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未来淀粉
——淀粉资源的挑战与思考

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摘　要：淀粉是人类活动的主要能量来源和重要的工业原辅料。然而，传统淀粉来源的植物受种植环境影响较大，土地资源有限，产量增长困难，满足不了人口增长的需要；另一方面，传统植物来源的淀粉，其结构相对固定、性能存在局限性，不能完全满足应用的需求，往往要通过结构修饰来调控其性能。化学方法是常用的结构修饰和性能调控手段，但化学反应过程带来的试剂用量受限、化工辅料残留、副产物的产生和淀粉分子中新化学基团的引入等问题，使其作为食品添加剂的使用存在安全隐患。因此，传统淀粉资源已经不能够完全满足人类可持续发展的要求，有必要开发具有“未来特点”的淀粉新资源。未来淀粉来源根据其特点可分为三类：一是将传统淀粉来源植物通过遗传育种或者基因编辑改造，实现淀粉结构的定向或定点改造，使淀粉具有特殊的应用性能；二是能够克服土地和自然环境限制、或者富含淀粉而尚未被充分开发利用的新淀粉资源等；三是不以植物和微生物为载体合成的无细胞合成新型淀粉。本文阐述了未来淀粉发展的必要性、可行性和发展趋势，以高直链淀粉、蜡质淀粉、浮萍淀粉、微藻淀粉、CO_2 合成淀粉和多糖生物合成淀粉等为例，重点介绍了三类未来淀粉的研究现状和特点，将对未来淀粉的开发研究具有指导意义。

关键词：淀粉；浮萍；微藻；结构；修饰；基因编辑；无细胞合成淀粉；未来淀粉发展趋势

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Future Starch
——Challenges and Reflections on Starch from New Sources

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Abstract: Starch serves as the primary energy source for human activities and is utilized as a crucial raw material in various industries. However, due to limited land resources and challenging yield growth, the

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traditional starch-producing plants are significantly influenced by environmental conditions, which made it unable to meet the demands of population expansion. On the other hand, the traditional source of starch exhibits a relatively stable structure but faces performance limitations that fail to fully meet application requirements. Consequently, structural modifications have been often employed to effectively regulate the performance of starch. Chemical modification is a commonly employed method for controlling performance, but it can pose potential risks to food safety due to the occurrence of chemical reactions caused by limited reagents, residues of chemical auxiliary materials, generation of by-products, and the introduction of new chemical groups into starch molecules. Therefore, the traditional starch resources are inadequate to meet the demands of sustainable development. It is imperative to explore novel starch resources possessing “future characteristics”. According to their characteristics, the sources of future starch could be divided into three categories: firstly, the traditional starch source plants could be genetic breeding or gene edited to achieve directional or site-directed transformation of starch structure, making starch with special application performance; secondly, new starch resources that could overcome the limitations of land and natural environment, or are rich in starch but have not been fully developed and utilized; thirdly, new cell-free synthetic starch that does not take plants and microorganisms as carriers. This review elucidates the necessity, feasibility and development trend of future starch development, and emphasizes on the research status and characteristics of three types of future starch, taking high amylose starch, waxy starch, duckweed starch, microalgae starch, CO_2 synthetic starch and polysaccharide biosynthesis starch as examples. This review will provide valuable guidance for future advancements in starch development.

Key words: starch; duckweed; microalgae; structure; modify; gene editing; starches synthesized without the cells; developing trends of future starches

淀粉是人类膳食的主要组成部分，每日为人类提供所需总能量的 45%~65%[1]，同时，淀粉是工业生产中重要的原辅料，被广泛应用于食品、饲料、造纸、纺织、医药、精细化工等工业中[2]。2022 年全球淀粉市场规模达 2 673.78 亿元，预计到 2028 年全球淀粉市场规模预计将达 3 041.46 亿元[3]。然而传统植物来源的商品淀粉种类较为有限，主要包括玉米淀粉、马铃薯淀粉、木薯淀粉、甘薯淀粉、小麦淀粉和大米淀粉等[4]。

传统植物来源淀粉一方面因结构较为固定，性能存在局限，导致其应用受限或应用效果不佳。另一方面，传统淀粉来源的原料作物生长需要占用大量的耕地和淡水资源，受种植环境和气候的影响较大[5-7]，而全球耕地和淡水资源有限[8-9]、全球极端天气、地区冲突和战争的发生，导致了相应作物的减产[10-11]和进一步的自然生态危机、能源危机和粮食危机，这严重影响了人类的可持续发展，因此开发具有“未来特点”的新资源淀粉——未来淀粉势在必行。

未来淀粉来源根据其特点可分为三类：一是将传统淀粉来源植物通过遗传育种或者基因编辑改造，实现淀粉结构的定向或定点改造，使淀粉具有特殊的应用性能，如将普通玉米经过基因育种、酶活调控等技术实现高直链玉米、蜡质玉米的创制等；二是能够克服土地和自然环境限制，或者富含淀粉而尚未被充分开发利用的新淀粉资源，如木本植物橡子、菠萝蜜中的淀粉，水生植物莲藕、浮萍和微藻中的淀粉等；三是不以植物和微生物为载体合成的无细胞合成新型淀粉，如 CO_2 人工合成淀粉、多糖定向合成淀粉等。

1 传统淀粉来源的育种改造

传统淀粉育种改造主要涉及玉米[12-13]、水稻[14-16]、小米[17-18]、小麦[19-20]、大麦[21-22]、木薯[23]、马铃薯[24]、青稞[25]等作物，通过遗传育种或者基因改造[12-15,18-21,23,25]，调控植物中直/支链淀粉含量合成相关酶作用[17,24]等手段可定向合成不同直支链比例或者引入特定基团的淀粉。目前研究和关注

较多的是高直链淀粉和蜡质淀粉。

1.1 高直链淀粉

1953 年 Dunn 等[26]首次发现玉米品种 *dususu2* 中直链淀粉含量高达 77%，但该品种中总淀粉含量较低。20 世纪以来，美国陆续培育出了直链淀粉含量为 50%的 ClassVI、70%~80%的 ClassVII 以及高于 94%的 ClassVII 和 ClassIX[27]玉米品种，高直链玉米淀粉也逐步实现产业化。而我国对高直链玉米及淀粉的研究起步较晚。2004 年，中国农业大学培育出中国首个直链淀粉含量为 50%玉米杂交种“ND-AE-0201”[28]；随之 2014 年西北农林科技大学开发了 13 个 *ae* 近等基因系，获得了直链淀粉含量从 44%到 78.81%的系列高直链玉米品种[29]；扬州大学江苏省作物遗传生理重点实验室也研发出 2 个高直链玉米杂交品种[30]。相关研究证实玉米基因库中主要有 *ae*、*du*、*wx* 和 *su2* 四种突变基因影响籽粒中直链淀粉含量，其中影响最为显著的是 *ae* 基因[31]。

美、澳等发达国家拥有自有知识产权，利用 *ae* 突变已培育出多种不同行业应用的高直链淀粉玉米品种，并规模化生产在市场上具有一定垄断性的高直链玉米淀粉及深加工产品。在我国，尽管不同育种团队在高直链淀粉玉米的育种中取得了一些进展，但仍存在无自有知识产权和商业化的优良品种，且现有种质不能满足特殊应用领域对产品品质的需求，从而无法实现针对性筛选和培育高直链淀粉玉米种质等诸多瓶颈，极大程度上限制了农产品以及相关领域的发展。

与普通淀粉相比，高直链淀粉性质具有一定特点：在糊化时需要更高的温度[32]；糊化时有限溶胀导致了高直链淀粉的峰值黏度低[33]。直链含量通常与短期回生率呈正相关，高直链淀粉易回生和形成凝胶网络，且凝胶硬度大，具有较好的成膜性。此外，高直链淀粉还具有较高的抗消化性[34]。基于其特殊的结构和性质，高直链淀粉可增加休闲食品的脆性、作为糖尿病病人理想的食品、使食用膜具有保鲜作用，可有效延长食品保质期。此外，高直链淀粉还可作为淀粉基生物可降解材料的主要原料，减少“白色污染”[35]。

1.2 蜡质淀粉

蜡质淀粉目前涉及作物较为广泛，主要有马铃薯、玉米、水稻、小麦和青稞等。1987 年，德国明斯特大学率先将辐射产生的蜡质突变基因用于改造马铃薯淀粉[36]，我国之后也连续培育出支链淀粉含量近 100%的鲁糯 1 号、春糯 1 号、白糯 1 号、白糯 2 号等蜡质玉米品种[37]。蜡质玉米发源于我国，20 世纪初传入美国走向世界。我国虽是蜡质玉米发源地，但是大规模种植化的推广和原料支链含量成为制约蜡质玉米淀粉发展的主要原因。1994 年 Nakamura 等[38]首次采用传统育种开发蜡质小麦品种；随着基因编辑技术的发展，相关研究人员使用 CRISPR/Cas9 技术编辑 TGW6 和 Wx 的主要基因，开发了高产糯质不育稻[39]、蜡质青稞等多种作物。

与高直链淀粉相比，蜡质淀粉具有糊化时颗粒溶胀快，峰值黏度高，不易回生[40-41]和强抗冻融稳定性的特点[42]，其凝胶呈现一定的黏弹性[41]。蜡质淀粉是食品中重要的增稠稳定剂，应用在烘焙食品可防止产品老化和延长烘焙产品保质期[42]；蜡质淀粉改性制备的淀粉基纳米晶[43-44]可作为填料、聚合物复合材料中的增强剂、药物递送的载体、阻隔涂层材料、乳液中的稳定剂[45]等。此外，蜡质淀粉也可用于医疗领域，如作为手术过程中体外循环使用的引物溶液[46]等。

2 新型来源类淀粉

新型来源类淀粉主要是来源于水生植物（微生物）的淀粉，如莲藕淀粉、浮萍淀粉和藻类淀粉，以及来源于木本植物的淀粉，如橡子淀粉和菠萝蜜淀粉。

2.1 浮萍淀粉

浮萍是一种在全世界广泛分布的水生植物[47]，有扁平无根萍属（Wolffiella）、绿萍属（Lemna）、多根紫萍属（Spirodela）、少根紫萍属（Landoltia）和无根萍属（Wolffia）5 个属[48]，其中紫萍和无根萍中淀粉含量较高。浮萍中淀粉主要储存在叶状体和/或休眠体，通常在休眠体中淀粉含量更高。国内外关注浮萍研究的国家有美国、中国、德国、印度等；研究方向主要集中在浮萍生长的

植物生理调控（如生态[53]、生长机制[54]、光温影响、激素影响[55]、重金属毒害等方面）、污水处理应用[56-59]、生物反应器构建[60]、基因工程的筛选[61-62]、能源和饲料利用研究[63-64]等，更聚焦在浮萍植株整体的研究和利用，浮萍淀粉的研究尚处于起步阶段。

2.1.1　高淀粉含量的浮萍植株筛选

中国科学院成都生物研究所已建立了全球最大的浮萍活体种质资源库与数据库，并筛选出了 2 株淀粉含量高于 35%的多根紫萍属，9 株淀粉含量高于 40%的少根紫萍属和 2 株绿萍属浮萍和[65-68] Sree 等[69] 通过 NaCl 处理不同天数后得到淀粉含量可达 40%~50%（d.b.）的 *S. intermedia* 9394、*S. intermedia* 7450 和 *L. minor* 9441 *L. punctata* 9589。

2.1.2　浮萍中淀粉积累的调控

浮萍生长中光、植物激素、盐离子、培养模式、营养物质和重金属离子等是影响淀粉积累的重要因素。Zhong 等[70]发现红光可加速 *Spirodela polyrhiza* 5510 浮萍中淀粉的积累。Yin 等[71]研究认为淀粉积累的最佳光照强度是 110 μmol/m^2/s。Liu 等[72]则认为全光照周期更利于浮萍中淀粉的积累。而植物激素烯效唑[73-74]、细胞分裂素[55]、脱落酸[75]等均有提高浮萍中淀粉积累的潜力，尤其是细胞分裂素。盐离子品种对浮萍中淀粉积累作用有不同的效果。氯化钠对浮萍进行盐胁迫能够增加淀粉含量，但同时会抑制浮萍植株生长[76]；硝酸盐可调节淀粉的合成但也分解淀粉[77]；一定浓度硒溶液能提高浮萍中淀粉的积累量[78]。浮萍培养模式的选择也是影响淀粉积累的因素之一。Li 等[79]发现适当的多种混养以促进生物量和淀粉的积累。通过调控磷、氮、硫等寡营养物质添加量能高效地促进浮萍中淀粉的积累[65,80]，其中硫限制的促进效果最佳[81-82]。重金属离子钴和镍能够促进浮萍中淀粉的积累[83-84]，而铬和镉则会干扰淀粉的积累[85-86]。

2.1.3　浮萍淀粉的提取、结构和应用

浮萍含有淀粉，具有作为生物燃料原料的潜力。相关研究表明，浮萍植株中淀粉含量变化影响乙醇生产效率，*S. polyrhiza*、*L. punctata*[87]和 *W. globosa*[88]具有较高的乙醇生产效率。Xu 等[67]发现淀粉含量高达 65.63%浮萍休眠体的乙醇产量可达 4.69 t/ha/年。

浮萍淀粉的提取方法主要包括液氮冷冻粉碎提取[89]、常规磨碎提取[90]、乙醇浸泡去色后进行粉碎[91]和分散法[92]，前三种提取方法以浮萍叶状体为原料，但提取率和纯度相对较低、淀粉颜色呈现浅绿色。分散法则主要以浮萍休眠体为原料，淀粉呈现白色，纯度和提取率可分别达到 98%、85%以上[52]。因浮萍研究更多关注在浮萍培养以及利用，对浮萍淀粉结构和性质研究较少。Moretti 等[93]考察了五种浮萍叶状体淀粉的分子结构及与体外酶降解动力学的关系，但该研究中涉及的分子结构较为浅显。Chen 等[91]发现 *Spirodela oligorrhiza* 和 *Lemna minor* 叶状体淀粉呈圆盘状，颗粒尺寸在 2~7 μm 之间，均为 B 型淀粉。Wang 等[52,94]系统研究了多根紫萍 ZH0196 休眠体淀粉的结构和性质，结果表明，与玉米淀粉和大米淀粉相比，休眠体淀粉的结构较为“疏松”，淀粉中高聚合度链段（DPw > 10 500）含量较高，达到 46.67%，支链淀粉分子大小差异较大而直链淀粉分子大小较为均一，其支化主要发生于链长较长的部分；其直链淀粉和支链淀粉的有序度介于其他两种淀粉之间，无定形态含量达到 45.93%；休眠体淀粉具有多孔致密的微观结构，在冷冻过程中，淀粉先形成片状的分子网络，然后网络向细密均匀的方向发展。在冷冻初期（0~4 h），休眠体淀粉凝胶形成了尺寸较大的凝胶网络，水分被束缚在网络中但未被完全冻结，这种尺寸较大的网络结构可能有助于水分的均匀分配。随着时间的增加，网络尺寸变小将水分包裹在小尺寸网络中一起冻结。更有益于淀粉凝胶冻融稳定性的提高，使其呈现良好的冻融稳定性和较强的凝胶强度和弹性，具有应用于冷冻食品中的潜力。

2.2　微藻淀粉

藻类是一种水生的原生低等生物，隐藻门、灰色藻门、裸藻门、绿藻门等微藻中主要储存物质为淀粉。橡子产于栎树，栎科在全世界均有分布，共 600 多种[49]。微藻的主要研究方向与浮萍基本一致。微藻淀粉研究主要集中于微藻中淀粉的积累，而微藻淀粉的提取、表征和应用等均处

于起步阶段。

研究者通过揭示相关酶在淀粉合成过程中的作用，调控微藻生长过程中氮[95]、磷[96]、硫[97]、碳[97-98]等营养素以提高淀粉累积量。如 Jiang 等[99]通过探究绿藻 *Tetraselmis subcordiformis* 淀粉积累过程中的酶特性和酶活变化，揭示了淀粉磷酸化酶在合成中的作用，发现氮限制可使 TsSP4 酶在淀粉生物合成的发育和成熟阶段表现出更高的活性。有学者利用微藻 *T. subcordiformis* 的蛋白质组确定积累藻类淀粉是海藻糖磷酸合酶和淀粉磷酸化酶[100]。Yao 等发现[96]在氮缺乏的条件下，过量磷促进了绿藻 *Tetraselmis subcordiformis* 中淀粉的合成。Hong 等[97] 则通过碳浓缩机制的操作以及硫限制的过程，促进了 *Chlamydomonas reinhardtii* 中淀粉的进一步合成。

微藻淀粉的提取方法主要包括乙醇法[101]、超声和珠磨法[102]，提取技术尚不成熟。Ramli 等[101]提取的 *Klebsormidium flaccidum* 淀粉纯度仅为 60%，该藻类淀粉呈椭圆形，淀粉颗粒直径约为 1 μm，淀粉的浊度、膨润力和溶解度均高于普通玉米淀粉。Di Caprio 等[102]发现球磨在 *Scenedesmus obliquus* 细胞破碎方面比超声速率更高，但淀粉分离效率较差。*Scenedesmus obliquus* 淀粉颗粒的尺寸呈正态和窄分布（0.93±0.14 μm），成糊温度在 45~55 ℃之间。

微藻淀粉应用主要集中于淀粉基生物塑料[103-104]和高效水解[105]生产生物燃料，但相关研究均较少。Mathiot 等[104]使用双螺杆挤压技术将 *Chlamydomonas reinhardtii 11-32A* 全株与甘油混合物进行塑化制备了微藻淀粉基生物塑料。Peng 等[105]发现微藻 *T. subcordiformis* 淀粉在 40 ℃下可被 α-淀粉酶有效地水解，水解度达到 74.4%，有效节约了传统水解淀粉前需糊化带来的能源成本。

浮萍和藻类均具有生长快、生长周期短[51]，不与粮争地，易于培养和采收，可实现空间化养殖和非地域、季节限制性养殖等优点[52]，也被认为是最具潜力的未来淀粉来源。

2.3 其他淀粉

2.3.1 莲藕淀粉

莲藕在中国和印度等亚洲许多地区已经种植了 7 000 多年，常作为食物食用，而莲藕淀粉是一种利用不足的新型淀粉资源。莲藕淀粉的提取方法一般为：莲藕去皮，切成小块，磨浆，过滤获得淀粉浆，离心，去杂，洗涤，干燥[106]。天然莲藕淀粉中直链淀粉含量高，冷水溶解度低，凝胶性能差，糊化粘度高，溶胀能力低[107]，是布丁、食用薄膜及可食用涂层、抗性淀粉、TiO_2 海绵等的原料[107]。天然藕淀粉的理化性质不能完全满足其在工业上的应用，通常采用改性以拓宽其在食品领域中的应用。常用的物理改性包括微波处理[108]、γ 辐照处理[108]、高压处理[109]、超声处理[110]等，化学改性包括氧化[111]、交联[111]等，酶法改性包括 a-淀粉酶[112]和葡萄糖淀粉酶水解等。微波和 γ 辐照复合改性可降低莲藕淀粉的回生率，使其更适合用于冷藏和冷冻食品[108]。氧化交联淀粉表现出较好的热稳定性；交联氧化淀粉则具有更好的糊状透明度、糊状和热特性，可用于可生物降解的薄膜和食用涂料、食品制剂和药物中的增稠剂和粘合剂、稳定剂和乳化剂等[111]。冷等离子体和微波联合处理显著改变了淀粉颗粒的形态结构，藕淀粉的相对结晶度和峰值粘度均有所下降[113]。采用高压灭菌冷却法制备的新型莲藕淀粉/黄原胶纳米颗粒，显著提高了淀粉的乳化活性和稳定性[109]。

2.3.2 橡子淀粉

橡子中淀粉含量可达干重的 50%~60%[114]，直链淀粉含量在 15%~39%之间。橡子淀粉可通过热水浸泡、碱处理、超声辅助乙醇浸泡和超声辅助热水浸泡等方法提取[115]，其提取难点在于橡子中单宁物质的去除。橡子淀粉颗粒以球状为主[114]，大小在 2~24 μm 之间，晶型多呈现 A 型和 C 型[115]。橡子淀粉溶解度和溶胀力较低，凝胶强度较高[114]。它主要用于生产乙醇，如 Chao 等[116]开发出一种以橡子淀粉为原料，通过单宁提取预处理和发酵技术生产生物乙醇的综合工艺。Zhang 等[117] 利用橡子粉通过耐单宁突变体发酵生产燃料乙醇，简化了生产工艺，降低了生产成本。橡子淀粉经过改性处理后应用范围得以扩大，如 Nuran 等[118]以橡子淀粉为原料，合成了不同取代度的橡子羧甲基淀粉，并将其用于果蔬涂膜，延长了果蔬的

保质期。Wang 等[119]使用脱支和湿热复合处理橡子淀粉，提高了橡子淀粉的冻融稳定性、慢消化淀粉和抗性淀粉含量，实现了橡子淀粉在冷冻食品、功能性食品中的应用。

2.3.3 菠萝蜜淀粉

菠萝蜜是热带和亚热带常绿树种之一[50]，其种子质量占整个果实的 8%以上[121]。其种子一般为工业加工副产物，菠萝蜜种子中淀粉含量丰富，含量占种子的 60%以上[121]。近年来菠萝蜜种植加工业发展迅速，菠萝蜜种子作为副产物大量产生，造成淀粉资源的浪费。菠萝蜜种子淀粉中直链淀粉含量为 32.58%~38.11%[121]，是直链淀粉含量较高的品种之一。菠萝蜜淀粉颗粒为球形、椭圆形和钟形[122-126]，也有呈现三角形和多边形[120,127-128]，淀粉颗粒更小、更光滑、更致密[120,123-124,129-130]，晶型通常为 A 型[120,123,131-132]。菠萝蜜种子淀粉因直链淀粉含量高，抗性淀粉含量较高[129,131,135,138-139]，呈现出较高的成糊温度（77.9~91.3 ℃[123,127,132-137]），该淀粉易形成凝胶[134]，冻融稳定性较差[127,133]，Kushwaha 等[10]认为退火和高压灭菌-冷却处理后的菠萝蜜淀粉可应用在面条、面团、烘焙产品、馅饼馅料、汤和香肠中，通过酸改性菠萝蜜淀粉则可作为口香糖、奶酪的胶凝剂，以及脂肪替代物[140]。挤压膨化或湿热处理、退火处理等方式可改变菠萝蜜淀粉消化性[141-143]。交联改性菠萝蜜淀粉可作为药片的赋形剂和崩解剂[144]，若经过纳米化处理则可实现对药物的包封[145]。此外，菠萝蜜淀粉还可应用在食品保鲜涂层[146-147]和生物降解塑料[148-150]。

3 无细胞合成淀粉

CO_2 人工合成淀粉在 *Science* 报道后引起广泛关注，该技术提出以 CO_2 和 H_2 为原料，经过合成代谢途径的设计和模块化组装，将 60 余步的代谢反应简化成 4 个阶段，11 步反应，将原来复杂的酶系简化成 10 个工程酶，成功合成了淀粉[151]。合成生物学的发展使设计和构建淀粉成为可能。

多糖的生物法合成主要是通过细菌和酶的作用实现的，早在 1946 年，Hehre 等[152]将蔗糖经由细菌合成支链淀粉样多糖，之后 Hehre[153]又通过细菌酶系统将蔗糖合成一种淀粉糖原类多糖。2014 年，Qi 等[154]采用蔗糖磷酸化酶和马铃薯 α-葡聚糖磷酸化酶组成的双酶法或补充了葡萄糖异构酶、葡萄糖氧化酶和过氧化氢酶的多酶法将蔗糖转化为直链淀粉。与直链淀粉相比，线性葡聚糖具有较低的聚合度和较好的水溶性，具有良好的抗老化、抗消化、乳化和成膜性能，在食品、医药、营养、化工等领域有着广泛的应用[155-159]。

线性葡聚糖可由属于 GT35 家族（EC 2.4.1.1）的 α-1,4-葡聚糖磷酸化酶（GP）合成，其合成路径为葡萄糖单元从 α-D-葡萄糖-1-磷酸（G-1-P）转移到淀粉引物的非还原端[160-163]。为降低成本，Waldmann 等[164]将蔗糖磷酸化酶（SP, EC 2.4.1.7）引入上述反应体系。尽管线性葡聚糖在食品生物学领域发挥着越来越重要的作用，但对其调控机制的研究却很少。G 作者研究团队设计了由双酶协同催化路径——将蔗糖转化为具有明确结构线性葡聚糖的合成途径，并在此基础上制备了一系列线性葡聚糖产物，以研究反应参数对线性葡聚糖分子结构的影响，此外还建立了反应相关的理论模型。将反应分为三个主要的阶段，第一个阶段为积累期（0~48 h），在这个阶段，SP 首先催化蔗糖生成果糖和 G-1-P。在 G-1-P 浓度较低的环境中，GP 会催化将少量的麦芽四糖转化为三糖和 G-1-P 的反应，这也与链长分布结果中会出现少量 DP<4 的产物线性相对应。这一阶段的时间占据总反应的 2/3，SP 和 GP 的平衡转化率分别为 81.68 %和 23.98 %，而磷酸根的浓度也会对反应速率产生影响。第二个阶段为震荡反应期（48~68 h），该阶段中会有大分子产物合成呈现不稳定性。在 52 h 时，DP>20 的产物由 0%增长至 40.1%±0.99%，在 56 h 时又下降到 3.98%±0.99%。在 64 h 时增长至 32.9%±3.03%，在 66 h 又下降至 9.08%±1.10%。在这一阶段内，GP 多次交替发生持续性的正反应和逆反应，最终获得了数量较多的短链线性葡聚糖。第三阶段是链长增长期（68~72 h），在该阶段，α-1,4-糖苷键的形成、引物伸长，正反应占据主导地位。目前针对 GP 延长碳链的研究集中于两种理论，一种是聚合遵循“多链”方案，另一种是“单链”方案，双酶

协同催化生成线性葡聚糖更倾向于“多链”方案的聚合。此外，由于线性葡聚糖产物会自发形成左旋双螺旋结构，通过 GP 催化聚合酶合成的直链淀粉会在反应体系中逐渐沉淀。因此，在第三个阶段，不断沉淀的线性葡聚糖产物也被认为会解除产物抑制，进一步促进合成反应的进行。

多糖合成淀粉的相关研究正在不断开展，但总体而言，多糖合成淀粉侧重在非定向合成研究，尚无法完全实现定向合成。而定向合成的关键在于酶选择性、稳定性和协效性、合成的动态稳定性等多方面。

4 未来淀粉发展可行性和趋势

未来淀粉开发具有很大的空间，人类发展的愿景、研究技术和手段的进步均构成了未来淀粉发展的有利条件。主要体现在：

（1）生物合成技术的不断进步及它的“工程”属性，在淀粉资源的开发中发挥着越来越重要的作用。基因工程和代谢工程等技术调控淀粉生物合成途径中关键酶的活性和表达水平，从而为开发特定结构、特定用途的新型未来淀粉提供了理论基础和技术支撑。

（2）新能源的发展（如光能、核能等）能够有效提供无细胞合成类淀粉在合成过程中所需的能源。

（3）现代科学仪器和分析技术的进步使得淀粉研究得到了极大的深入。多领域、多角度、信息化的相关测试手段和方法的建立和完善使研究人员能够更准确地分析淀粉的结构特征、分子量分布、晶体性质和功能性质等。

（4）随着全球对可持续发展和环境保护的关注日益增加，淀粉作为绿色、低碳的生物质材料，新型未来淀粉发展将成为必然。

基于综上分析，未来淀粉的发展趋势表现在：

（1）在阐明传统作物中淀粉合成和积累机制基础上，根据淀粉应用领域所需的结构和性质，通过分子育种、基因组编辑育种等精准设计特定结构的淀粉分子，并实现特定作物产量的提升。

（2）多角度开发新型未来淀粉的来源，挖掘和筛选高淀粉含量的植物（微生物）品种，解析新型来源植株中淀粉合成路径和调控手段，实现精准调控淀粉合成，并剖析结构性质和拓宽其应用。

（3）CO_2 人工合成淀粉仍存在淀粉合成步骤繁琐、合成过程稳定性不佳、酶活性和品种稳定性不高等瓶颈，需要通过相关研究开辟新的合成路径和提高淀粉合成过程的可调控性。

（4）低聚糖合成淀粉结构的精准性和稳定性、产物的高效分离、产物的功能性评价和应用研究仍将是未来的研究重点。

这些趋势将推动淀粉科学研究的进步，并为未来淀粉的应用提供更多机遇。

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