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燃料乙醇炼制及生命周期碳足迹研究进展

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摘　要　在全球能源短缺和加剧的气候变化双重压力的背景下，人们正积极探索替代化石燃料的新型生物燃料。从农业废弃生物质中的纤维素生产的燃料乙醇是一种绿色的可再生燃料，具备显著的能量收益和碳减排效果，对促进“碳中和”具有重要意义。本文主要针对燃料乙醇的生物炼制技术，综述了其在生命周期碳足迹方面的研究进展。论文首先介绍了制乙醇技术的基本原理和现状，重点探讨了其在减少温室气体排放方面的潜力，同时结合生命周期经济型分析，总结了各制乙醇技术的成本效益。研究表明，第二代燃料乙醇在碳减排能力上表现最佳，其次是第一代和第三代燃料乙醇，目前第二代燃料乙醇的成本价格高于汽油市场价格，研究高效低成本的纤维素酶和联产高附加值副产品是两个降低成本的主要方向，论文旨在为未来燃料乙醇炼制技术的研究提供重要参考。

关键字：燃料乙醇；生命周期评价；碳足迹；温室气体；生物质
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Research progress of fuel ethanol refining and life cycle carbon footprint

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ABSTRACT　Driven by the "dual carbon" goal, biomass liquid fuel has become an important solution to expand fossil fuel reserves, reduce greenhouse gas emissions and mitigate global warming and climate change because of its superior "carbon reduction" characteristics. Fuel ethanol is the most widely utilized bio-liquid fuel globally. It is a green renewable fuel product that is converted from cellulose in biomass such as agricultural waste and wood through microbial fermentation. It has the characteristics of high vaporization heat, high octane number and cleaner combustion, and can be commercially produced. Therefore, the development of fuel ethanol is an important energy strategy to deal with energy bottleneck and ensure the sustainable development of circular economy in China. The production process of fuel ethanol usually includes raw material pretreatment, cellulase hydrolysis and microbial fermentation, but there are still many challenges that hinder the implementation of large-scale production. This paper discusses the production processes of fuel ethanol and evaluates its lifecycle, with a particular focus on its potential to reduce greenhouse gas emissions. It also summarizes the economic benefits of various ethanol production technologies. In this study, the basic principles and current status of ethanol technology are first described, and some challenges in the production of fuel ethanol from lignocellulosic biomass are pointed out, including cell wall stubbornness, multi-step pretreatment process, extended hydrolysis time, degradation product generation, and high production costs. Future research endeavors will concentrate on the advancement of a comprehensive suite of technologies designed to optimize low-energy, high-efficiency, and environmentally friendly pretreatment processes for raw materials. This includes the development of cost-effective and high-performance hydrolases, which are critical for enhancing the efficiency of enzyme formulations used in biomass conversion. Additionally, utilizing genetic engineering techniques, we aim to cultivate microbial strains that exhibit heat resistance and resistance to inhibition. These engineered strains will be capable of efficiently utilizing both pentose and hexose sugars, thereby significantly improving ethanol yields. By integrating these innovative approaches, we anticipate not only elevating the overall efficiency of fuel ethanol production but also contributing to a more sustainable biorefining process. Life cycle evaluation studies of fuel ethanol production technologies have shown that fuel ethanol plays an important role in mitigating climate change and achieving net zero emission targets by sequestering carbon fixed during biomass growth compared to fossil fuels. Among them, the second generation of fuel ethanol performed best, followed by the first and third generation of fuel ethanol. And electricity is a major contributor to AP and GWP, that is, new technologies or alternative power structures can be developed to reduce the environmental load However, there are still some problems in the evaluation process, such as inconsistent system boundary, insufficient data list and diversified evaluation models, so it is necessary to establish a unified standard to further improve the life cycle evaluation system. In addition, a comprehensive analysis of the cost-effectiveness of various ethanol technologies was conducted through a comprehensive life cycle economic assessment. Current pricing makes second-generation fuel ethanol more expensive than gasoline, prompting a focus on improving the efficiency and affordability of cellulase while driving the production of high-value by-products. The purpose of this paper is to provide important reference for the research of fuel ethanol refining technology in the future.

KEY WORDS fuel ethanol; life cycle assessment; carbon footprint; greenhouse gases; biomass

国际能源署(IEA)在《2023 年可再生能源》报告中指出，为了实现到 2050 年净零排放目标，截至到 2030 年，全球生物燃料产量需年均增长 11%,全球生物燃料需求量将在 2022 年至 2027 年间每年增长 350 亿升。在“双碳"目标推动下，具有良好“降碳”属性的生物质液体燃料是扩大化石燃料储量、减少温室气体排放、缓解全球变暖和气候变化的有效对策。《3060 零碳生物质能发展潜力蓝皮书》预测，2021-2030 年，预计生物质液体燃料使用量将超过 2500 万吨，在交通领域减少 1.8 亿吨左右的碳排放量[1]。

液体生物燃料作为重要的生物储能形式，根据其使用的原料和合成技术，可分为四代，分别为粮食乙醇和粮食柴油、燃料乙醇和生物柴油、微藻燃料，以及利用合成生物学作为基础开发的合成生物燃料，燃料乙醇的排放较低，成为各国研究的重点[2,3]。燃料乙醇是世界使用量最大的生物液体燃料，2022 年世界燃料乙醇产量已达 8410 万吨，比 2021 年增长 3.2%,乙醇汽油超过全球车用汽油消费总量的 60%，全球有 66 个国家推广使用[4]。燃料乙醇是一种可行的可再生燃料，具有高汽化热、高辛烷值和更清洁的燃烧，二氧化碳排放更少，并且可以商业化生产[5]。发展燃料乙醇是我国应对能源瓶颈以及保障循环经济可持续发展的重要能源战略。

本文综述了国内外制燃料乙醇技术的全生命周期评价研究，重点分析其在减碳方面的潜力，并总结了各种原料制造燃料乙醇技术的成本效益，并对燃料乙醇产业的发展前景进行了展望，为燃料乙醇炼制技术的后续研究提供参考依据。

1 生物质制燃料乙醇的技术概述

燃料乙醇的发酵生产过程包括原料预处理、纤维素水解糖化、发酵及乙醇蒸馏回收等。目前燃料乙醇的生产工艺仍面临诸多挑战，如细胞壁的顽固性、多个预处理步骤、水解时间长、降解产物形成以及高昂成本。这些因素阻碍了其大规模生产的实施，需要找到解决方案[6]。

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1.1 原料分类

燃料乙醇生产的经济性取决于原料的可用性和可负担性，目前发展了四代不同的原料。第一代原料来自糖类（甘蔗、甜菜、甜高粱）和淀粉类（小麦、玉米、木薯等）作物，经过发酵用于乙醇生产。由于粮食和土地使用之间的竞争，这些原料引发了可持续性的争议。第二代原料来自木质纤维素生物质（Lignocellulosic Biomass, LCB），如农业残留物（秸秆、甘蔗渣等）、森林残留物（锯末、木屑等）、木材（松树、云杉）、能源作物（柳枝稷、芒草）和城市固体废物等[7,8]。LCB 具有使用非食用性原料，与食品工业不竞争的优点，存在生产成本高的问题。第三代原料来自微藻和大型藻类生物质，具备高碳水化合物含量、易于栽培、低木质素、高二氧化碳吸收，以及通过去除重金属来净化水的能力等优点[9]。目前对于藻类原料的研究较少，生物精炼技术效率低下。第四代原料是应用了分子生物学和基因工程等技术的作物或藻类。转基因藻类(如莱茵衣藻、褐藻和聚球藻)具有 CO_2 固存、减少温室气体排放等优势[10]，但转基因因子对环境的潜在影响需要进一步研究[11]。目前，第二代燃料乙醇的研发与应用正在加速推进，利用非粮食的生物质合成液体燃料是未来的主要发展方向。

1.2 预处理

木质纤维素生物质主要由纤维素、半纤维素和木质素三部分组成，三者之间通过特有的连接方式以及紧密的作用力相互关联，导致天然生物质中纤维素的酶促消化率偏低。有效的预处理通过降低纤维素结晶度、增加孔隙率、改善表面积，使其易于受酶水解，现阶段的处理方法主要包括物理法、化学法以及物理化学结合法。常见的预处理技术及优缺点汇集于表 1。研究表明：物理-化学预处理目前应用较为广泛，使用联合预处理技术比单一形式的预处理更易达到预期效果，以及规模化生产应用。

表 1 预处理技术

Table 1 Pretreatment technology

	Method	Principle	Advantage	Shortcoming	Reference
Physical pretreatment	Mechanical crushing pretreatment	The particle size of the raw material is reduced and the reaction contact area is increased	No harsh chemicals are involved, reducing the impact on the environment	High energy consumption and expensive equipment	[12]
	Microwave irradiation pretreatment	Molecular collisions promote the degradation of hemicellulose and lignin	Heating time and better performance, instant stop and start on the raw material	Expensive investment equipment, mostly in the lab	[13]
	Ultrasonic pretreatment	Break the hydrogen bond between cellulose and increase the contact rate of enzymes	The grain size of raw material is reduced, the conversion rate of enzymatic hydrolysis and the yield of fermented sugar are increased	High cost	[14]
	Liquid hot water pretreatment	The cellulose part breaks down into organic acids to facilitate subsequent reactions	Environmentally friendly, low sugar loss rate, simple process	Environmentally friendly, low sugar loss rate, simple process	[15]
Chemical pretreatment	Acid pretreatment	Dissolving hemicellulose increases the enzyme's accessibility to the cellulose portion	Inorganic acid has low cost and high sugar yield.Organic acids are non-toxic, recyclable and Mild conditions, simple technology and equipment	Strong corrosion and high energy consumption	[16]
	Alkali pretreatment	The cleavage of aryl ether bond leads to lignin depolymerization	Mild conditions, simple technology and equipment	Long pretreatment time and high alkali consumption	[17]
	Organic solvent pretreatment	Lignin and hemicellulose are separated by penetrating internal linking bonds	Reduced inhibitor formation and high lignin removal rate	Recovery solvent is complex, high cost, flammable and volatile	[18,19]
	Ionic liquid pretreatment	Destroy the structure between cellulose, hemicellulose and lignin	Green solvent with low toxicity, low melting point, high thermal stability and chemical stability	The price is expensive, the process is complex, the toxicity is not capable of large-scale production	[20]
	Oxidative pretreatment	Hydroxyl radicals are produced, which decompose the lignocellulosic structure by oxidation	High efficiency, less inhibitor formation	High cost, high energy consumption	[21]
	Deep eutectic solvent pretreatment	Break the hydrogen bond in lignocellulose and promote the hydrolysis of lignin and hemicellulose	Environmental friendly, biodegradable, low toxicity, simple synthesis process, low cost	The viscosity is relatively high and the fluidity is poor	[22]
Physicochemical pretreatment	Steam blast pretreatment	The lignocellulose structure is broken under high temperature and high pressure	Efficient, safe, green and pollution-free	High operating conditions are required to form inhibitors	[23]
	Ammonia fiber blasting pretreatment	Liquid ammonia removes lignin under high pressure and destroys the polymerization structure of cellulose	No inhibitors are produced, sugar recovery is high, and ammonia can be recycled	High cost of investment equipment, high energy consumption	[24]
	Acid gas blasting pretreatment	Acid gas is injected into the steam blasting process to	Carbonic acid is less harmful; SO_2 blasting treatment has the	There are few experimental studies and fermentation	[25,26]

	promote enzymatic hydrolysis	best treatment effect on cork raw materials	inhibitors are formed

1.3 糖化与发酵

糖化发酵工艺存在酶解抑制物，纤维素酶价格昂贵需求量大，工程菌株的选育等问题，目前的生产工艺主要包括 4 种类型，分步水解与发酵工艺（Separate Hydrolysis and Fermentation：SHF）、同步糖化发酵工艺（Simultaneous Saccharification and Fermentation：SSF），同步糖化共发酵（Simultaneous Saccharification and Cofermentation: SSCF）工艺和和联合生物加工过程（Consolidated Bio-processing：CBP），技术路线如图 1 所示。

从图 1 得出，SHF 工艺中纤维素首先在酶的作用下分解，后进行戊糖和已糖发酵，可以发挥酶的最大活性，但酶解糖会抑制酶活导致乙醇产量下降，设备成本较高[27]。SSF 工艺节省反应时间，降低纤维素酶的用量，但难以达到糖化和发酵均合适的反应条件。SSCF 工艺利用戊糖和已糖共发酵菌株进行酶水解同步发酵，提高了底物转化率，增加乙醇产量，降低工艺成本并消除酶的反馈抑制。转基因酵母酿酒酵母、大肠杆菌或移动热解杆菌使其能够满足上述要求，但成本较高[28]。CBP 工艺在单个容器中将纤维素酶生产、水解以及与糖共发酵产乙醇结合为一步反应，减少了基础设施与化学品投入，但转换效率低，微生物对较高乙醇浓度具有低耐受性[29]。近年来，研究者们积极开发经基因改良的微生物菌株，低成本的水解酶，有效提高了生物质的转化效率，有望在工业生产中实现大规模的应用。

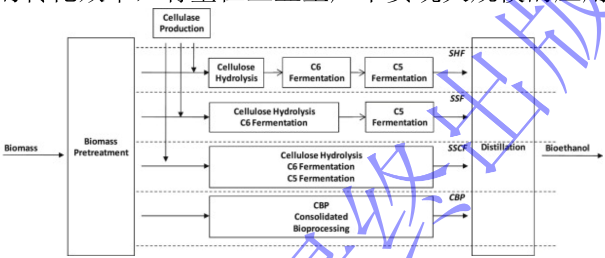

图 1 木质纤维素乙醇生产一体化[30]

Fig.1 Integration of lignocellulosic ethanol production [30]

2 燃料乙醇生命周期碳足迹研究

2.1 生命周期评价

生命周期评价(Life Cycle Assessment, LCA),又被称为“从摇篮到坟墓”分析(Cradle to Grave Analysis),是一个用于量化和评估与产品、过程或活动的整个生命周期中使用能源、材料和废物排放相关的环境负担的方法[31]。LCA 有四个阶段:目标和范围界定、清单分析、影响评价和结果解释阶段，目前，这些步骤大多是在专业软件中完成的，如 GaBi、SimaPro、TEAM、Balance、OpenLCA，使用最广泛的数据库有 GREET、ELCD、Ecoinvent、CLCD 等[32]。LCA 的框架如图 2 所示。燃料乙醇技术的生命周期评价旨在评估从生物质种植到乙醇成品储运过程中的环境和资源影响。评估过程汇总所有涉及到乙醇生产技术流程的详细清单数据，并综合分析各个环节对环境的潜在影响。最终，对评估结果进行综合分析和解释，并提出改进建议和发展策略[33]。

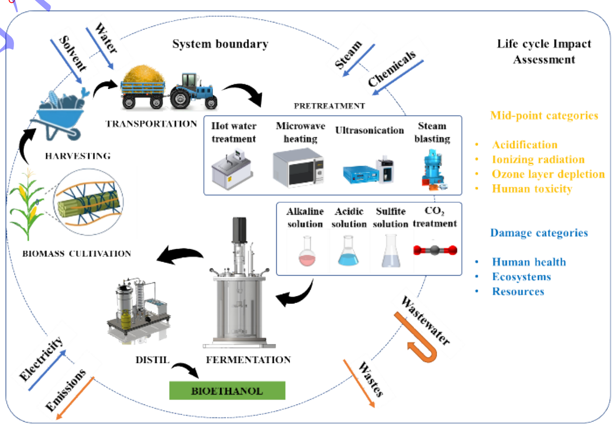

图 2 燃料乙醇生命周期评价[34]

Fig. 2 Life Cycle evaluation of fuel ethanol [34]

2.2 燃料乙醇碳足迹分析

全球变暖潜能值（Global Warming Potential，GWP）在生物燃料生产的 LCA 研究中是最常关注的影

响类别之一。它使用以二氧化碳当量表示的系数来量化各种排放因素对全球变暖的潜在影响。美国可再生燃料标准要求：与传统汽油（93.3 CO_2eq./MJ $_{gasoline}$)相比，第二代生物燃料必须减少 60%的温室气体排放。因此，从第二代生物质衍生的生物乙醇的温室气体排放量应小于 37g CO_2eq./MJ $_{ethanol}$ 使其在环境上具有可持续性。第三代生物燃料的温室气体排放量大（耗电量高），范围为 10.2~1910gCO_2eq./MJ $_{ethanol}$[35,36]。

LCA 在确定适当的生物质预处理策略方面发挥了重要作用，国内外研究者通过不同的工艺路线生产燃料乙醇，证实了燃料乙醇具有明显的碳减排能力。Prasad 等[37]对玉米秸秆燃料乙醇开展了全生命周期评价，比较了液态热水、蒸汽爆炸、稀酸和有机溶剂等四种预处理方法。研究表明液态热水工艺在糖转化率方面优势明显，葡聚糖和木聚糖转化率分别为 90.54 %、81.8%，是最适合玉米秸秆的预处理技术。Priadi [38]评估了超临界水处理、CO_2 水和催化水热水解在棕榈树叶生物乙醇生产中的应用。得到结论：催化水热水解工艺实现最高乙醇收率，碳足迹为 61gCO_2/MJ，乙醇生产成本为 1.11$/L，与酶水解工艺持平。HaTran M[39]研究了两罐和一罐合成对于银草糖化渣生产生物多元醇的差异，得出一锅合成可降低约 71.1%的单位生物多元醇成本。综上所述，选择适当的生物质原料和预处理方式对于提高燃料乙醇的碳减排潜力至关重要，同时也有助于降低生产成本。

负排放技术（Negative emission technologies，NETs）被认为是减少温室气体（Greenhouse Gas，GHG）排放中具有前景的方法。生物能源碳捕集与封存（Bioenergy with Carbon Capture and Storage，BECCS）是其中重要的负排放途径之一。Lovenskiold 等[40]研究得出每公顷土地可实现的最大气候变化缓解潜力是来自 BECCS 的-22tCO_2eq。当生物乙醇与碳捕集与封存（Carbon Capture and Storage，CCS）无关时，减排减少约四分之一。Lask J[41]评估了与 CCS 技术相结合生产的芒草乙醇的温室气体减排潜力，与汽油相比减少 GHG 排放潜力在 104%~138%之间。BECCS 能够通过永久储存生物质增长过程中固定的碳来实现负排放，促进燃料乙醇缓解气候变化。然而，BECCS 面临着一些挑战，包括土地供应和二氧化碳储存能力的限制、政策的适当性问题、后勤执行的复杂性等。

Roque 等[42]在柴油发动机中以柴油和加氢植物油用作先导燃料，并注入四种能量分数的生物乙醇。研究显示，双燃料的应用与纯柴油相比显著降低了 CO_2 排放，但发动机效率降低了 9.4%。Puricelli 等[43]考虑了由汽油和燃料（化石-叔丁基乙醚、生物-叔丁基乙醚、生物石脑油、生物乙醇、甲醇、生物甲醇）组成的混合油。研究得出所有混合物相比于纯汽油车辆，均能稍微减少气候变化，减排幅度在 0.8% ~10.1%。因此，将生物乙醇替代汽油或与汽油组成混合汽油，在交通运输领域具有减少 GHG 排放的潜力，但也存在整体发动机效率降低的问题，这是因为生物乙醇的能量密度相对较低，可能导致燃烧效率下降，未来需要继续研究和解决其对发动机效率的潜在负面影响。

国内外研究者采用不同生物质原料进行燃料乙醇的生产，并进行全生命周期分析，进一步验证了燃料乙醇在低碳环保方面的优势。沈钊丞等[44]以杨木、玉米秸秆、甘蔗渣为原料，研究燃料乙醇在其生命周期中的环境影响情况。研究得出：生产阶段所产生的 GHG 在全生命周期过程中占比最高；酸化潜值、全球变暖潜值、化石资源消耗潜值主要受到生产阶段影响；减碳能力杨木最好，玉米秸秆、甘蔗渣次之。Liu 等[45]用 GREET 模型评估巴西甘蔗乙醇的生命周期温室气体排放，平均置信区间为 35.2gCO_2/MJ，对比石油汽油减排量达到 62%，三个主要的 GHG 是 N_2O 排放（24.3%），甘蔗种植能源（24.2%）和甘蔗乙醇运输（19.3%）。Isler-Kaya 等[46]计算红花油甲酯、红花油乙酯和糖蜜基生物乙醇的对环境的影响。得出结论：三种生物燃料在所有类别中都比化石燃料更有利。碳强度为 16.72、15.24、22.23、99.45 和 108.48gCO_2/MJ，分别代表红花油甲酯、红花油乙酯、生物乙醇、柴油和汽油。Yin 等[47]研究得出玉米芯、玉米秸秆和小麦秸秆生产 1Mg 生物乙醇会排放 1267.58Kg、1418.36Kg 和 1444.30KgCO_2。与汽油产品排放相比，温室气体减排量分别为 54%、49%和 48%，玉米芯具有最佳的整体效益。扣除木质素和木糖固定的碳含量，减排量达 82%。Balan 等[48]研究表明：微藻能够固定大量温室气体如 CO_2，以及微藻作为碳汇和废水处理的带来的环境效益。杨淑媛[49]研究了不同的全株玉米乙醇方案,发现当秸秆利用率为 80%且利用纤维戊糖转化乙醇的情景的环境排放最低,具有最佳的环境效益,GWP 为 42.8gCO_2eq./MJ。

对不同原料生产的燃料乙醇的碳减排分析汇总于表 2，并将主要碳减排数据汇总于图 3，由上述研究得出各种生物质原料生产的燃料乙醇都具备降低温室气体排放的能力，其中第二代燃料乙醇碳减排能力最佳，然后是第一代燃料乙醇，由于耗电量高，部分第三代生物燃料在当前发展阶段的 GHG 排放量高于传统燃料。

表 2 不同原料纤维乙醇碳减排分析

Table 2 Carbon emission reduction analysis of ethanol from different raw materials

Biomass raw material	Production technology	Model/method	conclusion	Reference
Aspen	Dilute acid pretreatment, enzymatic hydrolysis, fermentation,	TRACI2.1 Life Cycle Impact Assessment method	The net GWP of poplar bioethanol was −1.05g CO_2eq/MJ, and its carbon sequestration capacity was higher than that of	[50]

	distillation and wastewater treatment		willow and eucalyptus	
Corn, wheat straw, switchgrass, corn straw, forest straw and municipal solid waste	Pretreatment and biorefining facilities	IMPACT World+ Midpoint v1.02	Compared with gasoline, forest straw has the best GHG emission reduction effect, followed by switchgrass, wheat straw, corn straw, and corn	[51]
Bark, sawn timber and wood residues	Acid pretreatment, enzymatic hydrolysis, fermentation, distillation recovery	ReCiPe1.1Hierarchist Method	With CCS technology, more than 85% of the ethanol/gasoline mixture is driven per 100 km	[52]
Grapevine bud	Pretreatment, delignification, simultaneous saccharification and fermentation (SSF)	ReCiPe Midpoint H and Endpoint H methods	Fuel ethanol will reduce greenhouse gas emissions compared to gasoline	[53]
Switchgrass	High gravity ionic liquid pretreatment, fermentation, ethanol recovery, wastewater treatment	DayCENT and RUSLE models	Ethanol production cost and carbon footprint can be reduced (126~223¢/gge) and 13~20 gCO_2eq/MJ to achieve significant emission reduction	[54]
Bagasse, molasses and yam shells	Pretreatment, simultaneous saccharification and fermentation (SSF), distillation, purification	GREET model	Emissions of 15.33gCO_2eq/MJ, an 82.5%GHG reduction compared to gasoline, meet the EPA's target for advanced biofuels	[55]

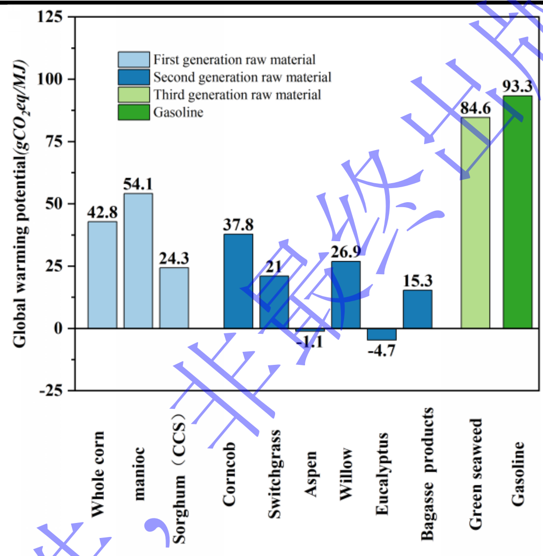

图 3 不同原料纤维乙醇碳减排分析[56,57]

Figure 3 Carbon emission reduction analysis of ethanol from different raw materials[56,57]

3 燃料乙醇生命周期碳足迹成本研究

在实际应用中，衡量燃料乙醇技术的优劣不仅要考虑其碳减排效益，也要兼顾生产成本等经济性指标。技术经济评估是一种用于同时评估木质纤维素生物质可行开发的经济可能性和环境可持续性的技术[58],通常包括五个步骤：工艺设计、质量和能量平衡、成本估算、盈利能力分析和敏感性分析，常见经济指标有最低乙醇销售价格（Minimum Ethanol Selling Price，MESP）、净现值（Net Present Value，NPV）和内部收益率（Internal Rate of Return，IRR）等。

技术经济分析有助于评估不同的原材料和处理方法。研究表明，从木质纤维素废物中生产乙醇在经济上是可行的，内部收益率在 8%至 20%之间[59]。Zheng 等[60]使用玉米秸秆生产燃料乙醇。得出对于直接和间接发酵途径，内部收益率分别为 25.6%和 41.5%；最低售价分别为 0.98$/gge 和 1.19$/gge，采用生物油间接发酵途径生产燃料乙醇在经济上更可行。Vasilakou 等[61] ASPEN Plus 中模拟了 4 种方法处理玉米秸秆生产乙醇，蒸汽爆炸和液态热水的资本支出最低，稀酸预处理模型的 MESP 最低，为 1.01€/L，其次是蒸汽爆炸和液态热水。通过考虑每种预处理模型的经济性和环境性能，稀酸和蒸汽爆炸技术在基础案例研究中显示出最大的潜力。

Correia 等[62]使用桉树残渣和玉米秸秆进行生物乙醇生产。桉树残渣和玉米秸秆的 MESP 分别为 2.19€/L 和 2.45€/L；生产成本分别为 1.31 €/L 和 1.50 €/L，高于 0.65€/L 的参考市场价格。魏庭玉[60]模拟一个玉米秸秆年处理量 80000 吨的纤维素乙醇生产工厂，每吨纤维素乙醇的原料成本为 6327.87 元/吨，总生产成本 8587.83 元/吨，难以与近年 6000 元/吨汽油市场价格竞争。研究表明纤维素乙醇需要通过改进技术提高产率降低成本。目前，研究高效低成本的纤维素酶和联产高附加值副产品是两个发展燃料乙醇

的主要方向。

提高水解产量从而降低水解成本的一种潜在途径是补充缺乏酶活性的真菌酶，例如 β-葡萄糖苷酶。Ferreira[64]提出了利用重组大肠杆菌生产低成本工业酶的概念，并进行了技术经济评估，结果显示，酶的生产成本主要受设施成本（占 45%）、消耗品（占 23%）和原材料（占 25%）的影响。通过用更便宜的替代品替换碳源、调整诱导策略或改进接种过程和生产体积，可能会显著降低酶的成本。副产品价值对生物乙醇生产经济性的起到重要影响，可以通过获得更高的正收入来进一步降低 MSP。Pati[65]提出了生物乙醇生产的共气化发酵混合模式，配备了热合成气的余热回收和未转化合成气的发电功能。MESP 与印度乙醇的售价分别为 0.65\$/L、0.70\$/L，净现值、内部收益率和投资回收期分别为 18.7 M\$、13.33%和 6.7 年。Larnaudie[66]从液态热水预处理柳枝稷中生产乙醇、电、糠醛、乙酸和甲酸的生物精炼策略在环境影响方面比仅生产乙醇和电具有更好的性能。Pan 等[67]建立了 4 种甘蔗渣衍生水解残渣技术经济与生命周期评估方案，其中纤维素乙醇的原料成本为 3.75\$/kg 木糖，净现值、内部收益率和投资回收期分别为 32.5M\$、18.98%和 4.14 年。Correia 等[62]使用桉树残渣和玉米秸秆进行生物乙醇生产。探索了热整合、生物质预处理糖蜜的销售和原位酶生产三种方案，以提高收入并最大限度地降低生产成本。桉树残渣和玉米秸秆的 MESP 降价幅度分别达到 1.83%~6.85%，1.22%~20.41%。对不同原料生产的燃料乙醇的经济分析汇总于表 3。

这些结果表明，通过优化生产过程和利用副产品，可以显著降低生物乙醇生产的成本，从而提高经济效益。小型生物精炼厂能够适应不断变化的生物质供应，降低风险和物流成本，热电联产将降低能源成本和环境影响。同时生物精炼系统具有多种副产品，如生物能源、化学品、电力、热能等，分配标准对结果影响很大。因此生命周期评估与经济技术分析部分需要尝试选择不同的功能单元和分配标准。

表 3 不同原料纤维乙醇成本分析

Table 3 Cost analysis of fiber ethanol from different raw materials

Species	Obtain product	Ability	Minimum selling price	Payback period	Internal rate of return	Net present value	Reference
Wheat straw and bagasse	Ethanol, electricity	60 tons per hour	0.65 \$/L	6.7 years	13.33%	18.7 M\$	[65]
Wheat straw	Ethanol, electricity	13 tons per hour	1.43 \$/L	10 years		5.05 M\$	[68]
Bagasse	Ethanol	0.8 tons per hour	1.08 \$/L	4.14 years	18.98%	32.5 M \$	[67]
Switchgrass	Ethanol	14 tons per hour	1.7 \$/L		10%		[69]

4 结语

面对液体燃料需求不断增长的挑战，利用纤维素生物质制备燃料乙醇显得尤为重要。本文介绍燃料乙醇的生产工艺及其生命周期评价，重点探讨其在减少温室气体排放方面的潜力，并总结各种制乙醇技术的经济效益。同时，针对当前面临的问题，提出以下建议和展望：

（1）在生物质转化为燃料乙醇的商业化生产中，研究重点在于开发成套集成技术。研发低耗能、高效、清洁的原料预处理技术;开发低成本高效率水解酶，提升酶制剂效率；通过基因工程技术，培育耐热，抗抑制物，能综合利用戊糖和已糖的微生物菌种，可以有效提升乙醇收率。

（2）燃料乙醇生产技术的生命周期评价的研究表明，与化石燃料相比，燃料乙醇通过封存生物质增长过程中固定的碳在减缓气候变化和实现净零排放目标方面发挥重要作用，且第二代燃料乙醇表现最佳，其次为第一代、第三代燃料乙醇，且电力是 GWP 的主要贡献者，即可以开发新技术或替代电力结构来减轻环境负荷；同时评估过程中存在系统边界不一致、数据清单不足以及多样化的评估模型等问题，因此，生命周期评估体系需要制定统一的标准进一步完善。

（3）目前纤维素乙醇的成本价格高于汽油市场价格，短期内依赖国家税收及财政补贴以维持企业运营，长期来看，需要建立完善的原料供应体系，对现有技术进行改进，其次将木质素和半木质素联产高附加值副产品，如木糖，粘合剂等，或者通过热电联产系统产生电力和蒸汽，用于生物精炼厂自身的需要，剩余能量出售以获取经济利益。这也减少了化石燃料的使用，并减轻了生物精炼过程中对环境的影响。

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