

绿色囊泡的跨界调控：果蔬来源细胞外囊泡在疾病防治中的新策略

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摘要

果蔬来源的细胞外囊泡是近年来发现在果蔬植物中天然存在的纳米级细胞外囊泡，具有脂质双层膜结构，携带蛋白质、脂质、核酸等生物活性分子。相对于其他细胞外囊泡，果蔬来源的细胞外囊泡源于日常食用的果蔬，不仅成本低、获取相对容易，而且解决了患者对治疗和环境危害的担忧。这些细胞外囊泡展现出卓越的生物相容性、低免疫原性和良好的肠道稳定性，能够通过参与调控细胞间通讯、影响多种疾病进程而发挥治疗作用。本文系统地阐述了果蔬来源的细胞外囊泡的形成、疾病治疗机制及作为药物递送载体等方面的最新研究进展，特别关注其在抗炎、抗肿瘤、代谢性疾病治疗中的应用潜力，并探讨了当前挑战和未来发展方向。尽管面临诸多挑战，但基于对果蔬来源的细胞外囊泡的疾病疗法的未来前景看好。持续的研究以及跨学科的合作对于充分挖掘基于果蔬来源的细胞外囊泡的天然疾病治疗的潜力至关重要，也为果蔬来源的细胞外囊泡的临床转化提供理论依据和技术参考。

关键词

细胞外囊泡，疾病治疗，药物递送，跨界调控，纳米载体

Cross-Border Regulation of Green Vesicles: A New Strategy for the Prevention and Treatment of Diseases Using Extracellular Vesicles Derived from Fruits and Vegetables

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Abstract

Extracellular vesicles derived from fruits and vegetables are nanoscale extracellular vesicles that have been discovered to naturally exist in fruit and vegetable plants in recent years. They have a lipid bilayer membrane structure and carry bioactive molecules such as proteins, lipids, and nucleic acids. Compared to other extracellular vesicles, fruit and vegetable-derived extracellular vesicles are derived from daily consumption of fruits and vegetables. They are not only low-cost and relatively easy to obtain, but also solve patients' concerns about treatment and environmental hazards. These extracellular vesicles exhibit excellent biocompatibility, low immunogenicity, and good intestinal stability, and can exert therapeutic effects by participating in the regulation of intercellular communication and affecting the progression of various diseases. This article systematically elaborates on the latest research progress in the formation of extracellular vesicles derived from fruits and vegetables, disease treatment mechanisms, and their use as drug delivery carriers. Special attention is paid to their potential applications in anti-inflammatory, anti-tumor, and metabolic disease treatment, and current challenges and future development directions are discussed. Despite facing many challenges, the future prospects of disease therapies based on extracellular vesicles derived from fruits and vegetables are promising. Continuous research and interdisciplinary collaboration are crucial for fully tapping into the potential of natural disease treatments based on fruit and vegetable-derived extracellular vesicles, and providing a theoretical basis and technical references for the clinical translation of fruit and vegetable-derived extracellular vesicles.

Keywords

Extracellular Vesicles, Disease Treatment, Drug Delivery, Cross-Border Regulation, Nanocarrier

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1. 引言

外泌体是直径 30~150 纳米的细胞外囊泡，源于内分泌体。质膜持续内陷会形成多泡体，后者能与细胞内其他囊泡和细胞器相互作用，从而丰富外泌体的成分组成。根据细胞来源的不同，外泌体可以包含细胞的许多成分，包括 DNA、RNA、脂质、代谢物、胞质和细胞表面蛋白等生物活性分子[1](图 1)。在调节细胞间通讯和影响多种疾病进展方面具有重要作用[2]。近年来，科学家在植物中发现并分离纯化，得到了与哺乳动物泌尿器相似的物理性质和组成成分的纳米微粒(plant exosome-like nanoparticles, PELNs)[3]。与动物来源的细胞外囊泡相比，植物来源的细胞外囊泡具有产量高、提取周期短、免疫原性低等优势，特别是 PELNs，从可食用水果和蔬菜中提取出来，生物相容性更好[4]。并有研究显示，它们对多种疾病有治疗作用，如肿瘤、肠道炎、细菌感染等[5]，也可将小分子药、生物大分子药作为载体送往患病部位[6]。由于植物来源的细胞外囊泡自身携带有蛋白质、RNA 等生物大分子，因此在携带外源性生物大分子药物时，PELNs 能有效保证内含物的稳定性与生物活性[7]。目前，从柚子、柠檬、葡萄、生姜、苹果等果蔬中提取的外泌体，也就是果蔬来源的细胞外囊泡，在多种疾病模型中，尤其是在炎症性疾病、肿瘤、代谢性疾病等方面，已经显示出潜在的治疗价值[8]。尽管取得了可喜的结果，但要全面认识其作用机理，优化生产提纯方法，确保果蔬来源的细胞外囊泡在临床环境中安全有效，还需要进一步的研究[9][10]。

本文探讨了水果和蔬菜来源的细胞外囊泡在疾病治疗中的新兴领域，作为一种新颖、绿色和可持续的疾病治疗方法。水果和蔬菜来源的细胞外囊泡是天然存在的细胞外囊泡，作为功能性食品，它提供了水果和蔬菜来源的细胞外囊泡的独特优势和潜在的食用益处。这种双重功能使它们成为治疗疾病的革命性工具，提供可获得的有针对性的治疗干预和营养支持。它们的生物相容性、固有的靶向能力和封装多种疾病治疗活性成分的能力凸显了它们在提高治疗效果的同时，减少脱靶效应和全身毒性的潜力。尽管它们有可能作为可食用成分纳入饮食，但需要进一步的研究来规范提取和表征方法，以确保一致的治疗效果和安全性。

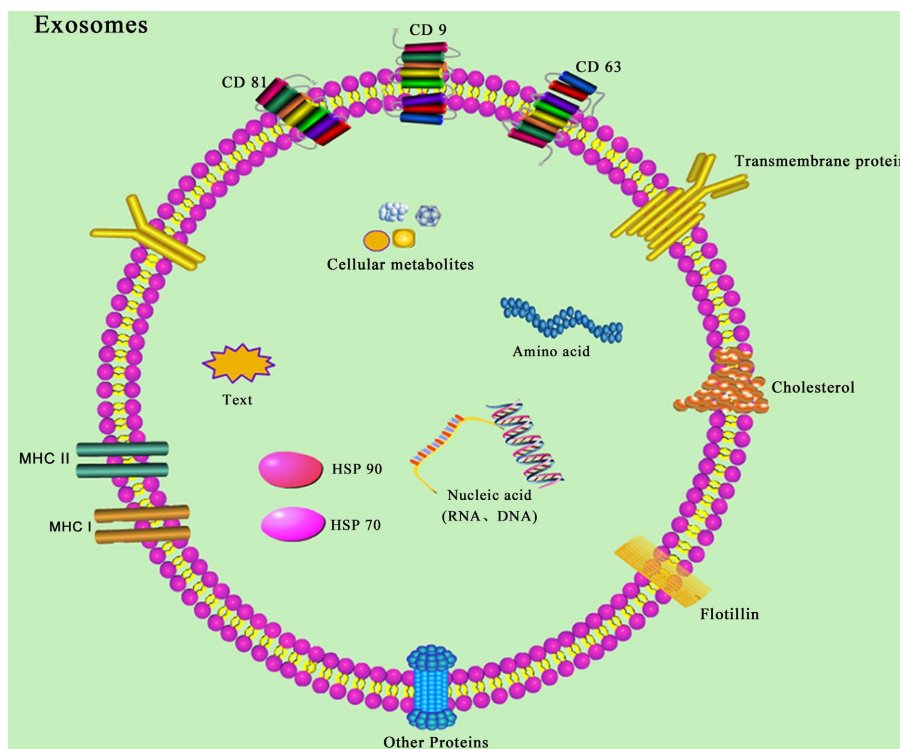


Figure 1. Structure and function of extracellular vesicles
图 1. 外泌体的结构及功能

2. 果蔬外泌体的形成

果蔬来源的细胞外囊泡与动物来源的细胞外囊泡有着相似的形态特征，具有脂双层结构，其中含有与植物免疫和应激相关的蛋白质与 miRNA 等生物大分子[11][12]。目前研究认为，果蔬来源的细胞外囊泡的发生有 3 种可能的途径[13]：1) MVB 途径；2) Exocyst-positive organelle 途径；3) 液泡途径[14]-[16] (图 2)。1967 年，Halperin 等[17]首次在胡萝卜悬浮细胞中观察到 MVB 可与质膜融合，释放细胞外囊泡。但 MVB 靶向质膜释放细胞外囊泡的机制在植物中尚不清楚[18]。Wang 等[19]在拟南芥和烟草的悬浮细胞中鉴定出一种名为 EXPO 的特殊细胞器，其呈球形双膜结构，与自噬体类似。EXPO 能够与质膜融合，将单层膜囊泡释放到细胞外部，进而形成细胞外囊泡。该分泌途径不同于 MVB 途径，是植物所特有的一种非传统囊泡运输方式[20]。此外，果蔬来源的细胞外囊泡的生物发生还有可能来自于液泡，Hatsugai 等[21]研究发现，在拟南芥受到番茄 Pst DC3000 病原菌侵染时，其液泡膜会与质膜发生融合，将液泡内的一些抗菌蛋白释放到细胞外，以应对病原菌的侵害，为植物的防御策略提供了新的证据。

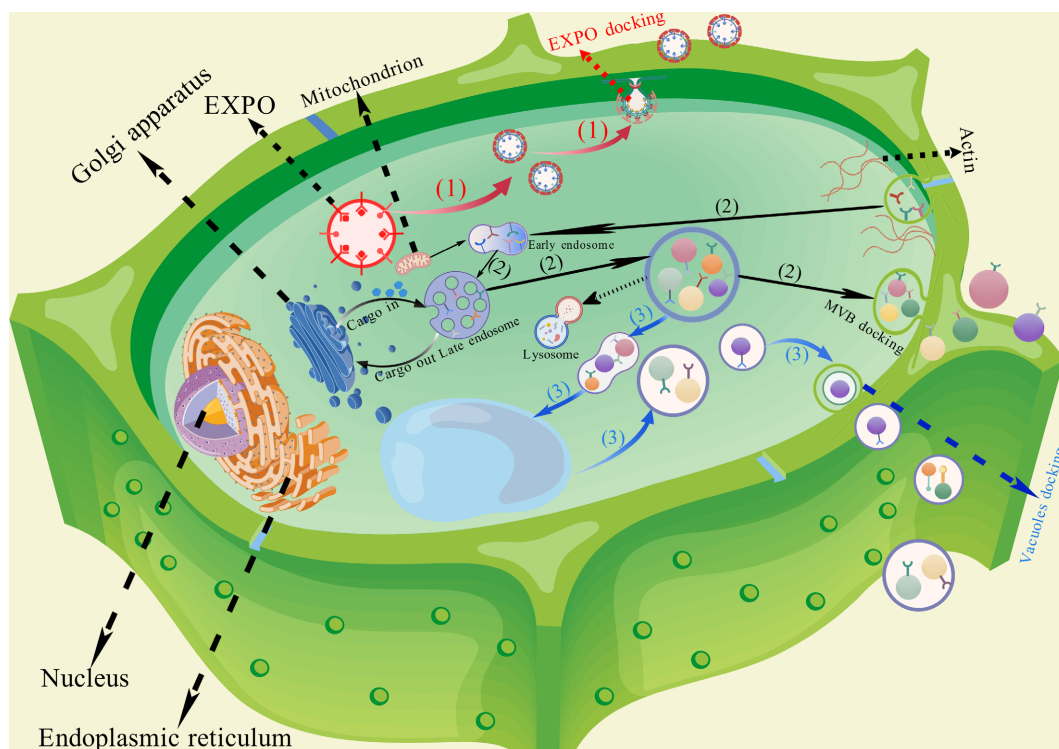


Figure 2. Biological pathways of extracellular vesicles in fruits and vegetables. 1) EXPO pathway: EXPO is a spherical double membrane structure that can fuse with the plasma membrane and release single-layer membrane vesicles; 2) Vacuole pathway: Vacuoles containing hydrolytic enzymes and defense components in plant cells can fuse with the plasma membrane and release defense substances into the extracellular space, inhibiting the proliferation of pathogens. 3) MVB pathway: MVB in plants can fuse with the plasma membrane and release extracellular vesicles into the extracellular space [22]

图 2. 果蔬外泌体的生物发生途径。1) EXPO 途径: EXPO 是一种球形双膜结构, 能与质膜融合并释放单层膜囊泡; 2) Vacuole 途径: 植物细胞中含有水解酶和防御成分的液泡可以与质膜融合, 并将防御物质释放到细胞外空间, 抑制病原体的增殖。3) MVB 途径: 植物中的 MVB 可以与质膜融合, 然后将外泌体释放到细胞外空间[22]

3. 果蔬外泌体在植物中的作用

在植物细胞中, 植物来源的细胞外囊泡是参与植物与微生物共生、免疫调节、细胞壁形成等多种生命活动的各种生物活性物质贮存和运输的保护室[15] [23] [24] (图 3)。De Palma 等[25]发现, 西红柿根来源的细胞外囊泡含有一些参与植物 - 微生物相互作用的蛋白质, 这些蛋白质通过细胞外囊泡进行种间信息交流, 参与植物 - 微生物共生体系。Regente 等[26]从太阳花的细胞外液中分离出来的细胞外囊泡处理真菌孢子后, 透过透射电镜与蛋白质组学分析, 发现真菌孢子在生长发育、形态甚至细胞死亡等各方面均有异常, 显示细胞外囊泡有能力影响真菌生长, 因此推测植物与病原菌间的互动是由细胞外囊泡参与的身体机能。但对于透过植物细胞壁进入根系周围的环境, 外泌体是如何穿行的, 其机理并不清楚。此外, 植物来源的细胞外囊泡也参与植物的免疫调节, 研究发现, 番茄根源细胞外囊泡含有多种参与植物防御的蛋白, 表明细胞外囊泡可能是植物天然免疫系统的组成成分[25]。柑橘源的细胞外囊泡能对柑橘果上的意大利青霉菌丝生长有明显抑制作用, 使柑橘果免受与泌尿系统中的 miRNA 有关的病原物质侵染[27]。虽然缺乏果蔬来源的细胞外囊泡参与细胞壁合成的直接证据, 但对拟南芥内皮层凯氏带缺失突变体 *Lotr2/EXO70A1* 的研究发现: 超微结构表明, 外泌体在内皮层特异性聚集的情况大量存在; 使用囊泡转运抑制剂 brefeldin A 处理可抑制木栓质积累。这些结果说明细胞外囊泡参与了植物细胞壁木栓质的沉积过程[28]。

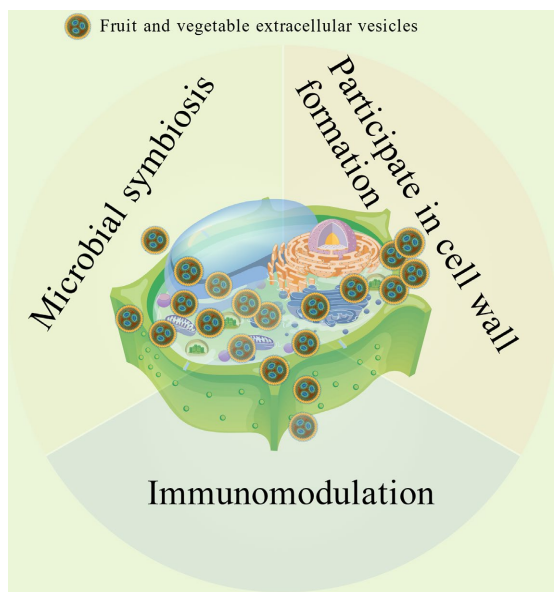


Figure 3. Extracellular vesicles derived from fruits and vegetables participate in plant life activities

图 3. 果蔬来源的细胞外囊泡参与植物生命活动

4. 果蔬来源的细胞外囊泡的疾病治疗潜能与分子机制

果蔬来源的细胞外囊泡含有一些特定的核酸、蛋白质等生物活性成分，这些生物活性成分被认为有有益的作用[29][30]。目前对药用植物来源的细胞外囊泡研究较多，但相对于果蔬来源的细胞外囊泡来说安全性较高，且相对容易获得果蔬来源的细胞外囊泡，具有更多的功能[14]。已有研究表明，许多果蔬来源的细胞外囊泡具备抗炎、抗癌和抗氧化等生物活性，部分果蔬来源的细胞外囊泡被证明可用于提高细胞活力，改善肠道功能等[6] (图 4)。

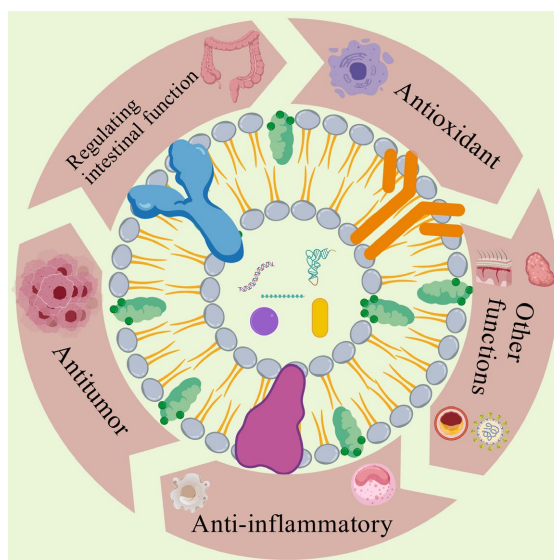


Figure 4. Pharmacological effects of extracellular vesicles derived from fruits and vegetables

图 4. 果蔬来源的细胞外囊泡的药理作用

4.1. 抗肿瘤

一些果蔬来源的细胞外囊泡可以用于预防或缓解癌症,具有抗癌活性。p53失活结直肠癌会激活巨噬细胞胞饮作用促进摄取柠檬外泌体,而柠檬来源的细胞外囊泡能抑制结直肠癌细胞的生长,该机制能预防p53失活结直肠癌的发生[31]。此外,柠檬来源的细胞外囊泡抑制脂质代谢,通过减少ACACA和DDHD1的表达而起到抗结肠癌的作用[32][33]。杨等[34]则发现,柠檬来源的细胞外囊泡可升高肿瘤细胞内活性氧水平,上调GADD45A基因表达,引起胃癌细胞周期停滞和凋亡,进而抑制肿瘤细胞增殖,实现抗胃癌作用。Anusha等[35]研究发现,生姜来源的细胞外囊泡浓度依赖地抑制癌细胞活性、诱导癌细胞凋亡,同时也会造成循环阻滞,使癌细胞迁延,形成集落。王等[36]研究表明,西兰花来源的细胞外囊泡可用于胰腺癌治疗,生物信息学显示这是因为西兰花来源的细胞外囊泡中mir167A的表达量增加。Raimondo等[37]指出,柠檬来源的细胞外囊泡可通过激活TRAIL受体触发凋亡信号通路,诱导肿瘤细胞凋亡,同时抑制血管生成相关细胞因子的分泌,进而有效遏制慢性髓系癌细胞增殖。此外,葡萄柚来源的细胞外囊泡能促进活性氧生成,而不影响正常细胞中的ROS储存,提高肿瘤细胞凋亡率,抑制人类白血病细胞和白血病患者衍生的骨髓母细胞生长的能力[38]。Stanly等[39]研究发现,葡萄柚来源的细胞外囊泡可通过调节cyclin B1、CCNB2及CDKN1的表达,降低细胞周期蛋白B1和B2表达水平和上调细胞周期抑制剂p21,有效抑制肿瘤细胞增殖。

4.2. 抗炎

已研究表明,生姜来源的细胞外囊泡具有抗炎作用[40]-[42]。Sundaram等[43]研究发现,生姜来源的细胞外囊泡可以直接杀灭牙龈卟啉单胞菌,并抑制促炎因子和骨吸收细胞因子生成。此外,Yan等[44]研究表明,生姜来源的细胞外囊泡osa-miR164d-MGELN可以有效地重新编程巨噬细胞以缓解结肠炎相关症状。大蒜来源的细胞外囊泡[45]可以抑制高糖饮食导致小鼠的脑部炎症。另有研究指出,多种水果来源的外泌体均具有抗炎效果[46]。其中,甜橙来源的细胞外囊泡通过增加紧密连接OCLN蛋白来限制炎症刺激并恢复胃肠道屏障功能[47][48]。葡萄柚来源的细胞外囊泡通过上调血红素加氧酶-1的表达和抑制肠巨噬细胞中IL-1 β 和TNF- α 的产生,维持肠道巨噬细胞的稳态,改善右旋糖酐硫酸钠诱导的小鼠结肠炎[49]。李等[50]的研究表明,柑橘来源的细胞外囊泡通过下调脂多糖诱导的炎症因子(如IL-6、TNF- α 、IL-1 β 及IL-10)表达来实现抗炎作用。此外,柠檬来源的细胞外囊泡抑制LPS刺激的小鼠巨噬细胞中NF- κ B的核转位,降低了IL-6、IL-1 β 和TNF- α 等促炎细胞因子的基因和蛋白质表达,发挥抗炎作用[51]。因此,果蔬来源的细胞外囊泡有望在临床上用于治疗肥胖、结肠炎及细菌感染等引起的慢性炎症。

4.3. 调节胃肠道

研究指出,生姜来源的细胞外囊泡能够通过调节肠道菌群及维护肠道屏障功能,从而促进肠道健康[52]。滕等[53]研究表明,生姜来源的细胞外囊泡进入机体后会被乳杆菌科摄取,其含有的microRNA可靶向鼠李糖乳杆菌的多个基因,并通过IL-22依赖途径改善小鼠肠道屏障。此外,生姜来源的细胞外囊泡被肠上皮细胞和巨噬细胞吸收,减少了急性结肠炎,增强了肠道修复[42]。口服橙源性细胞外囊泡则有助于保护肠道和肝脏免受高糖饮食引起的脂肪负荷损伤,同时富含肥胖患者所缺乏的氨基酸及生物活性脂质[54]。Kim等[55]研究发现,石榴来源的细胞外囊泡显著降低了血清内毒素水平,增强了肠道屏障功能,并有利地改变了肠道微生物群特征。段等[56]研究发现,西兰花来源的细胞外囊泡被肠道微生物吸收,恢复了洛派丁胺紊乱的肠道微生物群,并改变了短链脂肪酸和色氨酸的微生物代谢。此外,葡萄柚来源的细胞外囊泡被大鼠肠上皮细胞吸收[57],并被肠道微生物群吸收,诱导IL-22的产生[53],还通过诱导抗炎细胞因子、抗氧化来维持肠道健康[52]。此外,柠檬来源的细胞外囊泡增加胆汁抵抗力,下调LGG

中的 tRNA_{ser}^{UCC} 和 tRNA_{ser}^{UCG} 水平, 塑造肠道微生物群多样性, 维持肠道稳态[58]。

4.4. 抗氧化

源自柠檬、葡萄柚、血橙及柑橘的细胞外囊泡均展现出明显的抗氧化特性[46]。柠檬来源的细胞外囊泡将草酸钙的结晶改变为不太稳定的亚型外, 还抑制了草酸钙诱导的小管细胞内质网应激反应, 从而推迟肾结石的形成[59]。另外, 来源于葡萄柚细胞外囊泡体减少炎症因子的分泌, 维持 Th17 细胞活化, 诱导 Treg 细胞浸润和血橙来源的细胞外囊泡显著调高总抗氧化能力、抗坏血酸、过氧化氢酶、谷胱甘肽和超氧化物歧化酶 1 的水平, 从而发挥抗氧化功效[60][61]。研究证实, 草莓、蓝莓及胡萝卜来源的细胞外囊泡同样具备降低氧化能力, 提高抗氧化能力[8]。Perut 等[62]推测草莓来源的细胞外囊泡所含的维生素 C, 此外有文献指出其中还含有酚类与黄酮类物质[63], 可以有效提高人间质干细胞的抗氧化能力。赵等[64]发现, 蓝莓来源的细胞外囊泡能够改善鱼藤酮诱导的 HepG2 细胞和高脂饮食喂养的 C57BL/6 小鼠的氧化应激, 主要通过降低了活性氧水平, 增加了线粒体膜电位, 并通过诱导 Bcl-2 和血红素加氧酶-1 的表达和 Nrf2 通路实现。Kim 等[65]曾分离得到具有抗氧化功能的胡萝卜来源的细胞外囊泡, 能够抑制体外 ROS 生成和细胞凋亡。

4.5. 其他功能

果蔬来源的细胞外囊泡的生物活性呈现多样化, 除了抗氧化、抗炎、调节胃肠道和抗癌活性外, 部分果蔬来源的外泌体还具有独特的功效。一项研究表明, 葡萄柚来源的细胞外囊泡可以促进伤口愈合[66]。此外, 王等[67]研究发现, 香菜来源的细胞外囊泡可激活人体抗氧化“开关”Nrf2 通路, 显著加速伤口愈合。并且, 柠檬来源的细胞外囊泡参与免疫调节, 促进巨噬细胞上血管和纤维组织的再生, 从而促进糖尿病伤口愈合[68]。韩等[69]研究发现, 苦瓜来源的细胞外囊泡可以通过肠道淋巴转运实现胰腺富集, 不仅有效递送药物, 还能通过多通路调控修复 β 细胞功能, 改善胰岛稳态。王等[70]利用葡萄来源的细胞外囊泡, 作用于紫外线导致的皮肤光老化有很好的预防作用, 可以通过影响上皮细胞的增殖和分化来发挥对皮肤光老化的保护作用。Hwang 等[71]研究发现, 山药来源的细胞外囊泡可被成骨细胞摄取并特异激活 BMP2p38Runx2 轴, 从而促进成骨形成并在小鼠中预防骨质疏松。此外, 番茄来源的细胞外囊泡可以促进脂肪干细胞软骨分化[72]。Timms 等[73]研究发现, 西瓜来源的细胞外囊泡在体外被人类肠上皮细胞积极内化, 改变与远端组织(包括胎盘)的肠道通讯, 从而改善胎盘功能。大蒜来源的细胞外囊泡通过提高 Wnt-1、PDGF、VEGF、TGF- β 1 和 I 型胶原蛋白的水平, 从而促进毛发生长[74]。芹菜来源的细胞外囊泡对 PMA/离子霉素介导的 CD4⁺ T 淋巴细胞活化有抑制作用[75]。Kumar 等[76]指出, 生姜来源的细胞外囊泡通过阻止 Akt-1 介导的 Foxa2 磷酸化, 可预防高糖饮食诱导的肥胖与胰岛素抵抗。Kalarikkal 等[77]发现, 葡萄柚来源的细胞外囊泡能被肺泡上皮细胞特异性摄取, 靶向 SARS-CoV-2 基因, 抑制病毒复制, 发挥抗病毒作用。Teng 等[78]报道, 生姜来源的细胞外囊泡能抑制 SARS-CoV-2 的 S 蛋白及 Nsp12 表达, 从而减轻 Vero E6 细胞的病毒感染病变。此外, Suresh 等[79]预测, 生姜来源的细胞外囊泡可靶向调控 SARS-CoV-2 基因组。Raimondo 等[80]证实, 柠檬来源的细胞外囊泡可下调炎症因子表达, 降低人体低密度脂蛋白胆固醇水平, 调节脂质代谢, 产生调血脂作用。

5. 果蔬来源的细胞外囊泡在药物递送方面展现出良好的应用前景

工程化外泌体可装载核酸、化疗药等, 通过表面修饰实现靶向运输, 用于遗传病和恶性肿瘤的基因或化学治疗, 在较低剂量下提高疗效并显著减少不良反应[81]。研究表明, 葡萄柚来源的细胞外囊泡包裹阿霉素、紫杉醇、JSI-124、CX5461 等药物, 有效递送至肺癌、胶质瘤、乳腺癌、黑色素瘤和乳腺癌, 增

强抗肿瘤效果,降低对正常细胞的不良影响[60][82]-[86]。还可递送硫代硫酸钠至血管钙化部位,被钙化血管平滑肌细胞吸收,抑制骨血管轴,减轻炎症,显著预防血管钙化[87]。甜橙来源的细胞外囊泡可增强阿霉素在肿瘤的积累和渗透,从而有效抑制卵巢癌生长,触发受体介导的内吞作用,促进早期内体/再循环内体途径的胞吐作用,同时减少早期内体-晚期内体-溶酶体途径的降解,显著抑制癌细胞生长且未见明显不良反应[88];此外,姜黄素来源的细胞外囊泡合并地塞米松磷酸钠,导致肠道分泌的 IgA 减少和派尔氏结中 IgA⁺ B220⁺淋巴细胞减少,同时,姜黄素负载的葡萄汁、番茄汁和橙汁,表现出比其他果汁更高的包封效率,更容易进入细胞外囊泡,提升疗效[89][90]。柠檬来源的细胞外囊泡能有效装载阿霉素并被靶细胞高效摄取,消耗细胞内能量、减少 ATP 生成,从而克服多药耐药性[91]。柑橘来源的细胞外囊泡装载橘皮素后,抗炎活性优于游离药物[50]。Pomatto 等[92]发现,甜橙来源的细胞外囊泡可作为 SARS-CoV-2 的 mRNA 疫苗载体,保护疫苗免受降解,有效递送至靶细胞并诱导体液免疫。此外,葡萄柚来源的细胞外囊泡是牛血清白蛋白和热休克蛋白 70 递送到人外周血单核细胞和结肠癌细胞中的高效载体,改善了人类细胞对外源蛋白质的摄取,增强化疗敏感性,显著抑制胶质瘤和结肠癌细胞增殖,发挥抗肿瘤作用[93][94]。李等[95]研究表明,苦荞麦来源的细胞外囊泡转载绿原酸被上皮细胞内化,并通过内质网进行转胞作用,对高脂饮食诱导的肠肝轴高血糖表现出协同调节作用。葡萄来源的细胞外囊泡负载 Fisetin 后,能够降低肿瘤细胞存活率,增加细胞凋亡[96]。

6. 果蔬来源的细胞外囊泡研究领域的核心争议与挑战

首先,分离与表征方法的标准化缺失是首要争议点。目前常用的超速离心、密度梯度离心和尺寸排阻色谱等方法各有优劣,但不同实验室采用的离心速度、转子类型等参数差异导致结果重现性不佳[97]。此外,与哺乳动物外泌体拥有 CD63、CD81 等通用标志物不同,植物囊泡缺乏跨物种通用的标志蛋白,使得身份鉴定和质量控制面临挑战[98]。其次,跨物种 miRNA 转移假说的可重复性争议尤为突出。2012 年首次报道植物 miRNA 可通过消化道进入动物血液循环并调控基因表达,但后续多项独立研究未能复制这一发现[99]。有综述明确指出,植物研究争议的主要来源正是“缺乏结果的可重复性”[100],部分研究甚至认为外源性 miRNA 的跨物种转移在生物学上微不足道且不具相关性[99]。第三,生物安全性与免疫原性评估不足。尽管植物囊泡被认为具有低毒性和良好的生物相容性,但其长期安全性、免疫原性及体内靶向机制仍缺乏系统研究[101]。美国 FDA 已明确指出,目前尚缺乏细胞外囊泡商业产品的质量控制系统。最后,体外培养与天然来源的生物学差异引发质疑。体外培养的植物细胞囊泡缺乏完整植物组织的应激响应特征,且可能残留抗生素、植物激素等培养基成分,其生物学意义与天然果蔬来源囊泡存在本质区别[98]。

7. 小结

果蔬来源的细胞外囊泡作为一种天然纳米材料,具有低免疫原性、高生物相容性、良好的稳定性和多样的生物活性等优势,在疾病治疗和药物递送方面展现出巨大潜力。目前,研究已证实果蔬来源的细胞外囊泡在抗炎、抗肿瘤、代谢调节、抗氧化等方面具有显著效果,且可作为高效药物载体实现靶向治疗。然而,果蔬来源的细胞外囊泡的研究仍处于早期阶段,在标准化生产、安全性评价、监管框架和规模化生产等方面仍面临挑战。未来研究应着重于阐明其作用机制、优化提取工艺、开发工程化改造技术,并推动临床转化研究,最终实现果蔬来源的细胞外囊泡在医学领域的广泛应用。

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