-depleted beetroot juice placebo [J]. Nitric Oxide, 2014, 40: 67–74.

[39] 付瑛格, 李霆格, 潘庆龙, 等. 2A 肽介导的甜菜色素多基因表达载体构建及原核表达分析[J/OL]. 分子植物育种: 1-14. [2022-01-03]. http://kns.cnki.net/kcms/detail/46.1068.S.20210722.1535.028.html

FU YG, LI TG, PAN QL, *et al*. Construction of co-expression vector carrying betalains synthesis related genes by using 2A peptide-linked and prokaryotic expression analyses [J/OL]. Mol Plant Breed: 1-14. [2022-01-03]. http://kns.cnki.net/kcms/detail/46.1068.S.20210722.1535.028.html

[40] 晏兴珠, 毛琪, 王仕玉, 等. 藜麦甜菜红素的提取优化及稳定性研究[J]. 食品与发酵科技, 2021, 57(3): 44–48.

YAN XZ, MAO Q, WANG SY, *et al*. Study on extraction optimization and stability of betacyanin from quinoa [J]. Food Ferment Technol, 2021, 57(3): 44–48.

[41] 王飞, 董婕, 王思涵, 等. 甜菜素合成相关基因BvDDC1的克隆与表达分析[J]. 分子植物育种, 2021, 19(6): 1787–1792.

WANG F, DONG J, WANG SH, *et al*. Cloning and expression analysis of betalains synthesis related gene BvDDC1 [J]. Mol Plant Breed, 2021, 19(6): 1787–1792.

[42] FU Y, SHI J, XIE SY, *et al*. Red beetroot betalains: Perspectives on extraction, processing, and potential health benefits [J]. J Agric Food Chem, 2020, 68(42): 11595–11611.

[43] BAIAO DD, DA SILVA DVT, PASCHOALIN VMF. Beetroot, a remarkable vegetable: Its nitrate and phytochemical contents can be adjusted in novel formulations to benefit health and support cardiovascular disease therapies [J]. Antioxidants (Basel), 2020, 9(10): 960.

[44] RAHIMI P, ABEDIMANESH S, MESBAH-NAMIN SA, *et al*. Betalains, the nature-inspired pigments, in health and diseases [J]. Crit Rev Food Sci Nutr, 2019, 59(18): 2949–2978.

[45] DA SILVA DVT, PEREIRA AD, BOAVENTURA GT, *et al*. Short-term betanin intake reduces oxidative stress in Wistar rats [J]. Nutrients, 2019, 11(9). DOI: 10.3390/nu11091978

[46] VIEIRA TDSD, DOS SBD, DE OLIVEIRA SF, *et al*. Betanin, a natural food additive: Stability, bioavailability, antioxidant and preservative ability assessments [J]. Molecules, 2019, 24(3). DOI: 10.3390/molecules24030458

[47] MARTINEZ RM, HOHMANN MS, LONGHI-BALBINOT DT, *et al*. Analgesic activity and mechanism of action of a *Beta vulgaris* dye enriched in betalains in inflammatory models in mice [J]. Inflammopharmacology, 2020, 28(6): 1663–1675.

[48] AHMADI H, NAYERI Z, MINUCHEHR Z, *et al*. Betanin purification from red beetroots and evaluation of its anti-oxidant and anti-inflammatory activity on LPS-activated microglial cells [J]. PLoS One, 2020, 15(5): e0233088.

[49] MARTINEZ RM, LONGHI-BALBINOT DT, ZARPELON AC, *et al*. Anti-inflammatory activity of betalain-rich dye of *Beta vulgaris*: Effect on edema, leukocyte recruitment, superoxide anion and cytokine production [J]. Arch Pharm Res, 2015, 38(4): 494–504.

[50] CANADANOVIC-BRUNET JM, SAVATOVIC SS, CETKOVIC GS, *et al*. Antioxidant and antimicrobial activities of beet root pomace extracts [J]. Czech J Food Sci, 2011, 29(6): 575–585.

[51] VULIC JJ, CEBOVIC TN, CANADANOVIC VM, *et al*. Antiradical, antimicrobial and cytotoxic activities of commercial beetroot pomace [J]. Food Funct, 2013, 4(5): 713–721.

[52] KUMAR S, BROOKS MSL. Use of red beet (*Beta vulgaris* L.) for antimicrobial applications-a critical review [J]. Food Bioprocess Technol, 2018, 11(1): 17–42.

[53] RAHIMI P, MESBAH-NAMIN SA, OSTADRAHIMI A, *et al*. Effects of betalains on atherogenic risk factors in patients with atherosclerotic cardiovascular disease [J]. Food Funct, 2019, 10(12): 8286–8297.

[54] LEE EJ, AN D, NGUYEN CT, *et al*. Betalain and betaine composition of greenhouse- or field-produced beetroot (*Beta vulgaris* L.) and inhibition of HepG2 cell proliferation [J]. J Agric Food Chem, 2014, 62(6): 1324–1331.

[55] HENAREJOS-ESCUDERO P, HERNANDEZ-GARCIA S, GUERRERO-RUBIO MA, *et al*. Antitumoral drug potential of tryptophan-betaxanthin and related plant betalains in the caenorhabditis elegans tumoral model [J]. Antioxidants (Basel), 2020, 9(8): 646.

[56] ZHAO G, HE F, WU C, *et al*. Betaine in inflammation: Mechanistic aspects and applications [J]. Front Immunol, 2018, 9: 1070.

[57] ZEISEL SH, MAR MH, HOWE J, *et al*. Concentrations of choline-containing compounds and betaine in common foods [J]. J Nutr, 2003, 133(5): 1302–1307.

[58] DAY CR, KEMPSON SA. Betaine chemistry, roles, and potential use in liver disease [J]. Biochim Biophys Acta, 2016, 1860(6): 1098–1106.

[59] 林妮, 柯渠青, 蒋玲燕, 等. 同型半胱氨酸临床应用的研究进展[J]. 中华全科医学, 2021, 19(8): 1358–1361.

LIN N, KE QQ, JIANG LY, *et al*. The clinical application value of homocysteine [J]. Chin J Gen Pract, 2021, 19(8): 1358–1361.

[60] HASSANPOUR S, REZAEI H, RAZAVI SM. Anti-nociceptive and antioxidant activity of betaine on formalin- and writhing tests induced pain in mice [J]. Behav Brain Res, 2020, 390: 112699.

[61] ADJOUMANI JY, WANG K, ZHOU M, *et al*. Effect of dietary betaine on growth performance, antioxidant capacity and lipid metabolism in blunt snout bream fed a high-fat diet [J]. Fish Physiol Biochem, 2017, 43(6): 1733–1745.

[62] AIRAKSINEN K, JOKKALA J, AHONEN I, *et al*. High-fat diet, betaine, and polydextrose induce changes in adipose tissue inflammation and metabolism in C57BL/6J mice [J]. Mol Nutr Food Res, 2018, 62(23): e1800455.

[63] SHI H, WANG XL, QUAN HF, *et al*. Effects of betaine on LPS-stimulated

activation of microglial M1/M2 phenotypes by suppressing TLR4/NF-*κ*B pathways in N9 cells [J]. Molecules, 2019, 24(2). DOI: 10.3390/molecules24020367

[64] XIA Y, CHEN S, ZHU G, *et al*. Betaine inhibits interleukin-1beta production and release: Potential mechanisms [J]. Front Immunol, 2018, 9: 2670.

[65] VUKICEVIC D, ROVCANIN B, GOPCEVIC K, *et al*. The role of MIF in hepatic function, oxidative stress, and inflammation in thioacetamide-induced liver injury in mice: Protective effects of betaine [J]. Curr Med Chem, 2021, 28(16): 3249–3268.

[66] VESKOVIC M, MLADENOVIC D, MILENKOVIC M, *et al*. Betaine modulates oxidative stress, inflammation, apoptosis, autophagy, and Akt/mTOR signaling in methionine-choline deficiency-induced fatty liver disease [J]. Eur J Pharmacol, 2019, 848: 39–48.

[67] VESKOVIC M, LABUDOVIC-BOROVIC M, MLADENOVIC D, *et al*. Effect of betaine supplementation on liver tissue and ultrastructural changes in methionine-choline-deficient diet-induced NAFLD [J]. Microsc Microanal, 2020, 26(5): 997–1006.

[68] JUNG YS, KIM SJ, KWON DY, *et al*. Alleviation of alcoholic liver injury by betaine involves an enhancement of antioxidant defense via regulation of sulfur amino acid metabolism [J]. Food Chem Toxicol, 2013, 62: 292–298.

[69] SIVANESAN S, TAYLOR A, ZHANG J, *et al*. Betaine and choline improve lipid homeostasis in obesity by participation in mitochondrial oxidative demethylation [J]. Front Nutr, 2018, 5: 61.

[70] HUANG B, HU X, HU J, *et al*. Betaine alleviates cognitive deficits in diabetic rats via PI3K/Akt signaling pathway regulation [J]. Dement Geriatr Cogn Disord, 2020, 49(3): 270–278.

[71] YOUN J, CHO E, LEE JE. Association of choline and betaine levels with cancer incidence and survival: A meta-analysis [J]. Clin Nutr, 2019, 38(1): 100–109.

[72] SUN JY, WEN SL, ZHOU J, *et al*. Association between malnutrition and hyperhomocysteine in Alzheimer’s disease patients and diet intervention of betaine [J]. J Clin Lab Anal, 2017, 31(5). DOI: 10.1002/jcla.22090

[73] DU J, SHEN L, TAN Z, *et al*. Betaine supplementation enhances lipid metabolism and improves insulin resistance in mice fed a high-fat diet [J]. Nutrients, 2018, 10(2): 131.

[74] MILANI A, BASIRNEJAD M, SHAHBAZI S, *et al*. Carotenoids: Biochemistry, pharmacology and treatment [J]. Brit J Pharmacol, 2017, 174(11): 1290–1324.

[75] REBECCA J, SHARMILA D, DAS MP, *et al*. Extraction and purification of carotenoids from vegetables [J]. J Chem Pharm Res, 2014, 6: 594–598.

[76] FIEDOR J, BURDA K. Potential role of carotenoids as antioxidants in human health and disease [J]. Nutrients, 2014, 6(2): 466–488.

[77] SAINI RK, KEUM YS, DAGLIA M, *et al*. Dietary carotenoids in cancer chemoprevention and chemotherapy: A review of emerging evidence [J]. Pharmacol Res, 2020, 157: 104830.

[78] VIJAY K, SOWMYA PR, ARATHI BP, *et al*. Low-dose doxorubicin with carotenoids selectively alters redox status and upregulates oxidative stress-mediated apoptosis in breast cancer cells [J]. Food Chem Toxicol, 2018, 118: 675–690.

[79] AUNE D, KEUM N, GIOVANNUCCI E, *et al*. Dietary intake and blood concentrations of antioxidants and the risk of cardiovascular disease, total cancer, and all-cause mortality: A systematic review and dose-response meta-analysis of prospective studies [J]. Am J Clin Nutr, 2018, 108(5): 1069–1091.

[80] 国鸽, 张靖杰, 李鹏高. 甘薯中主要生物活性成分研究进展[J]. 食品安全质量检测学报, 2017, 8(2): 533–538.

GUO G, ZHANG JJ, LI PG. Research progress of main bioactive components in sweet potato [J]. J Food Saf Qual, 2017, 8(2): 533–538.

[81] OUCHEMOUKH S, AMESSIS-OUCHEMOUKH N, GOMEZ-ROMERO M, *et al*. Characterisation of phenolic compounds in Algerian honeys by RP-HPLC coupled to electrospray time-of-flight mass spectrometry [J]. LWT-Food Sci Technol, 2017, 85: 460–469.

[82] KUJALA TS, LOPONEN JM, KLIKA KD, *et al*. Phenolics and betacyanins in red beetroot (*Beta vulgaris*) root: Distribution and effect of cold storage on the content of total phenolics and three individual compounds [J]. J Agric Food Chem, 2000, 48(11): 5338–5342.

[83] POTI F, SANTI D, SPAGGIARI G, *et al*. Polyphenol health effects on cardiovascular and neurodegenerative disorders: A review and meta-analysis [J]. Int J Mol Sci, 2019, 20(2). DOI: 10.3390/ijms20020351

[84] WAHLE KW, BROWN I, ROTONDO D, *et al*. Plant phenolics in the prevention and treatment of cancer [J]. Adv Exp Med Biol, 2010, 698: 36–51.

[85] BAO TQ, LI Y, QU C, *et al*. Antidiabetic effects and mechanisms of rosemary (*Rosmarinus officinalis* L.) and its phenolic components [J]. Am J Chin Med, 2020, 48(6): 1353–1368.

[86] RODRIGUEZ-PEREZ C, SEGURA-CARRETERO A, CONTRERAS MD. Phenolic compounds as natural and multifunctional anti-obesity agents: A review [J]. Crit Rev Food Sci, 2019, 59(8): 1212–1229.

[87] CIZ M, DVORAKOVA A, SKOCKOVA V, *et al*. The role of dietary phenolic compounds in epigenetic modulation involved in inflammatory processes [J]. Antioxidants (Basel), 2020, 9(8). DOI: 10.3390/ antiox9080691

[88] AHMAD T, CAWOOD M, IQBAL Q, *et al*. Phytochemicals in daucus carota and their health benefits-review article [J]. Foods, 2019, 8(9). DOI: 10.3390/foods8090424

[89] CIMMINO L, NEEL BG, AIFANTIS I. Vitamin C in stem cell reprogramming and cancer [J]. Trends Cell Biol, 2018, 28(9): 698–708.

[90] GRANGER M, ECK P. Dietary vitamin C in human health [J]. Adv Food Nutr Res, 2018, 83: 281–310.

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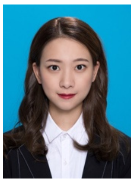

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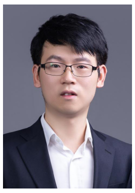

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