

Review

**BIOETHANOL AS A RENEWABLE ENERGY SOURCE: EFFICIENCY,
SUSTAINABILITY, AND ENVIRONMENTAL IMPACT**

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Abstract

*Bioethanol is one of the most widely used renewable liquid biofuels and a viable alternative to fossil fuels. Its use instead of fossil fuels can significantly reduce greenhouse gas emissions, contributing to climate change mitigation and improved energy sustainability. Beyond its role as a fuel, bioethanol is extensively used as a solvent, disinfectant, and basic chemical for a broad range of products in the chemical, food, and pharmaceutical industries. Industrial bioethanol production is primarily based on microbial alcoholic fermentation by the yeast *Saccharomyces cerevisiae*, which converts sugars derived from carbohydrate-rich biomass into ethanol. Traditionally, production relies on first-generation feedstocks, including sugar- and starch-based plant materials such as sugarcane, sugar beet, molasses, cereal grains, potatoes, cassava, etc. However, concerns regarding food security and land use have encouraged the development of second-generation lignocellulosic biomass and third-generation algal biomass as alternative feedstocks. Despite its well-recognized advantages, large-scale bioethanol production from non-food feedstocks continues to face important challenges related to energy efficiency, process optimization, long-term sustainability, and overall environmental performance. This paper therefore provides a comprehensive and critical assessment of bioethanol production efficiency, sustainability considerations, and environmental impacts across different feedstock generations, highlighting both technological progress and remaining limitations.*

Keywords: bioethanol, renewable energy, sustainability, efficiency, environmental impact.

INTRODUCTION

Bioethanol is an ethanol (C₂H₅OH) produced via microbial alcoholic fermentation by yeast, usually *Saccharomyces cerevisiae*, from carbohydrate-rich biomass. It is one of the most widely utilized renewable liquid biofuels and is recognized as an environmentally friendly alternative to fossil fuels [1]. Over the past few decades, global bioethanol production has increased several-fold, primarily driven by its use as a fuel-grade biofuel, reaching approximately 31.3 billion gallons in 2024, with a trend of continued growth [2]. Its use instead of fossil fuels enables a substantial reduction in greenhouse gas emissions up to 75%, while simultaneously addressing pressing environmental and energy challenges [3,4]. Bioethanol is extensively applied in the transport sector, either blended with gasoline at concentrations of 5, 10, or 85% (E5-E85) or as a component in octane enhancers such as ethyl

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tertiary butyl ether (ETBE). While low-percentage blends can be used in conventional engines without modification, high-percentage blends such as E85 require flexible fuel vehicles (FFVs) [4].

Industrial bioethanol production primarily relies on microbial alcoholic fermentation, in which sugars derived from carbohydrate-rich biomass are converted into ethanol by yeast [1,5]. Globally, first-generation (1G) feedstocks, such as sugar-containing (sugarcane, sugar beet, molasses, etc.), and starch-containing raw materials (corn, wheat, cassava, sweet sorghum, and potatoes), dominate commercial bioethanol production [1,5,6]. Starch-based feedstocks contribute approximately 60% of the worldwide bioethanol supply, whereas sugar-based feedstocks account for nearly 40% [6]. The prevalence of starchy and sugary biomass is attributed to its high conversion efficiency, ethanol yield, and cost-effectiveness, making it a preferred choice in industrial applications [5–7]. Globally, first-generation (1G) feedstocks are characterized by high quality, minimal pretreatment requirements, established conversion technologies, and large production volumes, resulting in efficient processing and relatively high ethanol yields that underpin the economic viability of bioethanol worldwide [8].

Despite the continued global reliance on first-generation (1G) feedstocks, increasing concerns about food security, land availability, and long-term sustainability have accelerated the transition toward the use of non-food biomass resources. Lignocellulosic biomass, classified as second-generation (2G), and algal biomass, representing third-generation (3G) feedstocks, are increasingly recognized as promising options for decoupling bioethanol production from competition with the food supply [2,8–10]. At the same time, advances in pretreatment strategies, enzymatic hydrolysis, and fermentation technologies have enabled the utilization of a broader spectrum of feedstocks, marking the progressive evolution of bioethanol production pathways. Nevertheless, achieving improved sustainability, enhanced energy efficiency, and economic viability, particularly for 2G and 3G bioethanol, remains a significant challenge that continues to shape current research and technological development efforts [5–11].

Fourth-generation (4G) biofuels rely on genetically engineered microalgae and designed microorganisms to enhance carbon capture and directly improve bioethanol productivity through advanced synthetic biology. Fifth-generation (5G) biofuels focus on genome-edited and metabolically engineered crops with modified cell wall structures to increase sugar yields and reduce processing costs. However, both approaches remain at an early research stage and are not yet commercially viable, while also raising important technical, environmental, and societal considerations [2].

METHODOLOGY

This review is based on a systematic analysis of scientific literature and analytical data related to bioethanol production, bioconversion processes, and analytical techniques. Publications were retrieved from electronic databases, including Google Scholar, Scopus, ScienceDirect, and PubMed, using predefined keywords related to bioethanol production, fermentation, sustainability, and life cycle assessment. The selected publications were published from 2018 to 2024, ensuring that the information is up-to-date and relevant.

THE CURRENT STATUS AND TRENDS OF BIOETHANOL PRODUCTION

Over the past few decades, global bioethanol production has expanded significantly as countries increasingly adopt renewable fuel strategies. As presented in Figure 1, according to the Renewable Fuels Association (RFA), worldwide fuel bioethanol output reached approximately 31.31 billion gallons in 2024, marking a new high in annual production driven by sustained demand for cleaner transport fuels. The United States remains the dominant producer, accounting for about 52% of global output, with production primarily based on corn, which benefits from well-established industrial infrastructure and high conversion efficiency. Brazil follows as the second-largest producer with roughly 28% of total global ethanol output, predominantly from sugarcane, while India contributes around 6%. EU countries contribute roughly 5% of global bioethanol production, primarily using sugar beet, corn, and wheat as feedstocks. According to the second revision of the EU Renewable Energy Directive (RED III, 2018/2001), the EU aims to achieve a minimum 45% share of renewable energy in overall consumption by 2030, with bioethanol playing an important role in meeting these targets [3].

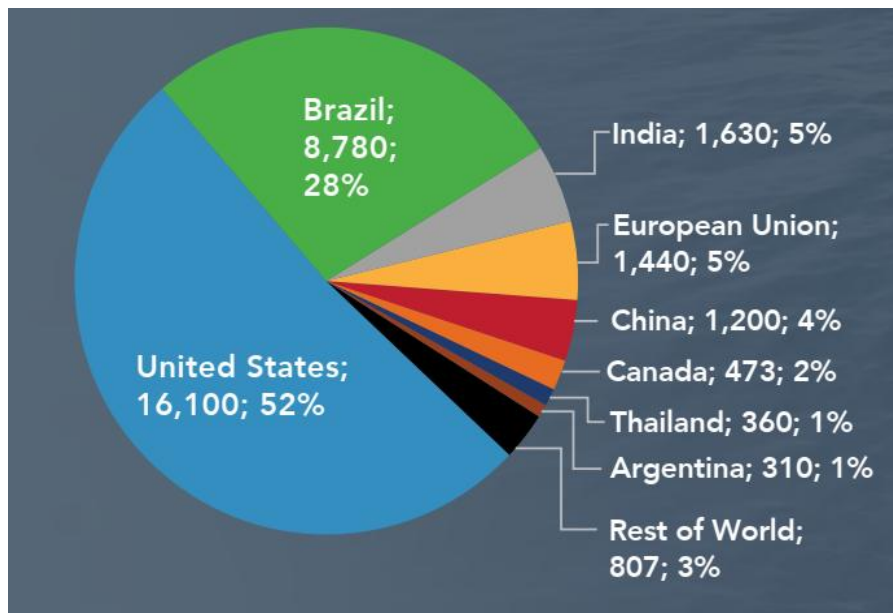


Figure 1 Global fuel ethanol production by country in 2024 [3]

Continued expansion of bioethanol production over recent decades (Figure 2) reflects policy support, technological progress, and industrial scaling to reduce transport-sector greenhouse gas emissions globally.

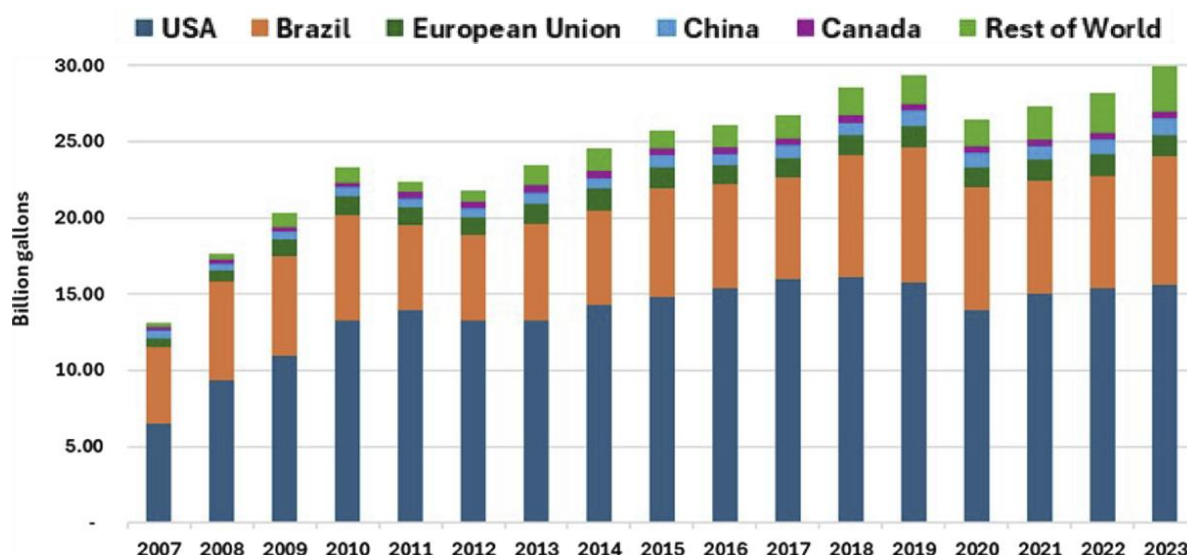


Figure 2 Historical overview of global ethanol production by leading countries in 2024 [2]

TECHNOLOGY READINESS LEVELS (TRLs) OF BIOETHANOL GENERATIONS

Bioethanol production technologies are generally classified into five generations based on feedstock type and level of technological maturity, as presented in Table 1.

First-generation (1G) bioethanol, obtained from sugar- and starch-rich crops such as corn, wheat, barley, potatoes, rice, sugarcane, and sugar beet, still dominates global production, accounting for approximately 99% of the total output. On a global scale, around 60% of bioethanol is produced from corn, 25% from sugarcane, 3% from wheat, and 2% from molasses, with the remainder derived from other cereals, cassava, and sugar beet [9]. Due to well-established processing infrastructure and optimized fermentation technologies, 1G bioethanol has achieved full commercial worldwide deployment (TRL 9).

Second-generation (2G) bioethanol is based on lignocellulosic biomass, including agricultural residues, grasses, wood, forestry by-products, and waste paper. Although extensive research and pilot-scale development have been conducted, large-scale commercialization remains limited because of high pretreatment costs, energy requirements, and techno-economic constraints [4,8]. Within the EU, lignocellulosic ethanol represented only about 1% of total bioethanol production in 2021 [13], and current technological readiness is estimated at TRL 7–8, with only a few early commercial facilities in operation [14].

Third-generation (3G) bioethanol, produced from microalgae, macroalgae, and cyanobacteria, remains largely at proof-of-concept and laboratory scale (TRL 3–4). Fourth-generation (4G) concepts involve genetically engineered microorganisms, such as modified algae and cyanobacteria, designed to enhance carbon fixation and biofuel yields, but these approaches are still confined to scientific research [2,10]. The emerging fifth generation (5G) builds upon genome editing, metabolic engineering, and synthetic biology to develop optimized energy crops with altered cell wall composition and improved biomass

characteristics; however, these strategies remain at an early experimental stage and face technical as well as environmental and societal considerations [2].

Table 1 Technological readiness level (TRL) of five bioethanol generations [2,10,12]

Generation	Feedstocks	Advantages	Limitations	TRL
1G	Edible biomass: corn, sugarcane, sugar beet, wheat, barley, potatoes, cassava	• Technologically developed • Established industrial infrastructure • High conversion efficiency • Up to ~75% GHG reduction vs. fossil fuels • Valorized by products and waste streams	• Competition with food and feed supply • Intensive use of arable land and water • Indirect land use change (ILUC) concerns	TRL 9
2G	Lignocellulosic biomass: straw, agricultural residues, wood, forestry waste, paper waste, grasses	• Utilization of non-edible biomass • Reduced food-fuel competition • High resource availability • Valorization of waste streams	• Complex pretreatment required • High energy demand • Formation of fermentation inhibitors • Higher production costs	TRL 7–8
3G	Algal biomass: microalgae, macroalgae, cyanobacteria	• High photosynthetic efficiency • No competition for arable land • Potential CO₂ sequestration • Can be integrated with wastewater treatment	• Early-stage development • High cultivation and harvesting costs • Energy-intensive processing • Scale-up challenges	TRL 3–4
4G	Genetically engineered microorganisms (modified microalgae, cyanobacteria, yeast)	• Enhanced carbon capture • Improved photosynthesis and biomass productivity • Potential direct CO₂-to-fuel conversion	• Experimental stage • Biosafety and ecological concerns • Regulatory and public acceptance issues	TRL 1
5G	Genome-edited and metabolically engineered energy crops	• Optimized cell wall composition • Reduced pretreatment requirements • Higher sugar yields • Improved biomass quality	• Research phase • Ethical and societal considerations • Regulatory uncertainty • Long-term environmental impact not fully assessed	TRL 1

Across all generations, bioethanol development aims to strengthen sustainability by reducing greenhouse gas emissions, enhancing carbon sequestration, supporting rural economies, and improving energy security through the use of renewable biomass resources.

EFFICIENCY, SUSTAINABILITY, AND LIFE CYCLE ASSESSMENT

Assessing the sustainability of bioethanol production requires an integrated evaluation of greenhouse gas (GHG) emissions, energy efficiency, life cycle performance, and economic viability across feedstock types and process pathways. Life cycle assessment (LCA) studies widely confirm that replacing fossil fuels with bioethanol can significantly reduce GHG emissions, though the degree of reduction depends strongly on the type of feedstock and system boundaries used in the analysis [14,15]. For example, first-generation (1G) ethanol

from corn or sugarcane typically shows moderate reductions in life cycle GHG emissions relative to conventional gasoline, depending on assumptions regarding land-use change and energy inputs [16]. In contrast, lignocellulosic (2G) bioethanol has been shown to deliver much greater emission reductions through the use of agricultural residues and biomass energy recovery, with GHG savings often exceeding 80–90% compared to gasoline in optimized scenarios [2,17,18].

Recent LCA modelling based on operational cellulosic ethanol data demonstrates that advanced waste valorization strategies, such as combined electricity generation from lignin and biogas recovery, can reduce primary energy consumption by over 60% and cut life-cycle GHG emissions by up to 95% compared with baseline fossil-intensive systems [17,18]. However, third-generation (3G) pathways, including algal biomass, can sometimes exhibit relatively higher GHG emissions per unit energy due to high electricity and processing demands, underscoring the need for improved cultivation and conversion technologies [16,18]. Methodological choices in LCA (such as system boundaries, functional units, and coproduct allocation) also significantly influence reported outcomes, which highlights the importance of harmonized assessment frameworks for reliable comparisons [14,15].

Overall, the efficiency and long-term sustainability of bioethanol production are determined not only by the physicochemical properties of the feedstock but also by the integration and optimization of key processing stages, including carbohydrate hydrolysis, alcoholic fermentation, and downstream ethanol recovery operations such as distillation, rectification, and dehydration (absolutization) [19–21]. The selection of an appropriate bioconversion configuration directly affects energy demand, enzyme consumption, process economics, and environmental performance. Conventional strategies such as separate hydrolysis and fermentation (SHF) and simultaneous saccharification and fermentation (SSF) differ in operational complexity and resource utilization, while the development of simultaneous saccharification and co-fermentation (SSCF) enables the efficient co-utilization of sugar, improving carbon conversion efficiency and overall ethanol productivity [2,19–21].

CONCLUSION

Bioethanol plays a strategic role in achieving climate neutrality and renewable energy targets, particularly within policy frameworks such as the EU Renewable Energy Directive. Although first-generation bioethanol remains economically dominant, sustainable long-term expansion requires accelerated deployment of advanced lignocellulosic and algal technologies. Strengthening policy support, harmonizing life cycle assessment methodologies, and fostering investment in innovative processing technologies will be essential to ensure that bioethanol contributes effectively to decarbonization, energy security, and the development of a circular bioeconomy.

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REFERENCES

- [1] Li, J., Zhao, T., Xu, Y., *et al.* *Renew. Energy*. 2022, 188, 223–239.
- [2] Ghazali, M.F.S.M., Mustafa, M. *Energy Convers. Manag.* X. 2025, 26, 100933.
- [3] Renewable Fuels Association. Annual world fuel ethanol production, 2024. Available from: <https://ethanolrfa.org/resources/annual-industry-outlook>
- [4] Bušić, M., Marđetko, N., Kundas, S., *et al.* *Food Technol. Biotechnol.* 2018, 56(3), 289–311.
- [5] Tse, T.J., Wiens, D.J., Reaney, M.J.T. *Fermentation*. 2021, 7(4), 268.
- [6] Assaf, J.C., Mortada, Z., Rezzoug, S.A., *et al.* *Processes*. 2024, 12(5), 1001.
- [7] Hans, M., Lugani, Y., Chandel, A.K., *et al.* *Biomass Convers. Biorefin.* 2023, 13, 7423–7440.
- [8] Moonsamy, T.A., Mandegari, M., Farzad, S., *et al.* *Ind Crops Prod.* 2022, 188, 115675.
- [9] Hoang, T.D., Nghiem, N. *Fermentation*. 2021, 7, 314.
- [10] Zuliani, L., Serpico, A., De Simone, M., *et al.* *Processes*. 2021, 9(9), 1583.
- [11] Jain, S., Kumar, S. *Energy*. 2024, 296, 131130.
- [12] Kowalski, Z., Kulczycka, J., Verhé, R., *et al.* *Front Energy Res.* 2022, 10, 919415.
- [13] Flach, B., Lieberz, S., Bolla, S. *Biofuels Annual 2021*, European Union. Washington (DC): USDA Foreign Agricultural Service, 2021.
- [14] Vasilakou, K., Nimmegeers, P., Thomassen, G., *et al.* *Appl Energy*. 2023, 344, 121263.
- [15] Soleymani, A.T, Grzesik, K., Rödl, A., *et al.* *Energies*. 2021, 14(10), 2939.
- [16] Elliot, P.E. *Int J Energy Environ Sci*. 2025, 5(2), 1–6.
- [17] Patel, K., Singh, S.K. *Clean Technol Environ Policy*. 2023, 25(8), 2489–2510.
- [18] Zhai, J., Liu, P., Xiong, Q., *et al.* *Bioresour Technol.* 2026, XXX, 133506.
- [19] Vučurović, D., Bajić, B, Vučurović, V., *et al.* *Fermentation*. 2022, 8(3), 114.
- [20] Katanski, A., Vučurović, V., Vučurović, D., *et al.* *Fermentation*. 2024, 10(3), 144.
- [21] Vučurović, V., Katanski, A., Vučurović, D., *et al.* *Fermentation*. 2025, 11(2), 80.