特约评述

DOI: 10.12211/2096-8280.2023-048

全碳素生物转化沼气制备生物航煤制造路线研究进展

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摘要：作为一种清洁可再生能源，沼气具有替代化石燃料的潜能。沼气的传统利用是通过直接燃烧获得电力和热量，但该过程会产生二氧化碳（CO_2），不仅降低了沼气利用的碳原子经济性，还会带来温室气体排放等问题。为了实现沼气全碳素转化，本文提出以餐厨垃圾厌氧消化产生的沼气为原料，利用合成生物学技术和生物制造策略，将其中的全部碳素（CO_2和CH_4）高效转化为生物航煤（SAF）。该制造路线利用光能自养微生物和好氧性嗜甲烷菌分别转化CO_2和CH_4合成生物油脂，再将油脂提取并升级加工制备SAF。文章通过介绍光能自养微生物和好氧性嗜甲烷菌的关键酶和代谢途径，总结菌种改造策略和发酵工艺优化在提升油脂积累方面的研究进展。在比较了不同生物油脂预处理和升级加工的工艺特点之后，分析了相关技术的经济性和应用场景。基于SAF的燃烧性能及其在生产过程中的全球变暖潜势值，讨论了SAF制造路线的技术可行性。最后，借助技术经济可行性分析，展望了提升SAF制造路线经济性的策略，为生物技术在燃料生产领域的商业化应用提供参考。

关键词：沼气；光能自养微生物；好氧性嗜甲烷菌；合成生物；生物航煤；生物制造

中图分类号：Q819 **文献标志码：**A

Progress in the bioconversion of biogas into sustainable aviation fuel

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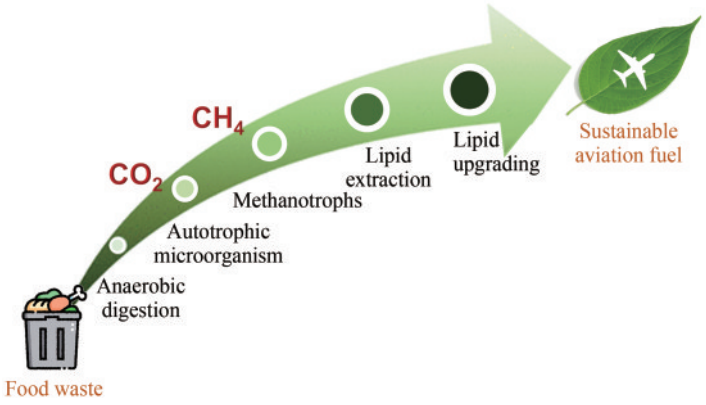
Abstract: Biogas primarily composed of methane (CH_4) and carbon dioxide (CO_2) is recognized as a clean and renewable energy source with potential to replace fossil fuels. Currently, the most common way to utilize biogas is by

收稿日期：2023-07-02 修回日期：2023-09-07
基金项目：国家重点研发计划（2021YFC2103500）；国家自然科学基金（22178281）；陕西省杰出青年科学基金（2022JC-09）；陕西高校青年创新团队项目
引用本文：张晨悦，马英群，王兴，傅容湛，黄技伟，花秀夫，范代娣，费强. 全碳素生物转化沼气制备生物航煤制造路线研究进展[J]. 合成生物学，2023，4(6)：1246-1258
Citation：ZHANG Chenyue，MA Yingqun，WANG Xing，FU Rongzhan，HUANG Jiwei，HUA Xiufu，FAN Daidi，FEI Qiang. Progress in the bioconversion of biogas into sustainable aviation fuel[J]. Synthetic Biology Journal，2023，4(6)：1246-1258

using combined heat and power (CHP) units to generate electricity and heat. However, burning CH_4 in biogas releases an equivalent amount of CO_2, resulting in a lower carbon-atom economy. To enhance the carbon-utilization efficiency of biogas and reduce greenhouse gas emission, this review suggests a novel route of biological converting both CH_4 and CO_2 in biogas produced from anaerobic digestion of food wastes for sustainable aviation fuel (SAF) production with applications of synthetic biology techniques and biomanufacturing strategies. Photoautotroph microorganisms and aerobic methanotrophs are used to convert CO_2 and CH_4 in biogas, respectively. Primary pathways and key enzymes for lipid biosynthesis from CO_2 and CH_4 by photoautotrophic microbes and methanotrophic bacterial and strategies for carbon flux improvement are introduced and discussed. As the precursor of SAF, the lipids produced by aforementioned microbes need to undergo recovery, pre-treatment, and upgrading procedures. The effects of different technologies developed for lipid recovery (flocculation, dissolved air flotation (DAF), centrifugation, coagulation, filtration) and upgrading (Hydrogenated Esters and Fatty Acids (HEFA), Fischer-Tropsch (F-T), Alcohol-to-jet (ATJ), Hydroprocessed Fermented Sugars (HFS) on efficiency and operation cost are evaluated. Besides, physical properties of SAF derived from different raw materials are compared. The global warming potential of SAF production using different feedstock by HEFA are summarized and the reduction of greenhouse emission can be up to 80% comparing with petroleum-based ones. This review discusses the metabolic pathways, biosynthesis strategies, fermentation technology, recovery and upgrading processes for the production of biogas-derived SAF. It also provides an outlook on strategies to improve the economic efficiency of microbes-based SAF manufacturing and guideline for commercial applications of biotechnology in fuel production.



Keywords: biogas; photoautotroph microorganisms; aerobic methanotrophs; synthetic biology; sustainable aviation fuel; biological manufacturing

据联合国粮农组织和环境规划署的统计，全球约 1/3 的粮食在生产流通和消费过程中被浪费，且大都被当作垃圾处理[1-2]。目前，中国餐厨垃圾总量已突破 1.3 亿吨/年，未来五年涨幅将达到 12%～15%[3]。《“十四五”城镇生活垃圾分类和处理设施发展规划》指出，2025 年底全国城市生活垃圾资源化利用率将达到 60% 左右[4]。其中，超过 3/4 的餐厨垃圾经厌氧消化方式处理并生产沼气[5-6]。

沼气是可以替代化石燃料的清洁可再生能源，通常由 50%～70% 的甲烷（CH_4）、25%～45% 的二氧化碳（CO_2）、1%～5% 的氢气（H_2）以及少量氨（NH_3）、水蒸气（H_2O）、硫化氢（H_2S）组成，其下游利用方式主要是燃烧或热电联产[7-8]。然而，沼气中的 CH_4 燃烧会释放等量的 CO_2，这将造成碳排放和碳损失[9]。因此，开发沼气全碳素综合利用的新型低碳生物制造路径，对生物经济和可持续发展有重要意义。基于合成生物学技术开发的

人工细胞工厂，能够转化CH_4和CO_2高效生产液体燃料前体，进而为沼气全碳素利用提供了理论基础和实践条件[10-11]。

为了应对气候变化，从源头管控温室气体的排放，美国、欧盟和中国部分试点城市基于市场机制，构建了碳排放交易体系并规定了碳排放配额。当实际排放量超出配额时，企业就必须从碳交易市场购买超额排放部分的排放权或接受经济处罚[12-13]。过去十年间，航空业已成为全球温室气体排放增长最快的行业之一。其排放量在未来20年将以3.8%～4.4%的速度持续增长[14-15]，这意味着航空公司将为此付出高昂的代价。构建绿色低碳循环发展的经济体系对能源转型的要求和碳税对企业成本的影响共同决定了生物航煤（sustainable aviation fuel， SAF）制造路径开发的重要地位。

鉴于此，本文提出了一条原料绿色化、过程绿色化、产品绿色化的沼气全碳素转化制备SAF路线。在通过厌氧消化工艺处理餐厨垃圾的基础上，利用光能自养微生物和好氧性嗜甲烷菌分别转化沼气中的CO_2和CH_4积累油脂，随后生物油脂经提取和升级加工后制备SAF（图1）。上述SAF生物制造路线不仅能够助力实现“双碳”目标，还能成为打开碳循环经济大门的钥匙[16-17]。

1 餐厨垃圾资源化处理

餐厨垃圾在复合菌群作用下，被分解为小分子化合物，经过一系列生物化学反应制得沼气[18]。碳元素转化效率决定沼气产率，并直接影响工艺经济性和环境友好程度。近年来，大量研究通过多级消化、预处理、优化操作条件、改变反应底物（共消化）等方式提高厌氧消化碳转化率。Kobayashi等[19]和Wu等[20]利用两阶段厌氧消化系统，分别将餐厨垃圾中93%和94.5%的挥发性固体（volatile solid， VS）转化为沼气，其CH_4产率分别为446 L/kg VS和502.9 L/kg VS，几乎实现了VS全碳转化。借助合成生物学和生物制造技术，有望利用微生物转化沼气中的全部碳素，实现餐厨垃圾的高值化处理。沼气先通过光能自养微生物反应体系生物催化CO_2合成油脂，随后再经好氧性嗜甲烷菌反应体系完成生物转化CH_4合成油脂，最终实现沼气全碳素生物利用。值得一提的是，Henard等[21]通过$^{13}CO_2$示踪实验证明*Methylococcus capsulatus* Bath可以通过核酮糖-1，5-二磷酸羧化酶/加氧酶（Rubisco）转化CO_2，说明好氧性嗜甲烷菌也具备转化CO_2的能力。但是，目前针对好氧性嗜甲烷菌转化CO_2的机理研究有限，其CO_2转化能力也未得到定量评估。因此，在本文提出的工业化生产路径中并未考虑嗜甲烷菌对CO_2的转化。H_2S也是沼气的成分之一，关于H_2S对微生物生长的研究大多集中于毒性作用，很少关注其生理功能。值得一提的是，硫是合成生物体所需半胱氨酸、甲硫氨酸和其他有机硫化合物的必需元素。已有研究表明，H_2S可以作为微生物电子受体、电子供体或硫源来产生还原力，以促进其生长[22-23]。

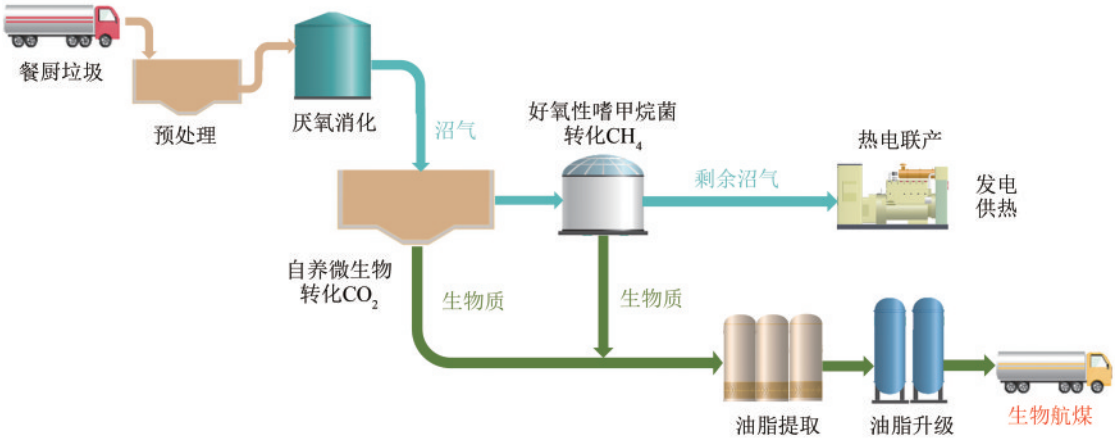


图1 餐厨垃圾升级为生物航煤的生物能源生产路径[6]

Fig. 1 Bioenergy production pathway from food waste to sustainable aviation fuel[6]

2　全碳素生物转化沼气合成油脂

2.1　光能自养微生物转化 CO_2 合成油脂

2.1.1　CO_2 的生物利用过程

自养微生物以光照（光能自养）或无机电子供体（化能自养）为能源，具有将 CO_2 转化为高附加值产品的能力，成为绿色生产领域研究者的关注对象[24-26]。蓝细菌的遗传工具开发较为完善，是生物制造的理想底盘微生物之一[23-24]。微藻适合生产油脂和烷烃的特点决定了它是另一发展潜力巨大的光合自养细胞工厂[23]。

光能自养微生物在电子供体和光照驱动下经卡尔文循环（Calvin-Benson-Bassham cycle，CBB cycle）转化 CO_2 产生丙酮酸。在丙酮酸脱氢酶复合体催化下发生的丙酮酸脱羧反应，可产生直接参与三羧酸循环（tricarboxylic acid cycle，TCA cycle）的中心代谢物乙酰辅酶 A。脂肪酸合成途径中的关键限速酶乙酰辅酶 A 羧化酶（acetyl CoA carboxylase，ACCase）再将乙酰辅酶 A 转化为丙二酰辅酶 A[27-29]。随后生成的丙二酰-酰基载体蛋白（acyl carrier protein，ACP）经脂肪酸合酶（fatty acid synthetase，FAS）聚合生成酰基 ACP。微藻通过 FAS 和 Kennedy 途径合成三酰甘油（triacylglycerol，TAG），实现 CO_2 到油脂的转化[30-31]。与微藻产生 TAG 不同，蓝细菌将以酰基 ACP 为底物生产膜脂作为 SAF 前体[32]（图 2）。

2.1.2　光能自养微生物合成油脂的进展

光合固碳能力是决定光能自养微生物油脂产率最重要的因素[24]。动力学和 ATP 的需求是影响 CO_2 固定效率的关键因素。CBB 循环的动力学缓慢、ATP 消耗量大是 CO_2 固定效率低的主要原因[23]。Rubisco 是介导 CO_2 固定的中心酶，但是 Rubisco 不仅作用缓慢、能量需求高，还会与氧气发生不良副反应，降低 CO_2 识别效率[23]。因此，大量研究试图寻找提升 Rubisco 氧化活性的策略，解决 CBB 循环固碳效率和能量转换低下的问题。例如，Cai 等[35] 已通过直接进化筛选出 *Synechococcus* sp. PCC7002 Rubisco 突变体，将 CO_2 催化效率提升了 45%。另外，操纵 CO_2 浓缩机制（CO_2 concentrating mechanism，CCM）可提高碳酸氢盐转运蛋白的活性，从而提升 CO_2 催化效率[23]。Gupta 等[36] 在 *Synechococcus* sp. PCC7002 中过表达碳酸盐转运蛋白（SbtA 和 BicA），将微生物的生物量增加了 50%。Kamennaya 等[37] 通过引入额外的碳酸氢盐转运蛋白策略，使 *Synechocystis* sp. PCC6803 的生物量增加了 2 倍。

此外，过表达光能自养微生物油脂积累途径中的关键基因也是提升产率的重要技术手段。研究表明，在蓝细菌中过表达脂肪酰基 ACP 至膜脂途径中的 *plsX* 和 *plsC* 基因可大幅提升以棕榈酸（16∶0）为代表的饱和脂肪酸含量（总油脂干重达到 39.1%）[38]；过表达 *Aas* 基因可实现 41.4 mg/(L·d) 的油脂积累速率[39]。微藻中从 3-磷酸甘油至 TAG

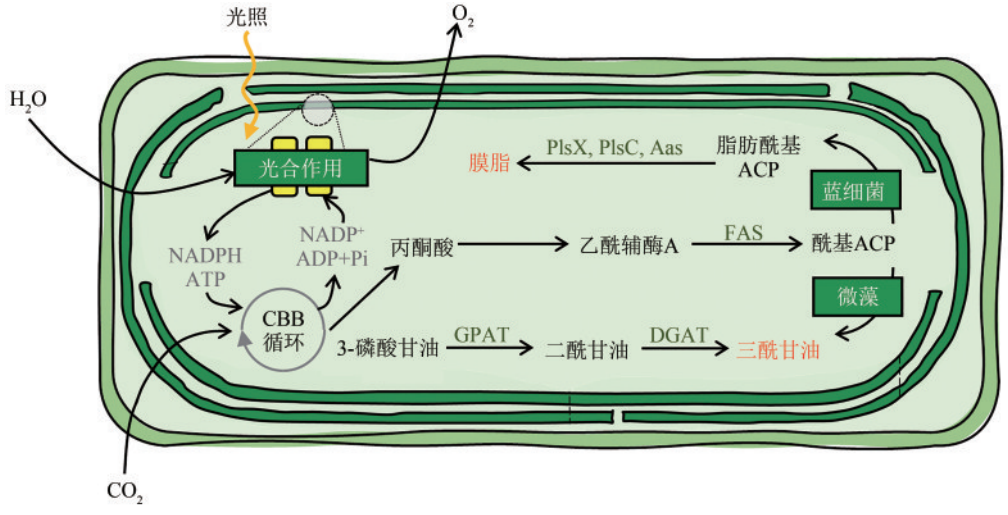


图 2　蓝细菌和微藻转化 CO_2 产油脂的主要路径和关键酶[24, 30, 33-34]

Fig. 2　Primary pathways and key enzymes for lipid production from CO_2 fixation by cyanobacteria and microalgae [24, 30, 33-34]

合成的途径被称为Kennedy途径，对该途径中限速酶（GPAT和DGAT）过表达的研究将其油脂积累水平提升至135%～200%不等[40-49]。另外，基于几种存在天然合成生物燃料前体途径的光能自养微生物，可在现有菌株中通过基因异源表达技术设计相关路径提升脂肪醇和游离脂肪酸的积累[45-46]。但是，基因过表达和异源表达均应考虑油脂大量积累带来的细胞毒性，以及基因表达水平提升后辅因子（如NADPH）的平衡。

除菌种改造技术外，实现SAF生产工程化的另一关键是发酵工艺优化。光生物反应器（photobioreactor， PBR）是人造光源封闭培养体系的代表，它的开发解决了开放培养中环境参数不可控的问题，有利于提升工艺稳定性、降低生产成本[50-52]。Hu等[53]的研究表明，压力条件的培养策略可有效提升光能自养微生物细胞油脂含量。已知油脂积累的胁迫因素包括盐浓度、pH值、温度、CO_2浓度、光照强度等[54]。其中，研究较多的胁迫因素之一是氮素添加水平[50，53-56]。但是，Widjaja等[57]和Rodolfi等[58]的研究证明光能自养微生物在不同饥饿期内油脂积累情况具有不确定性。因此，通过营养饥饿来提高油脂产率是复杂且不稳定的，还必须注意培养过程中生物量和油脂积累的平衡[57-58]。

2.2 好氧性嗜甲烷菌合成油脂

2.2.1 CH_4生物转化合成油脂的过程

好氧性嗜甲烷菌是以CH_4为主要或唯一碳源的甲基营养菌，分为γ-变形菌门（Ⅰ型、Ⅹ型）和α-变形菌门（Ⅱ型）。磷脂是好氧性嗜甲烷菌体的主要组成部分之一，主要源自细胞内膜，是碳链长度为14～18的脂肪酸酯[10，59]。嗜甲烷菌可以表达两种类型的甲烷单加氧酶（MMO）：位于细胞质中的可溶性MMO（sMMO）和与细胞膜结合的颗粒状MMO（pMMO）。与sMMO相比，pMMO对CH_4的亲和力更强，是自然界中主要的甲烷氧化催化剂[10，60]。如图3所示，在甲烷单加氧酶（MMO）催化下，CH_4首先被氧化生成甲醇，然后在甲醇脱氢酶（MDH）和吡咯喹啉醌（PQQ）的催化作用下被同化为甲醛[61]。通常，γ-变形菌门与α-变形菌门嗜甲烷菌可分别通过核酮糖单磷酸循环（RuMP）和丝氨酸途径转化甲醛。由甲醇同化而来的甲醛可以进一步氧化为CO_2，也可以由RuMP循环或丝氨酸循环产生丙酮酸和乙酰辅酶A。最后，细胞代谢的关键中间体乙酰辅酶A将被嗜甲烷菌转化为SAF前体磷脂酰甘油［1，2-dioctadecanoyl-*sn*-glycero-3-phospho-(1′-*sn*-glycerol)，PG］、磷脂酰乙醇胺［1，2-di-(11*Z*-hexadecenoyl)-*sn*-glycero-3-phosphoethanolamine， PE］、磷脂酰甲基乙醇胺［1-(9*Z*-octadecenoyl)-2-hexadecanoyl-*sn*-glycero-3-phospho-*N*-methylethanolamine，PME］和磷脂酰二甲基乙醇胺［1-hexadecanoyl-2-(9*Z*-octadecenoyl)-*sn*-glycero-3-phospho-*N*，*N*-dimethylethanolamine，PDME］（图3）[10]。

2.2.2 好氧性嗜甲烷菌的改造及发酵工艺优化

好氧性嗜甲烷菌油脂积累水平受到脂肪酸生物合成上游代谢通量和碳转化效率的限制[10]。由于MMO是直接影响CH_4同化率的酶，大量研究试图探索其活动位点结构和机制，从而通过菌种改造提高嗜甲烷菌氧化CH_4的速率[63]。然而，由于胞质内膜在pMMO活性中发挥的作用还未被完全解析，其重组表达迄今未获成功[64]。因此，通过合成生物学技术进一步解析MMO催化机理，提高其催化的酶促反应速率，是未来值得关注的研究方向。

除了通过增强CH_4同化效率提升初始碳通量外，油脂和脂肪酸的合成强化也是增加嗜甲烷菌油脂产率的直接技术手段。目前，增强丙酮酸或乙酰辅酶A等关键代谢节点物质的合成、优化RuMP循环或丝氨酸循环是好氧性嗜甲烷菌CH_4转化的主要代谢工程策略[65]。提高甲醛向细胞中油脂生产前体乙酰辅酶A和丙二酰辅酶A的转化水平，是克服油脂生产瓶颈的关键策略[60，62]。Henard等[62]和Demidenko等[60]利用上述思路，设计了过表达磷酸酮醇酶途径和敲除乙酸激酶、过表达乙酰辅酶A羧化酶的*Methylomicrobium buritense* 5GB1菌株，分别将油脂积累量提高2倍［细胞干重达到（111±2)mg/g］，可提取脂肪酸甲酯产量增加20%（图3）。此外，Fei等[66]通过限制*M.buritense*菌株中糖原合成，将其油脂含量提高了90%，最大油脂生产率达到45.4 mg/(L·h)。

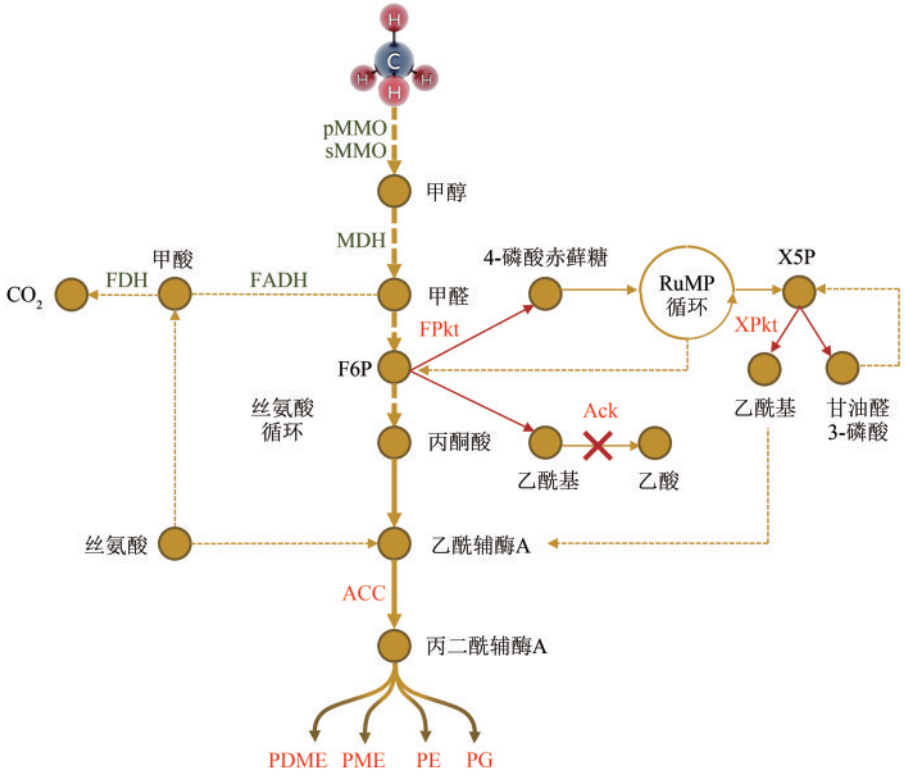


图 3　好氧性嗜甲烷菌转化甲烷生物合成油脂途径[10, 60-62]

MMO—甲烷单加氧酶；sMMO—可溶性甲烷单加氧酶；pMMO—颗粒状甲烷单加氧酶；MDH—甲醇脱氢酶；FADH—甲醛脱氢酶；FDH—甲酸脱氢酶；F6P—6-磷酸果糖；X5P—木酮糖-5-磷酸；FPkt—F6P 磷酸酮醇酶；XPkt—F6P 磷酸酮醇酶；Ack—乙酸激酶；ACC—乙酰辅酶 A 羧化酶；PG—磷脂酰甘油；PE—磷脂酰乙醇胺；PME—磷脂酰甲基乙醇胺；PDME—磷脂酰二甲基乙醇胺

Fig. 3　Lipid biosynthesis pathway by methane fixation in aerobic methanotrophs[10, 60-62]

MMO—methane monooxygenase; pMMO—particulate methane monooxygenase; sMMO—soluble methane monooxygenase; MDH—methanol dehydrogenase; FADH—formaldehyde dehydrogenase; FDH—formate dehydrogenase; F6P—fructose-6-phosphate; X5P—xylulose-5-phosphate; FPkt—F6P phosphoketolase; XPkt—X5P phosphoketolase; Ack—acetate kinase; ACC—acetyl-CoA carboxylase; PG—1,2-dioctadecanoyl-*sn*-glycero-3-phospho-(1′-*sn*-glycerol); PE—1,2-di-(11*Z*-hexadecenoyl)-*sn*-glycero-3-phosphoethanolamine; PME—1-(9*Z*-octadecenoyl)-2-hexadecanoyl-*sn*-glycero-3-phospho-*N*-methylethanolamine; PDME—1-hexadecanoyl-2-(9*Z*-octadecenoyl)-*sn*-glycero-3-phospho-*N*,*N*-dimethylethanolamine

上述研究结果均证明菌种改造技术可以有效提升好氧性嗜甲烷菌油脂积累水平。然而，目前 CH_4 生物催化和好氧性嗜甲烷菌工程应用仍受到嗜甲烷菌遗传工具开发不完善等问题的限制，阻碍了其工业平台的发展[67]。

发酵工艺优化也是油脂高效生产的必经之路。生物反应器传质效率和反应器内气体分压会影响运行稳定性和油脂产率。目前，气体底物与液体培养基传质效率低是限制气体发酵系统商业化的主要技术难题[68]。大量研究讨论了鼓泡塔反应器、垂直管状循环生物反应器、气升式生物反应器和膜生物膜反应器对保持定向流动循环和高效传质传热的作用[69-71]。也有研究通过设计新型生物反应器来提高 CH_4 传质效率，如 U 型生物反应器、中空纤维膜等[68]。另外，反应器内的分压（气相的组成）在气体发酵系统中也起着至关重要的作用。Timmers 等[72] 的研究证明，CH_4 分压与嗜甲烷菌生长率成正比。然而，高分压可能会干扰底物与关键酶之间的相互作用，导致菌种生长或产物生产受到抑制。生物反应器设计和分压条件优化是维持反应器内气体溶解度和生长/生产间平衡的关键。

3　微生物油脂制备生物航煤

3.1　生物油脂回收及预处理

生物油脂回收及预处理技术包括菌体回收、

细胞壁破碎和油脂提取。絮凝、浮选、离心、过滤和重力沉降是常见的菌体脱水工艺[73]。与离心、过滤、重力沉降相比，絮凝和浮选工艺操作快速简便、占地面积小、能量需求低，更适合大规模运行。但是，应注意絮凝剂或表面活性剂的选择，避免对生物油脂下游加工造成影响[73-76]。

化学预处理是目前最高效的细胞壁破碎方法[77]。强碱和强酸在120～150 ℃条件下可有效催化纤维素和淀粉分解，破坏细胞壁中的化学键[78]。Dong等结合碱处理的菌体水解能力和酸处理的反乳化作用，开发了一种酸碱两阶段预处理方式，在短时间内实现了最高100%的脂肪酸回收率[10, 79]。但是，酸和碱对反应器的腐蚀以及化学品添加对下游产品的污染也是工业化中应当考虑的问题。有机溶剂萃取是从破碎细胞中回收油脂直接且热门的技术[76, 80]。己烷对油脂的溶解效果好且不溶于水，沸点较低便于与油脂分离，来源广泛，价格低廉，是一种适合工业化萃取油脂的溶剂[81]。Sathish和Sims[82]通过酸碱两阶段水解结合己烷萃取技术，实现了79%可酯交换油脂的提取，为上述油脂回收及预处理技术提供了实验室数据支撑。生物油脂回收技术的优缺点分析及关键因素比较总结于表1。

3.2 油脂升级加工制备生物航煤

生物油脂制备SAF需要通过酯和脂肪酸加氢（hydrogenated esters and fatty acid，HEFA）、费托（Fischer-Tropsch，F-T）合成、醇制航煤（alcohol-to-jet，ATJ）、发酵糖加氢（hydroprocessed fermented sugar，HFS）等经认证的技术路线升级（表2）。

其中，HEFA是目前商业化程度最高的生产方式。自2011年以来，通过该技术路线生产的SAF超过310万～336万吨/年，并以高达50%的混合比

表1 生物油脂回收技术比较及分析[73-76]

Table 1 Comparisons of different lipid recovery technologies [73-76]

回收技术	优点	缺点	影响成本的关键因素
混凝/絮凝	回收率较高、简便快捷、能耗低	絮凝剂的使用可能影响下游加工	絮凝剂添加
浮选	回收率较高、快速、占地面积小	表面活性剂可能影响下游加工	表面活性剂添加
离心	回收率较高、快速	能耗高、经济可行性低	能源密集型工艺
过滤	能耗低、小规模应用时经济性好	回收率低、容易造成膜污染/堵塞、需提供压力差、不适用于小尺寸微生物或高浓度菌液	滤膜更换昂贵
重力沉降	操作简便	回收率低、耗时	回收效率低下
絮凝+离心	回收率高、快速	能耗高	絮凝剂的添加、能耗高
絮凝+浮选	回收率高、快速、占地面积小	工艺复杂	絮凝剂和表面活性剂的添加

表2 生物油脂深加工技术路线比较及商业化应用[75, 83-84]

Table 2 Comparisons of different lipid upgrading routes and their applications [75,83-84]

技术路线	方法	优点	缺点	商业化项目
HEFA	280～340 ℃、5～10 MPa条件下，通过加氢脱氧、异构化、裂化和分馏去除油品中的氧，将直链石蜡分子裂解并异构为SAF	可利用现有炼油设备，技术成熟	依赖催化剂和H_2	UOP Honeywell、Neste、Haldor Topsoe、Axens
F-T合成	600～1000 ℃下将菌体转化为合成气，再升级为SAF	产品脱硫，芳烃含量低于化石燃料	对合成气清洁程度要求高（无固体、焦油、含氮和含硫化合物）	Sierra BioFuels、BioTfueL、Velocys/Red Rock Biofuels
ATJ	1.4 MPa，288～343 ℃条件下，添加H_2和PtO_2催化剂完成脱水、低聚和氢化生产SAF	产品选择性、收率高	昂贵复杂，对催化剂和原料要求高	UOP Honeywell、LanzaTech、Coskata、Cobalt/Navy
HFS	酶水解和发酵精炼糖，再通过分馏和加氢裂化生产SAF	产率和回收率高	研究少，大规模应用困难	Amyris、Total

广泛使用于商业航班[75，85-87]。F-T合成的技术成熟度也相对较高，但是它对原材料清洁程度的高要求使其工业发展受限[86]。以农林废弃物为基础的ATJ工艺尚处于实验室开发阶段。虽然LanzaTech和LanzaTech Global已进入第二阶段的研究，但其技术成熟度仍有较大提升空间[88]。HFS技术主要关注甘蔗、玉米等易提取和发酵的简单糖类，关于第三代生物燃料的研究还不足以支撑其工业化[86]。

3.3 生物航煤性能评价及工程化应用

SAF燃烧性能关乎航空安全，评估其能否符合商用飞机燃料Jet A/A-1的燃烧特性是必要环节[89]。ASTM D1655定义了Jet A/A-1的最低性能要求[90]。第一代、第二代和第三代生物精炼的原料分别为糖类、木质纤维素和以CO_2为代表的一碳气体[91]。如表3所示，第一代SAF均能满足ASTM D1655标准，但其大量生产会不可避免地引发“与人争粮，与粮争地”的问题，给国家粮食安全带来挑战。第二代SAF和第三代SAF的热物理性能均与Jet A/A-1相当，但微生物SAF具有高热值、强挥发性（高闪点）和低运动黏度等优势，决定了其具备进一步商业化的可能[92]。

Jet A/A-1的全生命周期内全球变暖潜能（global warming potential， GWP）为89 g CO_2-eq/MJ[94]。经HEFA制备的SAF温室气体减排量在27.1%～84.2%（表4）。与木质纤维素相比，具备高生长率和油脂产率的微生物SAF在其生命周期内温室气体排放量更少，这使得第三代SAF成为更具吸引力的航空燃料替代品[94-96]。

近年来，航空公司、机场与生物燃料生产商之间的密切合作已极大促进了覆盖全球的商业化活动[83，97]。位于四川省遂宁市的四川金尚环保科技有限公司将推广Honeywell的Ecofining技术，将SAF产量提升至近30万吨/年（约6000桶/天），有望成为中国最大的SAF制造工厂之一[98]。目前我国每年经HEFA生产的SAF约为15万吨，远低于2647万吨（2021年）的航空燃煤消耗量[99]。因此，进一步扩大SAF生产规模是未来航空业适应碳配额的合理解决方案。

表3 来源于不同原料的生物航煤的物理特性比较[89-90，92-93]

Table 3 Summary of SAF physical properties from different raw materials [89-90, 92-93]

原料	−20 ℃运动黏度/（mm^2/s）	15 ℃密度/（kg/m^3）	闪点/℃	凝固点/℃	热值/（MJ/kg）
ASTM D1655	<8	775～840	>38	<−40	>42.8
Jet A/A-1	8	775～840	38	−47	42.8
大豆	—	775	38	−47	43.4
椰子	6.52	788	55	−16	43.5
麻风树	3.66	751～840	46.5	−57	44.3
亚麻荠	3.3	751	43	−77	44.1
蓖麻	5.3	758	55	−62	—
桐树	—	839	39	−66	42.3
牛油	5.3	758	55	−62	44
废弃食用油	3.8	760	42	−54.3	44
Chlorella pyrenoidosa	2.9	856	68	−38	44
Nannochloropsis sp.	2.8	1380	68	−30	44

表4 基于HEFA方法加工不同原料制备生物航煤的温室变暖潜能值[94-96]

Table 4 Global warming potential of SAF production using different feedstock by HEFA[94-96]

原料	GWP/（g CO_2-eq/MJ）	与石油基对比GWP减排量
大豆	64.9	27.1%
玉米	17.2	80.7%
菜籽油	47.4	46.7%
亚麻荠	42.0	52.8%
废弃食用油	13.9	84.3%
微藻	14.1	84.2%

4 挑战与展望

实验室数据和成功实施的工业化案例均证明沼气全碳素转化为SAF的路径具有广阔发展前景。经微生物油脂制备的第三代生物燃料在热物理性能与Jet A/A-1相当的同时，还表现出全生命周期内GWP的减排优势。但是，根据技术经济可行性分析，利用热化学方法和生物方法制备的SAF成本约为石油基燃料（3美元/gal）的2倍[100]。虽然经微生物油脂升级加工制备的SAF可以满足燃料燃烧特性的要求，且绿色低碳环保，但是其工业化还面临诸多技术和经济层面的瓶颈与挑战。

研究人员可以通过最大化微生物生长率、提

升微生物油脂积累水平和探索简便高效的新工艺等策略，提升SAF制造路径的经济性[101]。寻找含油量更高/生长更快的微生物物种，或采用基因工程技术增强沼气碳素气体转化效率、改变内源碳通量分布均是提升油脂产率的策略[102]。另外，降低设备复杂程度、简化生产过程、开发联产工艺等方式也可有效控制SAF成本[102]。随着合成生物学研究的深入和生物制造技术的拓展，全新生物制造路线将为进一步扩大SAF生产提供思路，填补SAF产量缺口，在助力解决国际能源安全问题的同时，推动应对全球气候变化历史进程。

参 考 文 献

[1] POUR F H, MAKKAWI Y T. A review of post-consumption food waste management and its potentials for biofuel production[J]. Energy Reports, 2021, 7: 7759-7784.

[2] FAO. Towards the future we want: end hunger and make the transition to sustainable agricultural and food systems[EB/OL]. 2012[2023-06-01]. https://www.fao.org/3/an894e/an894e00.pdf.

[3] 李晨曦, 王铭娅, 吴春东, 等. 餐厨垃圾厌氧消化残余物的利用现状及展望[J]. 中国沼气, 2023, 41(2): 3-8.
LI C X, WANG M Y, WU C D, et al. Utilization status and prospect of anaerobic digestion residue of food waste[J]. China Biogas, 2023, 41(2): 3-8.

[4] 中华人民共和国国家发展和改革委员会. “十四五”城镇生活垃圾分类和处理设施发展规划[EB/OL]. (2021-05-06)[2023-06-01]. https://www.ndrc.gov.cn/xxgk/zcfb/tz/202105/t20210513_1279763_ext.html.
National Development and Reform Commission of the People's Republic of China. Development plan for urban domestic waste classification and treatment facilities during the 14th Five Year Plan[EB/OL]. (2021-05-06) [2023-06-01]. https://www. ndrc. gov. cn/xxgk/zcfb/tz/202105/t20210513_1279763_ext.html.

[5] LI Y Y, JIN Y Y, BORRION A, et al. Current status of food waste generation and management in China[J]. Bioresource Technology, 2019, 273: 654-665.

[6] JIN C X, SUN S Q, YANG D H, et al. Anaerobic digestion: an alternative resource treatment option for food waste in China [J]. Science of the Total Environment, 2021, 779: 146397.

[7] AHMED S F, MOFIJUR M, TARANNUM K, et al. Biogas upgrading, economy and utilization: a review[J]. Environmental Chemistry Letters, 2021, 19(6): 4137-4164.

[8] KAPOOR R, GHOSH P, TYAGI B, et al. Advances in biogas valorization and utilization systems: a comprehensive review [J]. Journal of Cleaner Production, 2020, 273: 123052.

[9] MEIER L, PÉREZ R, AZÓCAR L, et al. Photosynthetic CO_2 uptake by microalgae: an attractive tool for biogas upgrading [J]. Biomass and Bioenergy, 2015, 73: 102-109.

[10] FEI Q, GUARNIERI M T, TAO L, et al. Bioconversion of natural gas to liquid fuel: opportunities and challenges[J]. Biotechnology Advances, 2014, 32(3): 596-614.

[11] FU R Z, KANG L X, ZHANG C Y, et al. Application and progress of techno-economic analysis and life cycle assessment in biomanufacturing of fuels and chemicals[J]. Green Chemical Engineering, 2023, 4(2): 189-198.

[12] FAGEDA X, TEIXIDÓ J J. Pricing carbon in the aviation sector: evidence from the European emissions trading system [J]. Journal of Environmental Economics and Management, 2022, 111: 102591.

[13] HUANG W Q, WANG Q F, LI H, et al. Review of recent progress of emission trading policy in China[J]. Journal of Cleaner Production, 2022, 349: 131480.

[14] IPCC. AR6 climate change 2021: the physical science basis[R/OL]. 2021[2023-06-01]. https://www. ipcc. ch/report/sixth-assessment-report-working-group-i/.

[15] YANG L S, HU Y J, WANG H L, et al. Uncertainty quantification of CO_2 emissions from China’s civil aviation industry to 2050[J]. Journal of Environmental Management, 2023, 336: 117624.

[16] LIANG B B, FU R Z, MA Y Q, et al. Turning C_1-gases to isobutanol towards great environmental and economic sustainability *via* innovative biological routes: two birds with one stone[J]. Biotechnology for Biofuels and Bioproducts, 2022, 15(1): 107.

[17] WEUSTER-BOTZ D. Process engineering aspects for the microbial conversion of C_1 gases[M/OL]//ZENG A P, CLAASSENS N J. One-carbon feedstocks for sustainable bioproduction. Cham: Springer International Publishing, 2022: 33-56[2023-06-01]. https://link. springer. com/chapter/10.1007/10_2021_172.

[18] DALKE R, DEMRO D, KHALID Y, et al. Current status of anaerobic digestion of food waste in the United States[J]. Renewable and Sustainable Energy Reviews, 2021, 151: 111554.

[19] KOBAYASHI T, XU K Q, LI Y Y, et al. Effect of sludge recirculation on characteristics of hydrogen production in a two-stage hydrogen-methane fermentation process treating food wastes[J]. International Journal of Hydrogen Energy, 2012, 37(7): 5602-5611.

[20] WU C F, HUANG Q Q, YU M, et al. Effects of digestate recirculation on a two-stage anaerobic digestion system, particularly focusing on metabolite correlation analysis[J]. Bioresource Technology, 2018, 251: 40-48.

[21] HENARD C A, WU C, XIONG W, et al. Ribulose-1,5-bisphosphate carboxylase/oxygenase (RubisCO) is essential for growth of the methanotroph *Methylococcus capsulatus* strain bath[J]. Applied and Environmental Microbiology, 2021, 87 (18): e00881-21.

[22] BARTON L L, FARDEAU M L, FAUQUE G D. Hydrogen sulfide: a toxic gas produced by dissimilatory sulfate and sulfur reduction and consumed by microbial oxidation[M/OL]// KRONECK P, TORRES M. The metal-driven biogeochemistry of gaseous compounds in the environment. Dordrecht: Springer, 2014: 237-277[2023-06-01]. https://link. springer. com/chapter/10.1007/978-94-017-9269-1_10.

[23] CLAASSENS N J, SOUSA D Z, DOS SANTOS V A P M, et al. Harnessing the power of microbial autotrophy[J]. Nature Reviews Microbiology, 2016, 14(11): 692-706.

[24] SRISAWAT P, HIGUCHI-TAKEUCHI M, NUMATA K. Microbial autotrophic biorefineries: perspectives for biopolymer production[J]. Polymer Journal, 2022, 54(10): 1139-1151.

[25] 赵青云, 韩飞, 石向星, 等. 微藻生物柴油固碳减排和经济效益研究[J/OL]. 工业水处理[2023-06-01]. https://doi. org/10. 19965/j.cnki.iwt.2022-1132.
ZHAO Q Y, HAN F, SHI X X, et al. Research on carbon sequestration, emission reduction and economic benefit of microalgae biodiesel[J/OL]. Industrial Water Treatment[2023-06-01]. https://doi.org/10. 19965/j.cnki.iwt.2022-1132.

[26] 张艺博, 薛永常, 刘长斌. 转录因子在调控微藻油脂合成中的作用[J/OL]. 中国油脂[2023-06-01]. https://doi.org/10.19902/j.cnki.zgyz.1003-7969.220758.
ZHANG Y B, XUE Y C, LIU C B. The important role of transcription factors in the regulation of lipid synthesis in microalgae[J/OL]. China Oils and Fats[2023-06-01]. https://doi.org/ 10.19902/j.cnki.zgyz.1003-7969.220758.

[27] BEHERA B, UNPAPROM Y, RAMARAJ R, et al. Integrated biomolecular and bioprocess engineering strategies for enhancing the lipid yield from microalgae[J]. Renewable and Sustainable Energy Reviews, 2021, 148: 111270.

[28] ZENG X H, DANQUAH M K, CHEN X D, et al. Microalgae bioengineering: from CO_2 fixation to biofuel production[J]. Renewable and Sustainable Energy Reviews, 2011, 15(6): 3252-3260.

[29] MIAO R, XIE H, LIU X F, et al. Current processes and future challenges of photoautotrophic production of acetyl-CoA-derived solar fuels and chemicals in cyanobacteria[J]. Current Opinion in Chemical Biology, 2020, 59: 69-76.

[30] MUÑOZ C F, SÜDFELD C, NADUTHODI M I S, et al. Genetic engineering of microalgae for enhanced lipid production[J]. Biotechnology Advances, 2021, 52: 107836.

[31] MA X M, MI Y W, ZHAO C, et al. A comprehensive review on carbon source effect of microalgae lipid accumulation for biofuel production[J]. Science of the Total Environment, 2022, 806: 151387.

[32] KNOOT C J, UNGERER J, WANGIKAR P P, et al. Cyanobacteria: promising biocatalysts for sustainable chemical production[J]. Journal of Biological Chemistry, 2018, 293(14): 5044-5052.

[33] YUNUS I S, JONES P R. Photosynthesis-dependent biosynthesis of medium chain-length fatty acids and alcohols[J]. Metabolic Engineering, 2018, 49: 59-68.

[34] VELMURUGAN R, INCHAROENSAKDI A. Metabolic transformation of cyanobacteria for biofuel production[J]. Chemosphere, 2022, 299: 134342.

[35] CAI Z, LIU G X, ZHANG J L, et al. Development of an activity-directed selection system enabled significant improvement of the carboxylation efficiency of rubisco[J]. Protein & Cell, 2014, 5(7): 552-562.

[36] GUPTA J K, RAI P, JAIN K K, et al. Overexpression of bicarbonate transporters in the marine cyanobacterium *Synechococcus* sp. PCC 7002 increases growth rate and glycogen accumulation[J]. Biotechnology for Biofuels, 2020, 13: 17.

[37] KAMENNAYA N A, AHN S, PARK H, et al. Installing extra bicarbonate transporters in the cyanobacterium *Synechocystis* sp. PCC6803 enhances biomass production[J]. Metabolic Engineering, 2015, 29: 76-85.

[38] TOWIJIT U, SONGRUK N, LINDBLAD P, et al. Co-overexpression of native phospholipid-biosynthetic genes *plsX* and *plsC* enhances lipid production in *Synechocystis* sp. PCC 6803[J]. Scientific Reports, 2018, 8: 13510.

[39] EUNGRASAMEE K, MIAO R, INCHAROENSAKDI A, et al. Improved lipid production *via* fatty acid biosynthesis and free fatty acid recycling in engineered *Synechocystis* sp. PCC 6803 [J]. Biotechnology for Biofuels, 2019, 12(1): 8.

[40] ISKANDAROV U, SITNIK S, SHTAIDA N, et al. Cloning and characterization of a GPAT-like gene from the microalga *Lobosphaera incisa* (Trebouxiophyceae): overexpression in *Chlamydomonas reinhardtii* enhances TAG production[J]. Journal of Applied Phycology, 2016, 28(2): 907-919.

[41] NIU Y F, WANG X, HU D X, et al. Molecular characterization of a glycerol-3-phosphate acyltransferase reveals key features essential for triacylglycerol production in *Phaeodactylum tricornutum*[J]. Biotechnology for Biofuels, 2016, 9: 60.

[42] BALAMURUGAN S, WANG X, WANG H L, et al. Occurrence of plastidial triacylglycerol synthesis and the potential regulatory role of AGPAT in the model diatom *Phaeodactylum tricornutum*[J]. Biotechnology for Biofuels, 2017, 10: 97.

[43] HUNG C H, HO M Y, KANEHARA K, et al. Functional study

of diacylglycerol acyltransferase type 2 family in *Chlamydomonas reinhardtii*[J]. FEBS Letters, 2013, 587(15): 2364-2370.

[44] LI D W, CEN S Y, LIU Y H, et al. A type 2 diacylglycerol acyltransferase accelerates the triacylglycerol biosynthesis in heterokont oleaginous microalga *Nannochloropsis oceanica*[J]. Journal of Biotechnology, 2016, 229: 65-71.

[45] YAO L, QI F X, TAN X M, et al. Improved production of fatty alcohols in cyanobacteria by metabolic engineering[J]. Biotechnology for Biofuels, 2014, 7: 94.

[46] KAISER B K, CARLETON M, HICKMAN J W, et al. Fatty aldehydes in cyanobacteria are a metabolically flexible precursor for a diversity of biofuel products[J]. PLoS One, 2013, 8(3): e58307.

[47] NIU Y F, ZHANG M H, LI D W, et al. Improvement of neutral lipid and polyunsaturated fatty acid biosynthesis by overexpressing a type 2 diacylglycerol acyltransferase in marine diatom *Phaeodactylum tricornutum*[J]. Marine Drugs, 2013, 11(11): 4558-4569.

[48] WEI H H, SHI Y, MA X N, et al. A type-Ⅰ diacylglycerol acyltransferase modulates triacylglycerol biosynthesis and fatty acid composition in the oleaginous microalga, *Nannochloropsis oceanica*[J]. Biotechnology for Biofuels, 2017, 10: 174.

[49] 王何瑜, 龚一富, 郑小恽, 等. 三角褐指藻DGAT1基因生物信息学分析及表达调控研究[J]. 宁波大学学报(理工版), 2021, 34(4): 1-7.
WANG H Y, GONG Y F, ZHENG X Y, et al. Bioinformation analysis and expression regulation of DGAT1 gene in Phaeodactylum tricornutum[J]. Journal of Ningbo University (Natural Science & Engineering Edition), 2021, 34(4): 1-7.

[50] PARMAR A, SINGH N K, PANDEY A, et al. Cyanobacteria and microalgae: a positive prospect for biofuels[J]. Bioresource Technology, 2011, 102(22): 10163-10172.

[51] SIROHI R, KUMAR PANDEY A, RANGANATHAN P, et al. Design and applications of photobioreactors- a review[J]. Bioresource Technology, 2022, 349: 126858.

[52] KHATOON N, PAL R. Microalgae in biotechnological application: a commercial approach[M/OL]//BAHADUR B, VENKAT RAJAM M, SAHIJRAM L, et al. Plant Biology and Biotechnology. New Delhi: Springer, 2015: 27-47[2023-06-01]. https://link. springer. com/chapter/10.1007/978-81-322-2283-5_2.

[53] HU Q, SOMMERFELD M, JARVIS E, et al. Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances[J]. The Plant Journal, 2008, 54(4): 621-639.

[54] PATHAK J, RAJNEESH, MAURYA P K, et al. Cyanobacterial farming for environment friendly sustainable agriculture practices: innovations and perspectives[J]. Frontiers in Environmental Science, 2018, 6: 7.

[55] NAGAPPAN S, DEVENDRAN S, TSAI P C, et al. Potential of two-stage cultivation in microalgae biofuel production[J]. Fuel, 2019, 252: 339-349.

[56] NAGAPPAN S, DEVENDRAN S, TSAI P C, et al. Metabolomics integrated with transcriptomics and proteomics: evaluation of systems reaction to nitrogen deficiency stress in microalgae[J]. Process Biochemistry, 2020, 91: 1-14.

[57] WIDJAJA A, CHIEN C C, JU Y H. Study of increasing lipid production from fresh water microalgae *Chlorella vulgaris*[J/OL]. Journal of the Taiwan Institute of Chemical Engineers, 2009, 40(1): 13-20[2023-06-01]. https://www. sciencedirect. com/science/article/abs/pii/S1876107008001429?via%3Dihub.

[58] RODOLFI L, CHINI ZITTELLI G, BASSI N, et al. Microalgae for oil: strain selection, induction of lipid synthesis and outdoor mass cultivation in a low-cost photobioreactor[J]. Biotechnology and Bioengineering, 2009, 102(1): 100-112.

[59] 刘丰源, 辛嘉英, 孙立瑞, 等. 甲烷氧化菌的高密度培养及其在生物柴油炼制中的应用[J]. 分子催化, 2018, 32(4): 370-381.
LIU F Y, XIN J Y, SUN L R, et al. High density culture of methane oxidizing bacteria and its application in biodiesel refining[J]. Journal of Molecular Catalysis (China), 2018, 32 (4): 370-381.

[60] DEMIDENKO A, AKBERDIN I R, ALLEMANN M, et al. Fatty acid biosynthesis pathways in methylomicrobium buryatense 5G(B1) [J]. Frontiers in Microbiology, 2017, 7: 2167.

[61] GĘSICKA A, OLESKOWICZ-POPIEL P, ŁĘŻYK M. Recent trends in methane to bioproduct conversion by methanotrophs [J]. Biotechnology Advances, 2021, 53: 107861.

[62] HENARD C A, SMITH H K, GUARNIERI M T. Phosphoketolase overexpression increases biomass and lipid yield from methane in an obligate methanotrophic biocatalyst [J]. Metabolic Engineering, 2017, 41: 152-158.

[63] CULPEPPER M A, ROSENZWEIG A C. Architecture and active site of particulate methane monooxygenase[J]. Critical Reviews in Biochemistry and Molecular Biology, 2012, 47(6): 483-492.

[64] KHIDER M L K, BRAUTASET T, IRLA M. Methane monooxygenases: central enzymes in methanotrophy with promising biotechnological applications[J]. World Journal of Microbiology and Biotechnology, 2021, 37(4): 72.

[65] ZENG A P, CLAASSENS N J. One-carbon feedstocks for sustainable bioproduction[M/OL]. 2022[2023-06-01]. https://link.springer.com/book/10.1007/978-3-031-06854-6.

[66] FEI Q, PURI A W, SMITH H, et al. Enhanced biological fixation of methane for microbial lipid production by recombinant *Methylomicrobium buryatense*[J]. Biotechnology for Biofuels, 2018, 11(1): 129.

[67] HENARD C A, SMITH H, DOWE N, et al. Bioconversion of methane to lactate by an obligate methanotrophic bacterium[J]. Scientific Reports, 2016, 6: 21585.

[68] HWANG I Y, NGUYEN A D, NGUYEN T T, et al. Biological conversion of methane to chemicals and fuels: technical challenges and issues[J]. Applied Microbiology and Biotechnology, 2018, 102(7): 3071-3080.

[69] GHODDOSI F, GOLZAR H, YAZDIAN F, et al. Effect of carbon sources for PHB production in bubble column bioreactor: emphasis on improvement of methane uptake[J]. Journal of Environmental Chemical Engineering, 2019, 7(2): 102978.

[70] RAHNAMA F, VASHEGHANI-FARAHANI E, YAZDIAN F, et al. PHB production by *Methylocystis hirsuta* from natural gas in a bubble column and a vertical loop bioreactor[J]. Biochemical Engineering Journal, 2012, 65: 51-56.

[71] ALI GHAZ-JAHANIAN M, KHOSHFETRAT A B, HOSSEINIAN ROSTAMI M, et al. An innovative bioprocess for methane conversion to methanol using an efficient methane transfer chamber coupled with an airlift bioreactor[J]. Chemical Engineering Research and Design, 2018, 134: 80-89.

[72] TIMMERS P H A, GIETELING J, WIDJAJA-GREEFKES H C A, et al. Growth of anaerobic methane-oxidizing Archaea and sulfate-reducing bacteria in a high-pressure membrane capsule bioreactor[J]. Applied and Environmental Microbiology, 2015, 81(4): 1286-1296.

[73] MOLINA GRIMA E, BELARBI E H, ACIÉN FERNÁNDEZ F G, et al. Recovery of microalgal biomass and metabolites: process options and economics[J]. Biotechnology Advances, 2003, 20(7/8): 491-515.

[74] MATA T M, MARTINS A A, CAETANO N S. Microalgae for biodiesel production and other applications: a review[J]. Renewable and Sustainable Energy Reviews, 2010, 14(1): 217-232.

[75] MARTINEZ-VILLARREAL S, BREITENSTEIN A, NIMMEGEERS P, et al. Drop-in biofuels production from microalgae to hydrocarbons: microalgal cultivation and harvesting, conversion pathways, economics and prospects for aviation[J]. Biomass and Bioenergy, 2022, 165: 106555.

[76] VENKATA SUBHASH G, RAJVANSHI M, RAJA KRISHNA KUMAR G, et al. Challenges in microalgal biofuel production: a perspective on techno economic feasibility under biorefinery stratagem[J]. Bioresource Technology, 2022, 343: 126155.

[77] YOO G, PARK M S, YANG J W. Chemical pretreatment of algal biomass[M/OL]//Pretreatment of biomass. Amsterdam: Elsevier, 2015: 227-258[2023-06-01]. https://www. sciencedirect. com/science/article/abs/pii/B9780128000809000128?via%3Dihub.

[78] MISHRA V, DUBEY A, PRAJAPTI S K. Algal biomass pretreatment for improved biofuel production[M/OL]//GUPTA S, MALIK A, BUX F. Algal biofuels. Cham: Springer, 2017: 259-280[2023-06-01]. https://link. springer. com/chapter/10.1007/978-3-319-51010-1_13.

[79] DONG T, FEI Q, GENELOT M, et al. A novel integrated biorefinery process for diesel fuel blendstock production using lipids from the methanotroph, *Methylomicrobium buryatense* [J]. Energy Conversion and Management, 2017, 140: 62-70.

[80] SIDDIKI S Y A, MOFIJUR M, KUMAR P S, et al. Microalgae biomass as a sustainable source for biofuel, biochemical and biobased value-added products: an integrated biorefinery concept[J]. Fuel, 2022, 307: 121782.

[81] GRIMA E M, GONZÁLEZ M J I, GIMÉNEZ A G. Solvent extraction for microalgae lipids[M/OL]//BOROWITZKA M, MOHEIMANI N. Algae for biofuels and energy. Dordrecht: Springer, 2013: 187-205[2023-06-01]. https://link. springer. com/chapter/10.1007/978-94-007-5479-9_11.

[82] SATHISH A, SIMS R C. Biodiesel from mixed culture algae *via* a wet lipid extraction procedure[J]. Bioresource Technology, 2012, 118: 643-647.

[83] NG K S, FAROOQ D, YANG A D. Global biorenewable development strategies for sustainable aviation fuel production [J]. Renewable and Sustainable Energy Reviews, 2021, 150: 111502.

[84] RONY Z I, MOFIJUR M, HASAN M M, et al. Unanswered issues on decarbonizing the aviation industry through the development of sustainable aviation fuel from microalgae[J]. Fuel, 2023, 334: 126553.

[85] Airbus. Sustainable aviation fuel: a “drop-in” fuel with reduced lifecycle emissions[EB/OL]. 2023[2023-06-01]. https://www.airbus.com/en/sustainability/respecting-the-planet/decarbonisation/sustainable-aviation-fuel.

[86] MAWHOOD R, GAZIS E, DE JONG S, et al. Production pathways for renewable jet fuel: a review of commercialization status and future prospects[J]. Biofuels, Bioproducts and Biorefining, 2016, 10(4): 462-484.

[87] SHIN H Y, SHIM S H, RYU Y J, et al. Lipid extraction from *Tetraselmis* sp. microalgae for biodiesel production using hexane-based solvent mixtures[J]. Biotechnology and Bioprocess Engineering, 2018, 23(1): 16-22.

[88] DEERFIELD I. Selected by air New Zealand and New Zealand government to undertake study for domestic sustainable aviation fuel production in New Zealand[EB/OL]. (2023-06-15) [2023-06-18]. https://www. lanzajet. com/lanzajet-and-lanzatech-selected-by-air-new-zealand-and-new-zealand-government-to-undertake-study-for-domestic-sustainable-aviation-fuel-production-in-new-zealand/.

[89] HEYNE J, RAUCH B, LE CLERCQ P, et al. Sustainable aviation fuel prescreening tools and procedures[J]. Fuel, 2021, 290: 120004.

[90] RUMIZEN M A. Qualification of alternative jet fuels[J]. Frontiers in Energy Research, 2021, 9: 760713.

[91] LIU Z H, WANG K, CHEN Y, et al. Third-generation biorefineries as the means to produce fuels and chemicals from CO_2[J]. Nature Catalysis, 2020, 3(3): 274-288.

[92] LIM J H K, GAN Y Y, ONG H C, et al. Utilization of microalgae for bio-jet fuel production in the aviation sector: challenges and perspective[J]. Renewable and Sustainable Energy Reviews, 2021, 149: 111396.

[93] SAID Z, NGUYEN T H, SHARMA P, et al. Multi-attribute optimization of sustainable aviation fuel production-process from microalgae source[J]. Fuel, 2022, 324: 124759.

[94] CAPAZ R S, SEABRA J E A. Life cycle assessment of biojet fuels [M/OL]//CHUCK C J. Biofuels for aviation. New York: Academic Press, 2016: 279-294[2023-06-01]. https://www.sciencedirect.com/science/article/abs/pii/B9780128045688000123?via%3Dihub.

[95] STRATTON R W, WONG H M, JAMES I H. Life cycle greenhouse gas emissions from alternative jet fuels[R/OL]. 2023[2023-6-01]. http://web. mit. edu/aeroastro/partner/reports/proj28/partner-proj28-2010-001.pdf.

[96] VARDON D R, SHERBACOW B J, GUAN K Y, et al. Realizing “net-zero-carbon” sustainable aviation fuel[J]. Joule, 2022, 6(1): 16-21.

[97] GATES D. New $800M sustainable aviation fuel plant planned for Washington state[EB/OL]. (2023-05-18) [2023-06-01]. https://www. seattletimes. com/business/boeing-aerospace/new-800m-sustainable-aviation-fuel-plant-planned-for-washington-state/.

[98] SAPP M. Chinese company to use honeywell ecofining technology for SAF production[EB/OL]. 2023[2023-06-01]. https://www. biofuelsdigest. com/bdigest/2023/05/08/chinese-company-to-use-honeywell-ecofining-technology-for-saf-production/.

[99] 北京大学能源研究所. 中国可持续航空燃料发展研究报告现状与展望[R/OL]. 2022[2023-06-01]. https://energy.pku.edu.cn/docs/2022-10/5eeef85e13ed4d7098e79e677b7ae78d.pdf. Institute of Energy, Peking University. The present and future of sustainable aviation fuels in China[R/OL]. 2022[2023-06-01]. https://energy.pku.edu.cn/docs/2022-10/5eeef85e13ed4d7098e79e677b7ae78d.pdf.

[100] KARGBO H, HARRIS J S, PHAN A N. “Drop-in” fuel production from biomass: critical review on techno-economic feasibility and sustainability[J]. Renewable and Sustainable Energy Reviews, 2021, 135: 110168.

[101] PENG K, LI J S, JIAO K L, et al. The bioeconomy of microalgal biofuels[M/OL]//JACOB-LOPES E, QUEIROZ ZEPKA L, QUEIROZ M I. Energy from microalgae. Cham: Springer International Publishing. 2018: 157-169[2023-06-01]. https://link.springer.com/chapter/10.1007/978-3-319-69093-3_7.

[102] SINGH J, GU S. Commercialization potential of microalgae for biofuels production[J]. Renewable and Sustainable Energy Reviews, 2010, 14(9): 2596-2610.

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