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Advancing bioethanol: exploring feedstock diversity, production pathways, and environmental implications

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The depletion of finite fossil fuel reserves, coupled with the ever-growing global demand for energy, has raised significant concerns about the long-term sustainability of fossil fuel consumption. As these conventional energy sources become increasingly scarce, the need for viable alternatives has become more urgent. This pressing challenge has driven researchers, policymakers, and industries to explore and develop sustainable energy solutions that can reduce dependence on fossil fuels. Bioethanol, a sustainable substitute for gasoline, is produced globally, supporting economic growth in both developed and developing nations. It is derived from a wide range of feedstocks, including industrial waste and by-products like steel mill gases and glycerol from biodiesel production. Different bioethanol generations vary in technological readiness and environmental impacts, assessed using Life Cycle Assessment (LCA). This review explores the environmental consequences of different bioethanol production pathways, with a focus on advances in biotechnological methods. It also highlights the potential of lignin-rich biomass, which has been challenging to process but offers significant promise. The review underscores the importance of transparency in biorefinery LCA to fully understand the various environmental impacts. Additionally, it examines the role of genetic engineering, enzyme technologies, and government policies in promoting sustainable bioethanol production. Integrating bioethanol production with green chemistry and circular economy principles can strengthen its position in the bioeconomy, delivering long-term benefits to both the biofuel sector and society at large.

Sustainability spotlight

The transition to sustainable biofuels is critical to reducing dependence on finite fossil resources and mitigating climate change. This review highlights advancements in bioethanol production by exploring diverse feedstocks, including lignin-rich biomass and other industrial by-products, contributing to circular bioeconomy principles. The integration of genetic engineering, enzyme technologies, and green chemistry enhances process efficiency while minimizing environmental trade-offs. Transparent life cycle assessments (LCAs) are emphasized to ensure an accurate evaluation of sustainability metrics, including biogenic carbon storage. This work aligns with UN SDGs 7 (Affordable and Clean Energy), 12 (Responsible Consumption and Production), and 13 (Climate Action) by promoting renewable energy, resource efficiency, and reduced carbon emissions, fostering a more sustainable biofuel industry.

1. Introduction

Bioethanol, recognized as a renewable and sustainable biofuel, has garnered considerable attention as a viable alternative to fossil fuels in global efforts to mitigate greenhouse gas (GHG) emissions and combat climate change. As a biofuel, bioethanol is primarily produced through the fermentation of sugars derived from various feedstocks, ranging from food crops to agricultural residues and dedicated energy crops, with a technology readiness level (TRL) of 8–9.[1] The ongoing research into alternative feedstocks such as algae, genetically modified (GM) crops, industrial gas effluents, glycerol, and direct bioethanol-producing microbes, with TRLs ranging from 2 to 8, is evidence of the dynamic nature of bioethanol production.[1] The versatility of bioethanol production, coupled with its potential environmental benefits, positions it as a critical component of current and future energy needs. However, the production and utilization of bioethanol require careful assessment to ensure they deliver genuine environmental and economic advantages.

The selection of feedstocks is a crucial factor influencing the overall sustainability of bioethanol production. Feedstocks can be categorized into first-generation (*e.g.*, sugarcane, corn), second-generation (*e.g.*, lignocellulosic biomass (LCB), chitin, glycerol), third-generation (*e.g.*, algae and seaweed), and fourth-generation (GM feedstocks),[2–4] as summarized in the supplementary information (Table S1). Each type of feedstock presents unique advantages and challenges. For instance, while first-

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generation feedstocks are well-established and yield high bioethanol outputs, they often compete with food resources and may contribute to food insecurity.[5,6] Second-generation feedstocks offer greater sustainability potential since they use waste materials and non-food crops. However, their economic viability is hampered by the high costs of the processing technologies, which are still under development to reduce pretreatment expenses.[7–9] Dedicated energy crops under second-generation, explicitly grown for biofuel (biodiesel or bioethanol) production, have higher adaptability and biomass yield per hectare.[10–14] Examples include energy cane (sugarcane bred for higher fiber content), jatropha and camelina (oil-rich seeds for biodiesel, with remaining biomass for bioethanol), and grasses like napier grass, switchgrass, giant reed, and miscanthus, known for their high biomass yield and adaptability to various climates.[15] Third-generation feedstocks (summarized in Table S2 of SI) present a promising frontier due to their high yield potential and minimal land use, yet their commercial viability is still being explored.[16] GM feedstocks are developed to maximize bioethanol yields using advanced biotechnological techniques that reduce lignin content while maintaining or improving other key agronomic traits to boost carbohydrate content.[15,17] This innovation aims to enhance bioethanol production efficiency and economic viability, though it presents potential environmental risks if not managed according to proper protocols.[18,19] Other unconventional feedstocks, such as industrial gas effluents and glycerol from biodiesel production facilities, offer innovative opportunities for bioethanol production, contributing to a circular economy by reducing waste.[20,21]

Although there are many pathways suitable for different feedstocks for the production of bioethanol, making the proper selection is challenging due to various factors like regional availability, ease of processing, economic factors, yield, and TRL. Bioethanol yield from various feedstocks is typically evaluated using two different metrics. The first expresses yield as liters of bioethanol produced per ton of biomass feedstock (L ton^{-1}, as shown in Table 1), reflecting conversion efficiency and process performance. The second measures bioethanol output (generally in liters) per hectare of cultivated land (kL ha^{-1}, as shown in Fig. 1), which integrates conversion efficiency, process performance, and the crop's agronomic productivity. Further, assessing the overall impact of a production pathway on the environment, from raw material extraction to processing, distribution, use, and disposal of the product, is vital for selecting a bioethanol process. LCA is a detailed methodology used to assess the overall environmental impacts throughout a product's life.[22] In bioethanol production, LCA is instrumental in evaluating and comparing the environmental advantages and trade-offs of various feedstocks and production processes.[23] It involves analyzing energy usage, GHG emissions, land-use changes (LUCs), water consumption, and other environmental effects.[24,25] Using LCA, stakeholders can make informed choices regarding the most sustainable and efficient feedstocks and production methods.

While several studies have explored various feedstocks for bioethanol production and their environmental impacts through LCA, no study has comprehensively addressed both feedstocks and their life cycle analysis in a unified manner. For instance, Uppalapati *et al.*[37] focused solely on the LCA of sugarcane molasses, while Osman *et al.*[38] broadened their scope to bioenergy as a whole, leaving bioethanol-specific discussions incomplete. Moreover, newer and more sustainable feedstocks were not explored in these studies, creating a gap in the literature. Zhan *et al.*[39] analyzed the environmental impact of cassava-based bioethanol production, but their focus was limited to first-generation bioethanol and a specific geographic context. Bernstad Saraiva[40] reviewed LCA studies in biorefineries, focusing mainly on feedstock provision and system boundary issues without delving into specific bioethanol feedstocks. Jain *et al.*[1] examined various feedstocks across multiple bioethanol generations, highlighting their technological readiness and economic aspects, but neglecting environmental

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Table 1 A summary of the current status of the production of different generations of bioethanol. L: liter

Generation	Intermediate processing	Yield (L ton^{-1})	Cost (US$ per gal)	TRL	Ref.
First	Milling, enzymatic hydrolysis, fermentation, distillation	70–590	∼0.9	9	1 and 26–28
Second[a]	Route-1: pretreatment, enzymatic hydrolysis, fermentation, distillation Route-2: gasification, preconditioning, fermentation, distillation	40–350	∼1.5	8–9	1, 7, 28 and 29
Third	Cultivation, harvesting, lipid extraction, fermentation, distillation	70–660	—	4–6	1, 30 and 31
Fourth	Novel pretreatment, engineered microorganisms/substrates, fermentation	Data not fully established[b]	—	2–3	1

[a] Excluding unconventional feedstocks like glycerol. [b] Highly variable and depends on the specific genetic modifications and synthetic biology strategies employed. However, theoretical yields suggest improvements over previous generations.

impact. Liu *et al.*[41] presented an LCA review on waste-feedstock biorefineries with a broader focus on various biofuels, diverting attention from bioethanol production.

This study contributes significantly to the existing literature by addressing gaps in current reviews and providing a comprehensive overview of bioethanol synthesis. It critically evaluates various feedstocks for bioethanol production, considering their suitability, associated yields, processing technologies, and TRL. A distinctive feature of this review is the tabulated comparison of the key intermediate steps, namely hydrolysis and fermentation, which play a crucial role in bioethanol production. The review also highlights the latest advancements, efficiencies, and challenges in the bioethanol production landscape. It goes further by examining the economic and policy factors that are often overlooked in other reviews. In particular, it underscores the importance of policies that promote sustainable practices and provide consistent incentives to ensure the long-term viability of bioethanol as a renewable energy source. A significant emphasis of the study is placed on the environmental impacts of bioethanol production, assessed through LCA. This approach enhances understanding of the bioethanol production process and aids in making informed decisions for researchers, engineers, and policymakers working to advance bioethanol technologies.

The review is organized as follows: Section 1 introduces the topic, outlining the scope and objectives of the review on sustainable bioethanol production. Section 2 examines current bioethanol production technologies from various feedstocks, highlighting advancements and challenges. Section 3 provides a detailed analysis of LCA studies on bioethanol production, assessing environmental impacts and identifying key factors influencing sustainability. Section 4 explores the economics and policies related to bioethanol production, including cost analysis and supportive policy frameworks. Section 5 integrates the findings, offering insights and strategies to improve the sustainability of bioethanol production. Section 6 concludes the review, emphasizing the outcome of the review. Through a comprehensive analysis of bioethanol production from various feedstocks and their environmental impacts, this review seeks to advance the dialogue on sustainable bioenergy and guide the development of more sustainable bioethanol production practices.

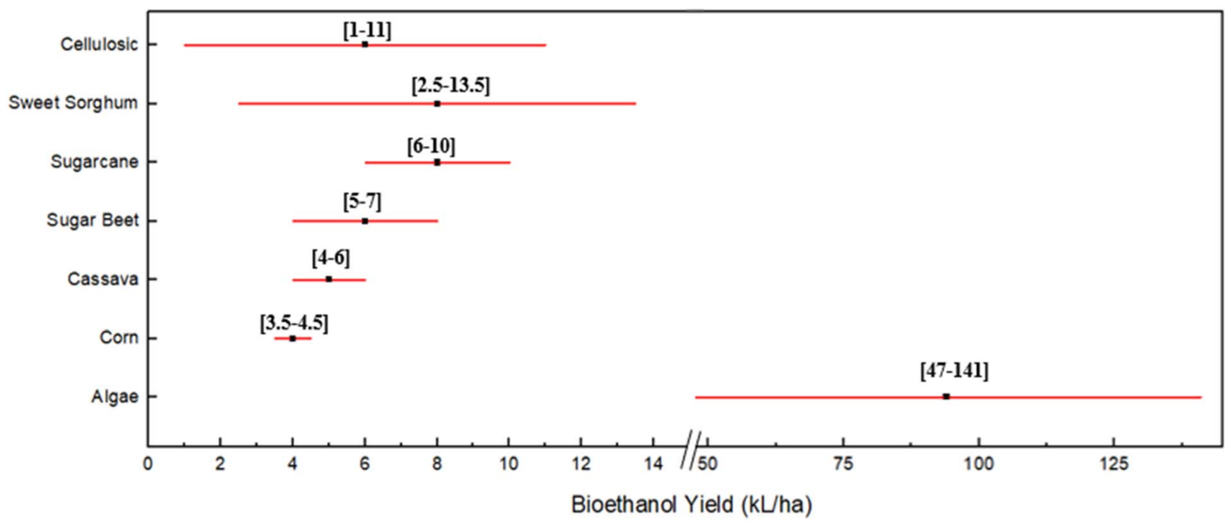

Fig. 1 Ethanol yield per hectare (this figure was drawn based on data provided in ref. 32–36).

2. Advancements in bioethanol production pathways

There are numerous feedstocks available for bioethanol production, as discussed in the supplementary information (Table S1). Various processing pathways can convert these carbon-rich feedstocks into bioethanol, as illustrated in Fig. 2. Typically, these feedstocks go through multiple processing stages, which depend on the biomass composition, including the weight percentages of carbohydrates, lignin, and other components such as ash, proteins, and oil, as well as the degree of polymerization of the carbon source. These include monosaccharides (such as glucose, mannose, fructose, rhamnose, galactose, and others), disaccharides (like sucrose, lactose, maltose, and cellobiose), oligosaccharides like *N*-acetyl-D-glucosamine, and polysaccharides (such as starch, cellulose, and hemicellulose). In recent years, various waste streams from industries,[42] including effluent gases[43] and atmospheric carbon,[44] have been explored for bioethanol production potential. This section examines the significant advancements in the pathways for converting different feedstocks into bioethanol.

2.1 Advancements in biochemical conversion pathways

Bioethanol production through biochemical pathways involves several key steps applicable to all four generations of biomass feedstocks. The key conversion steps in bioethanol synthesis are hydrolysis and fermentation, which include using biological enzymes and microbes under mild processing conditions to convert the substrate into desired products.[45] The primary cost involved with hydrolysis and fermentation is due to the microbes and enzymes used,[46] as the operating conditions are close to ambient. First-generation feedstocks, which include sugar-based feedstocks, contain readily available monomeric and dimeric sugars that can be fermented to bioethanol using either fungal or bacterial fermenting microbes.[47] However, starch-based crops require additional processing steps to extract the starch through wet or dry milling.[48] The extracted starch is then hydrolyzed using the enzyme amylase, followed by fermentation to produce bioethanol.[49,50] The byproduct streams from wet milling, dry milling, and oil crop processing (such as hulls, DDG, or oilcake) are rich in lignocellulosic content. They are, therefore, used as second-generation feedstocks.[14,51,52] However, their nutritional quality makes them more suitable as livestock feed.[53] Oil from the germ part of starchy crops and oil crops is transesterified into biodiesel,[54] and the byproduct stream (glycerol) has also been shown to have the potential for conversion to bioethanol,[55] thus being categorized as a second-generation feedstock.

Second-generation feedstocks require a crucial pretreatment step not needed for first-generation feedstocks.[7,56] These are generally categorized into four main types, with emerging innovations such as hybrid pretreatment and nanotechnology interventions (summarized in Fig. 3). The discussion about the

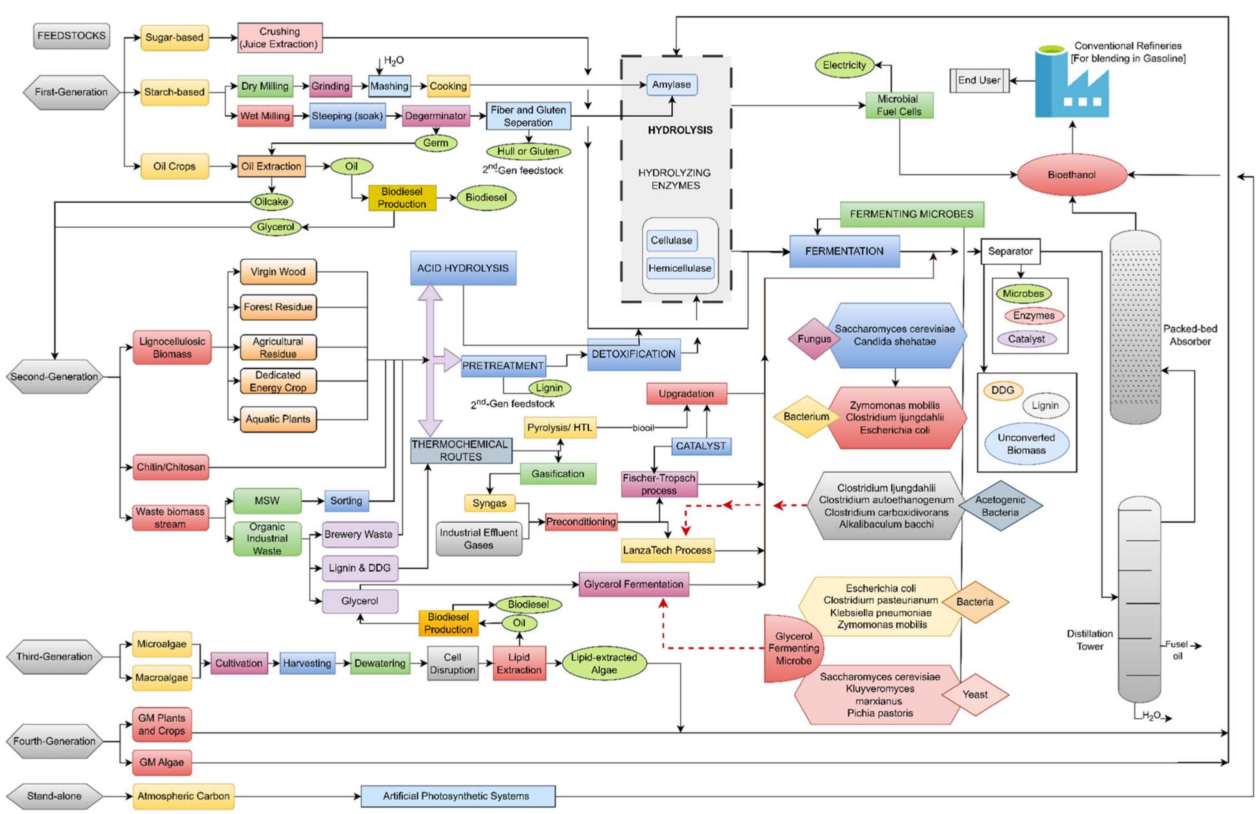

Fig. 2 Comprehensive overview of bioethanol production pathways from various raw materials. DDG: dry distillers' grains; GM: genetically modified.

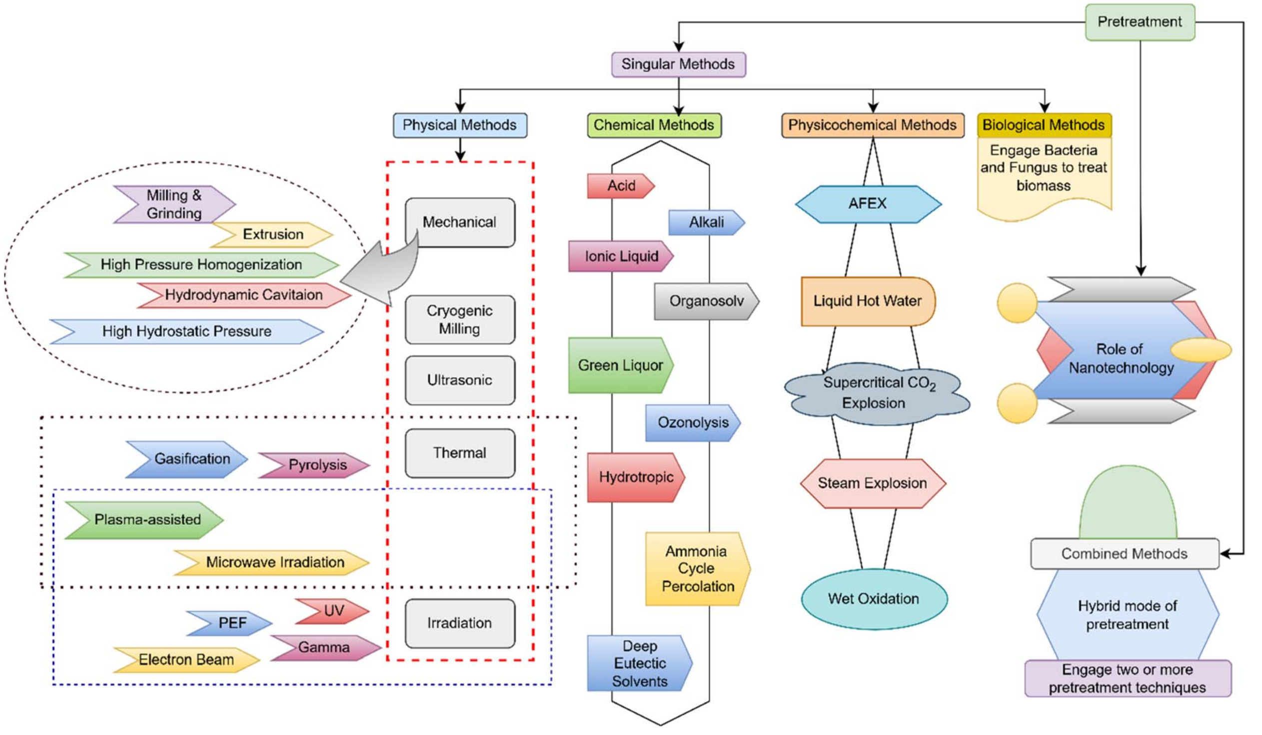

Fig. 3 Various pretreatment techniques for second-generation feedstocks. Reproduced from our previous work in *Sustain. Chem. Clim. Action*, 2024, **5**, 100053 (ref. 57) under a CC-BY license agreement.

pretreatment methods is beyond the scope of this review, but has been extensively covered in other studies.[57,58] Feedstocks such as LCB, chitin, chitosan, dry distillers' grains (DDG), oil-cake, and brewery waste undergo pretreatment to fractionate lignin and concentrate the cellulosic and hemicellulosic substrates.[59,60] This is followed by detoxification to remove toxicants such as hydroxymethylfurfural, acetic acid, and furfurals, which inhibit enzyme and microbial activity during hydrolysis and fermentation.[61,62] However, municipal solid waste (MSW) is initially sorted to gather only organic-rich material to ensure higher productivity and feed consistency.[63] The detoxified feed, from LCB or MSW, is hydrolyzed using cellulase and hemicellulase enzymes to convert cellulose and hemicellulose into fermentable sugars, followed by fermentation.[64,65] In some cases, acid hydrolysis is preferred over enzymatic hydrolysis for second-generation feedstocks,[66] followed by detoxification and fermentation, as depicted in Fig. 2.

Third-generation algal biomass feedstocks are grown in various open pond systems or more advanced photobioreactors, each with advantages and disadvantages.[67,68] After cultivation, the algae are harvested and dewatered, a process associated with high drying costs. Next, the cell walls are broken down to extract lipid content, leaving behind carbohydrate-rich feedstocks that are hydrolyzed and fermented.[69] However, the lipid fraction is used in biodiesel production, and the glycerol side stream is used for bioethanol production, similar to the case with oil crops. Genetically engineered plants, crops, and algae are designed to have high carbohydrate content and are classified as fourth-generation feedstocks. These can be hydrolyzed and fermented, producing higher bioethanol yields than previous generations.[18,70,71]

The various hydrolysis and fermentation pathways for bioethanol production, each with its own advantages and disadvantages, are shown in Table 2. Direct Fermentation (DF) is the most straightforward process with minimal processing steps, and it is best suited for first-generation sugar-based feedstocks.[72,73] Separate Hydrolysis and Fermentation (SHF) needs to be optimized for both hydrolysis and fermentation stages separately, and it takes a longer processing time.[109] Contrary to SHF, we have Simultaneous Saccharification and Fermentation (SSF), which reduces process time, is carried out in a single reactor, and potentially offers higher yields. Yet, it requires compatible enzymes and microbes, making it difficult to optimize both stages simultaneously.[75,80–82] Semi Simultaneous Saccharification and Fermentation (SSSF) is carried out in a single reactor for a set time for both hydrolysis and fermentation. However, SSSF gives a better yield than SSF, but the process control is more complex.[110] Solid-state Fermentation (SF) has low water requirements and is suitable for certain biomass types, but offers lower productivity.[85–87] Non-isothermal Simultaneous Saccharification and Fermentation (NSSF) optimizes temperature for each step, potentially increasing efficiency, but requires complex temperature control and higher energy.[111,112] Simultaneous Saccharification and Co-fermentation (SSCF) pathway is efficient for mixed sugar substrates, yielding higher bioethanol outputs.[88,90–93] Simultaneous Saccharification, Filtration, and Fermentation (SSFF) integrates filtration to reduce inhibitors, improving efficiency,

Table 2 Hydrolysis and fermentation (HnF) pathways utilized for different substrates from varied biomass sources for bioethanol production

Fermentation route	Feedstock	Overview	Pros	Cons	Ref.
DF	MDS & glycerol	Fermenting microbes directly convert the substrate to bioethanol	No complex hydrolysis step is needed	Substrate may inhibit microbes	72–74
SHF	PCs	PCs are hydrolyzed to MSs, followed by fermentation	HnF: operated individually at optimum conditions	Time-consuming and expensive; cellulase inhibition by sugars	75–79
SSF	PCs	Simultaneous HnF prevent sugar build-up and prevent cellulase inhibition	HnF carried out in a single reactor; better bioethanol yield	Operating reaction temperature may not be optimal for cellulase or yeast	75 and 80–82
SSSF	PCs	Similar to SSF with additional pre-saccharification using enzymes	Lower enzyme loading compared to SSF; pre-saccharification results in higher bioethanol yield	Higher operational complexity; longer process time	83 and 84
SF	PCs	Microbes thrive on solid, low-moisture substrates	No water required that reduces bacterial contamination and effluent generation; reduced space and energy requirements; consistent product formation	Smaller substrates hinder microbial growth due to limited aeration and heat dissipation	56 and 85–87
NSSF	PCs	Simultaneous hydrolysis (50 °C) and fermentation (30 °C) in separate reactors at respective optimals	Higher productivity, unlike isothermal SSF; requires fewer enzymes (30–40%) than SSF	Higher fixed capital cost compared to SSF	66, 81, 88 and 89
SSCF	PCs	Co-fermentation of xylose and glucose. Slow glucose release during hydrolysis maintains a high xylose/glucose ratio, compelling fermenting microbes to prioritize xylose consumption	Cost-effective as xylose is also converted to give high bioethanol yield; lowers inhibitory effect of xylose on fermenting microbes	Microorganisms will consume ample glucose in the broth, preventing co-fermentation	88 and 90–93
SSFF	PCs	Enzyme recycling post-filteration back to hydrolysis, while fermenting microbes are retained using flocculation and settling	Fermenting microbes and enzymes are reused; operates at optimum conditions; prevent enzymes inhibition, unlike in SSF	More complex than SSF due to an additional filtration step	89 and 94
CBP	PCs	Microbes directly convert biomass to bioethanol in a single reactor by releasing specific enzymes	Single microbe performs enzyme synthesis, along with HnF; enzyme inhibition by sugar is avoided; reduces capex and opex; no costly enzymes needed	Under research phase; lower process efficiency; GM of microbes could enhance productivity	92 and 95–98
VHG	MDS	Conventional process: normal to high sugar concentration. Here, >240 g L^{-1} sugar concentration is maintained (very high gravity)	High bioethanol yield (15 vol%) than conventional yield (<10 vol%); lower production cost, energy consumption, and effluents	Multiple stresses in yeast due to metal ions; yeast inhibition by product; lower pH below optimum; temperature rise	99–103
SGF	Syngas[a]	Wood–Ljungdahl pathway, employing acetogenic microbes under anaerobic conditions	Industrial exhausts rich in CO and H_2 can serve as feedstock; lower temperature and pressure requirement; tolerate sulfur in feed with no specific CO to H_2 ratio	Gas-liquid mass transfer resistance; lower productivity; microbes inhibition	104–108

[a] Typical composition: 30–60% CO, 25–30% H_2, 5–15% CO_2, and 0–5% CH_4; DF: direct fermentation; SHF: separate hydrolysis and fermentations; SSF: simultaneous saccharification and fermentation; SSSF: semi simultaneous saccharification and fermentation; SF: solid-state fermentation; NSSF: non-isothermal simultaneous saccharification and fermentation; SSCF: simultaneous saccharification and co-fermentation; SSFF: simultaneous saccharification, filtration, and fermentation; CBP: consolidated bioprocessing; VHG: very high gravity fermentation; SGF: syngas fermentation; MDS: monomeric and dimeric sugars; PCs: polymeric carbohydrates (*e.g.*, starch, hemicellulose, and cellulose); MSs: monomeric sugars.

but involves higher operational complexity and potential membrane fouling.[89,94] Consolidated Bioprocessing (CBP) is a novel approach to bioethanol production. It is the best example of process integration and optimization, combining enzyme production, biomass hydrolysis, and fermentation in a single step.[97] This integration reduces the need for added enzymes and pretreatment steps, significantly reducing costs and process complexity. However, it requires highly efficient and robust microbes that can streamline all three processes: enzyme production, saccharification, and fermentation.[92,95–98] Very High Gravity Fermentation (VHG) results in higher bioethanol concentrations, reducing distillation costs, but imposes higher osmotic stress on cells, demanding robust microbes.[99–103] Lastly, it is essential to study bioreactor configurations in bioethanol production as it allows the optimization of yield, productivity, resource efficiency, process stability, scale-up feasibility, economic viability, and product quality, all of which are critical for the success and sustainability of bioethanol production processes, summarised in the supplementary information (Table S3).

The bioethanol produced from microbial fermentation is a lean solution containing less than 10 vol% bioethanol in water, as high ethanol concentrations cause product inhibition to fermenting microbes during fermentation.[113] However, novel strains of fermenting microbes have been developed to tolerate higher ethanol concentrations.[114] Divate *et al.*[115] performed metabolic engineering on the yeast *Saccharomyces cerevisiae* and produced a strain that demonstrated tolerance to ethanol concentrations as high as 14 vol%, whereas the growth of the wild strain was inhibited at 6 vol%. Finally, the lean bioethanol solution is concentrated and purified through distillation and dehydration to achieve fuel-grade standards.[116] Table 3 provides the recent advancements in bioethanol production and their yield through various techniques and innovations.

2.2 Advancements in thermochemical conversion pathways

The thermochemical conversion of biomass to bioethanol is a two-step process involving high temperatures.[127] Initially, biomass is converted into gas or bio-oil, which is then transformed into bioethanol *via* fermentation[128] or catalytic synthesis.[129,130] Gasification, pyrolysis, and hydrothermal liquefaction are employed to gasify or liquefy the biomass.[127] In gasification, biomass is converted to syngas (a mixture of CO, H_2, and CO_2) by gasifying the raw material at high temperatures (500–1200 °C) with controlled oxygen and/or steam.[131] The raw syngas and industrial effluent gases from steel mills or refineries contain impurities and undergo deoxygenation, tar removal, particulate and sulfur compound removal, and compression.[3] In the next stage, direct gas fermentation (similar to the LanzaTech process[132]) uses acetogenic bacteria like *Clostridium ljungdahlii*,[105] *Clostridium autoethanogenum*,[133] *Clostridium carboxidivorans*,[134] *Butyribacterium methylotrophicum*,[135] and *Alkalibaculum bacchi*,[136] leveraging their unique metabolic pathways to convert syngas into bioethanol efficiently.[104–108] It is compared with other fermentation technologies (Table 2) that vary in process complexity, efficiency, and feedstock suitability. *Clostridium ljungdahlii* produced 198.76 liters of bioethanol per ton of syngas in a two-stage continuous fermentation process.[105] Alternatively, catalytic conversion involves passing cleaned syngas over a catalyst bed, typically composed of metals like copper, zinc, or their alloys supported on materials such as alumina or silica, including processes like Fischer–Tropsch synthesis[137] or catalytic methanol synthesis followed by methanol-to-ethanol conversion.[138] These versatile processes can utilize a variety of feedstocks, including LCB, MSW, and industrial byproducts such as DDG, lignin, or hulls. LanzaTech employs a proprietary strain of *Clostridium autoethanogenum*, genetically engineered to optimize the conversion of industrial waste gases (containing CO & CO_2) into bioethanol and valuable chemicals like 2,3-butanediol.[139] Ongoing research focuses on optimizing microbial and catalytic performance, improving yields, and enhancing the industrial viability of these processes to make bioethanol production more efficient and sustainable.

Another thermochemical conversion pathway is pyrolysis, which thermally degrades biomass without oxygen at temperatures between 400 and 600 °C, producing bio-oil, syngas, and char.[140] The bio-oil is then processed through catalytic upgrading or fermentation to produce bioethanol.[141] Similarly, hydrothermal liquefaction (HTL) converts wet biomass into biocrude oil using high pressure (200–350 bar) and moderate temperatures (250–350 °C) in the presence of water.[142] The biocrude is refined and catalytically upgraded to produce bioethanol, much like pyrolysis. Algal biomass, sewage sludge, and wet agricultural residues with high moisture content are particularly suitable for HTL, as they eliminate the need for costly drying, like in the biochemical conversion pathway.[143]

2.3 Advancements in non-conventional pathways

2.3.1 Microbial and chemical lignin degradation. Lignin presents a formidable challenge due to its diverse structure and resistance to degradation.[144] Nonetheless, recent advancements in biotechnological and chemical processes have significantly enhanced the efficiency of converting lignin into bioethanol. Certain microorganisms, including white-rot fungi like *Phanerochaete chrysosporium*[145] and *Trametes versicolor*,[146] bacteria such as *Pseudomonas putida*, and select species of Clostridium,[147] as well as various other genetically engineered microbes, have demonstrated the capability to degrade and/or metabolize lignin-derived compounds (either by thermal, chemical, or biological routes), such as aromatic substances, directly into bioethanol and other biofuels.[148,149]

Salvachúa *et al.*[147] recently showed that lignin with high molecular weight can be broken down into smaller oligomers and monomers using microbes' extracellular ligninolytic enzymes, such as laccases and peroxidases, through biological conversion pathways. Certain microbes can metabolize these lower molecular weight aromatic compounds (derived from lignin) and convert them into triacylglycerides,[150,151] or polyhydroxyalkanoates,[148] depending on the specific microbe. Triacylglycerides can be further processed into bioethanol, as discussed in other studies.[152,153] Several microbes, including

Table 3 Comparative analysis of bioethanol production from diverse biomass feedstocks: yields, methodologies, and innovations. SHF: separate hydrolysis and fermentation; SSF: simultaneous saccharification and fermentation

Raw material	Yield (L ton^{-1})	Methodology	Advancement/innovation	Ref.
Sorghum juice and sugarcane molasses	560[a]	Direct fermentation using yeast	Integrated biorefinery using a mix of juice and molasses	117
Water hyacinth	—	SSF without pretreatment	Bacterium or fungus-assisted fermentation without pretreatment	118
Soybean waste	550	Cell adhesion on soybean meal-coated (3D printed templates)	Recyclable 3D-printed systems; stable yields after 30 cycles of reuse	119
Oak	160	Steam explosion followed by SHF	Explored trade-offs between yields and pretreatment costs	120
Poplar	140			
Spruce	60			
Rice straw	300	Chemical pretreatment (H_3PO_4 and H_2O_2) followed by SHF	Mesophilic Aspergillus fungi showed high cellulase activity	121
Wheat straw	630	Acid hydrolysis, membrane-based acid recovery, fed-batch fermentation	Glucose yield (>90%) using fractional acid hydrolysis technology	122
Chitin	770[b]	Solid-state fermentation with *Pleurotus ostreatus*	Chitin to bioethanol and mushroom production	123
Glycerol	320	Direct microbial fermentation	Microbes from an anaerobic digester (wastewater treatment) convert glycerol to bioethanol	124
Kappaphycus alvarezii (red algae)	340	Fungal pretreatment followed by SHF	Fungal pretreatment increased sugar yields 2.3-fold and bioethanol yield by 38.23% at a lower cost	125
Genetically modified rice straw (Cesa7 mutant)	770[c]	Green liquor pretreatment followed by SHF	GM rice straw cellulose nanofibrils enhanced bioethanol yield and reduced production cost	126

[a] Bioethanol yield in L ton^{-1} of total reducing sugars in hydrolysate. [b] Theoretical yield. [c] Bioethanol yield in L ton^{-1} of cellulose obtained from rice straw.

Pseudomonas putida, *Rhodococcus opacus*, *Pseudomonas fluorescens*, and *Acinetobacter baylyi*, have shown potential for the valorization of lignin-derived aromatic monomers.[147,148,150,151,154] Zhao *et al.*[155] demonstrated that adding commercial laccase to degrade Kraft lignin into monomers, which were then consumed by *Rhodococcus opacus*, produced 145 mg of triacylglycerides per liter of solution. These ligninolytic microbes break down complex lignin substrates and catabolize the resulting monomers into target compounds such as bioethanol.

There are also chemical methods for processing monomeric lignin-derived compounds. Aromatic compounds can be transformed into cyclohexanol through hydrodeoxygenation, which involves reacting these compounds with hydrogen gas under controlled conditions, typically at temperatures between 100 and 250 °C and pressures of 10–50 atm, using catalysts.[156–159] Typical catalysts include metals like nickel (Ni), palladium (Pd), platinum (Pt), and ruthenium (Ru), which facilitate the hydrogenation of aromatic rings.[159] Once cyclic alcohols like cyclohexanol are produced, they are mixed with low-grade hydrous bioethanol for use in spark-ignition gasoline engines by combining gasoline, low-grade bioethanol, and cyclohexanol.[160–162] This oxygenated additive enhances performance and reduces emissions.[160] At the same time, biological methods tend to produce lower bioethanol yields from lignin due to less direct conversion. Chemical methods, while more efficient, often involve high energy demands and added complexity since they do not directly yield bioethanol.

2.3.2 Microbial glycerol fermentation. Glycerol ($C_3H_8O_3$), or glycerin, is a byproduct of biodiesel production resulting from the transesterification of triglycerides found in vegetable oils or animal fats.[163] Depending on its origin and purity level, glycerol may need pretreatment to remove impurities that could negatively impact fermentation, making it suitable as a feedstock for microbial processes.[164] Common microorganisms used are GM bacteria (such as *Escherichia coli*, *Clostridium pasteurianum*, *Klebsiella pneumoniae*, and *Zymomonas mobilis*)[74,165–167] and yeasts (like *Saccharomyces cerevisiae*, *Kluyveromyces marxianus*, and *Pichia pastoris*)[168–170] that possess the metabolic pathways necessary for efficient glycerol conversion into bioethanol. Genetic engineering has improved these microbes for better glycerol utilization and higher bioethanol production rates.[168] The choice of microbes depends on factors like substrate concentration, pH, temperature, and environmental conditions, all of which affect fermentation efficiency.[153] The process typically starts with glycerol being converted into pyruvate through glycolysis, followed by bioethanol production *via* specific fermentation pathways of the microorganisms.[171] Depending on the method and microbe used, byproducts like acetate, lactate, or succinate may also be generated, which can be processed or repurposed for other industrial uses to improve overall efficiency and sustainability.[172] Liu *et al.*[173] reported the highest bioethanol yield of 0.27 g g^{-1} of glycerol by engaging the *Pachysolen tannophilus* fermenting microbe. Khattab *et al.*[174] reported a bioethanol yield of 0.47 g g^{-1} of glucose and glycerol mixture by engaging engineered yeast *Saccharomyces cerevisiae*. Research continues to optimize these yields to make bioethanol production viable at the industrial level.

2.3.3 Microbial fuel cells (MFCs). Microbial fuel cells are bioelectrochemical systems that leverage microorganisms' catabolism to convert the chemical energy found in organic compounds into electrical energy.[175] In bioethanol production, MFCs offer an innovative approach by combining the microbial conversion of organic materials with electricity generation, all while minimizing GHG emissions.[176,177] These cells generate low to moderate electrical power, which is affected by microbial activity, substrate concentration, electrode design, and operating conditions.[177–179] The bioethanol yield from MFCs is influenced by how effectively microbes metabolizes substrates and the availability of appropriate feedstocks.[180–182] MFCs can utilize various organic substrates, including sugars like glucose, organic acids, and even ethanol.[183] For bioethanol production, LCB serves as an effective feedstock, which can be enzymatically broken down to release sugars that microorganisms in the MFC can then ferment into bioethanol. MFCs use microbial metabolism to oxidize organic compounds, releasing electrons that are transferred to an anode and generating an electric current.[184] At the cathode, these electrons combine with protons and an electron acceptor, such as oxygen, completing the electrochemical circuit and forming water or other reduced products.[185,186]

2.3.4 Artificial photosynthetic systems (APS). This cutting-edge method for bioethanol production is categorized as fourth-generation bioethanol production.[187] Unlike traditional algae cultivation and gas fermentation processes that rely on carbon-rich gas sources, this approach utilizes atmospheric CO_2 and H_2O.[188] These systems mimic natural plants, which convert sunlight into carbohydrates and lipids, but instead, they directly generate bioethanol. They consist of a carefully designed assembly of components housed in a reaction chamber known as photoelectrochemical cells (PECs) aimed at maximizing bioethanol yields.[189] Semiconductor materials like titanium dioxide serve as photocatalysts to capture sunlight and create electron–hole pairs.[190] These are enhanced by organic dyes or metal complexes that act as photosensitizers, efficiently absorbing light.[191–193] The solar energy harnessed by these components is then transferred to catalytic sites to drive reduction reactions. In PECs, the anode facilitates the oxidation of water to oxygen, while the cathode enables the reduction of CO_2 to bioethanol or other intermediates.[194] Specific enzymes and engineered microbes, which function as biocatalysts, are immobilized on the electrode surface to improve the selectivity and efficiency of CO_2 reduction to bioethanol.[195,196] This multi-step process involves creating intermediates like formate and carbon monoxide, which can be further converted chemically or biologically into bioethanol, often employing engineered microbes or specialized enzymes.[196]

3. Comparative life cycle assessment of various bioethanol generations

Several intermediate processing steps are required for bioethanol production, as discussed earlier. A comprehensive LCA is essential to evaluate and optimize the sustainability of bioethanol production, guiding future research, policy development, and industrial practices toward more sustainable bioenergy solutions. This assessment must encompass all stages of production, from cultivating feedstocks to their final use and disposal. This section reviews the life cycle impact of first and second-generation bioethanol production. The limited literature on third-generation biorefineries focuses on LCA for micro and macroalgae growth and non-energy applications.[197,198] When energy generation is considered using algal feedstock, it often focuses on biodiesel due to the higher lipid content.[199–201] Third and fourth-generation bioethanol production, at lower TRL, lacks substantial data on environmental impact. This section provides a holistic understanding of LCA, encapsulating different feedstocks and system boundaries related to those biorefineries.

Various feedstocks are compared using different environmental impact parameters across the entire value chain, product, or service, as shown in Tables 4 and 5. All values in the tables are based on the production of one kg of bioethanol (functional unit chosen). Many system boundaries exist, and we have limited ourselves to a few, expressly: cradle-to-gate (all emissions from feedstock production to the end product), cradle-to-grave (emissions from feedstock production, refining, and disposal after the product's end of life), and well-to-tank (emissions from raw material acquisition, biorefining, and distribution to storage fuel tanks). Users are free to choose the system boundaries during the LCA study. However, the cradle-to-grave approach considers most emissions, from raw material generation to disposal.[202] The newly emerging cradle-to-cradle approach is increasingly appreciated due to its emphasis on sustainable development.[203,204] It aims to create products and systems with positive environmental and societal impacts throughout their life cycles.[203] Unlike traditional linear cradle-to-grave systems, where products end up as waste, cradle-to-cradle systems strive for continuous cycles of use and reuse.[205,206] Products are designed to return safely to natural systems (biological nutrients) or be perpetually recycled as technical nutrients in industrial processes.[207]

When assessing the impact of a process on carbon emissions, factors like LUCs must be considered, as they can significantly affect results.[216] Dłuzewski *et al.*[217] note that LUCs can disrupt carbon stocks in soil and vegetation, increasing GHG emissions. LUC is further subdivided into two: direct LUC and indirect LUC.[208] Direct LUC occurs when land is shifted for feedstock production (*e.g.*, converting forests or grasslands), leading to higher CO_2 emissions than in the typical case of moving toward renewable energy sources from conventional petroleum.[218] Indirect LUC happens when bioethanol production causes food shortages, prompting deforestation to expand croplands and further increase emissions.[219] LCAs with narrow boundaries may overlook these global impacts. For second-generation bioethanol, it is crucial to allocate the environmental effects from cultivation, including fertilizer and pesticide use, before conducting an LCA.[220]

We have compared the three major categories of the environmental impact of biorefineries: ecosystem quality, human

Table 4 Comprehensive life cycle impact assessment of bioethanol production from first-generation feedstocks (functional unit = 1 kg of bioethanol). C-GT: cradle to gate; C-GRV: cradle to grave; W-T: Well to tank; SE: system expansion; En: energy; EC: economic; BC: biochemical conversion

(A) Environmental impact category		Corn	Corn	Cassava	Cassava	Sweet potato	Sweet sorghum	Sugar beet	Wheat	Sugarcane	Sugarcane
(A1) Ecosystem quality											
GWP (kg CO_2-eq.)	Short term	91.48	—	—	0.69–1.30	—	—	—	—	0.53	—
	Long term	88.95	0.21	0.25	—	2.53	0.21	1.29	1.26–2.04	—	0.64
Acidification potential (kg SO_2-eq.)	Freshwater	1.13×10^{-6}	4.60×10^{-3}	4.70×10^{-3}	—	8.30×10^{-3}	2.05×10^{-2}	3.26×10^{-3}		2.41×10^{-2}	1.07×10^{-2}
	Terrestrial	9.49×10^{-4}									
Eutrophication potential	Freshwater (kg PO_4-eq.)	2.6×10^{-3}	1.50×10^{-3}	1.70×10^{-3}	—	1.01×10^{-2}	4.30×10^{-3}	1.38×10^{-4}	—	5.57×10^{-5}	2.61×10^{-3}
	Marine (kg N-eq.)	1.31×10^{-2}						—		3.54×10^{-3}	—
Photochemical oxidant formation (kg ethylene-eq.)		7.34×10^{-1b}	7.60×10^{-3}	8.90×10^{-3}	—	6.70×10^{-3}	8.20×10^{-3}	1.46×10^{-4}	—	5.44×10^{-3b}	1.10×10^{-3}
Ozone layer depletion (kg CFC-11-eq.)		1.08×10^{-5}	—	—	—	—	—	2.40×10^{-7}	—	3.80×10^{-8}	4.26×10^{-8}
Ionizing radiation (kg U^{235} eq.)		8.69×10^{-6e}	—	—	—	—	—	—	—	4.59×10^{-7e}	3.14×10^{-7}
Land (m^2 year arable)	Transformation, biodiversity	2.40×10^{-2}	—	—	—	—	—	—	—	—	—
	Occupation, biodiversity	3.72	—	—	—	—	—	—	—	—	1.62
Water scarcity (m^3 world eq.)		11.94	—	—	—	—	—	—	—	—	—
(A2) Human health											
Freshwater ecotoxicity (kg 1,4-DB eq.)		—	—	—	—	—	—	2.09×10^{-2}	—	—	5.63×10^{-2}
Human toxicity potential (kg 1,4 DB eq.)	Cancer	2.04×10^{-5a}	1.07×10^{-2}	6.00×10^{-4}	—	4.60×10^{-3}	1.42×10^{-2}	2.85×10^{-1}	—	—	1.77×10^{-1}
	Non-cancer	1.34×10^{-5a}			—						
Particulate matter formation (kg PM 2.5 eq.)		5.49×10^{-2}	—	—	—	—	—	—	—	1.39×10^{-3}	—
(A3) Resources											
Abiotic depletion (kg Sb eq.)	Fossil and nuclear energy use	1222.45^{c}	—	—	—	—	—	9.32×10^{-3}	—	9.24×10^{-6}	2.06×10^{-3}
	Mineral resources use	6.93^{d}	—	—	—	—	—				
(B) System boundaries		C-GT	C-GRV	C-GRV	C-GRV	C-GRV	C-GRV	C-GT	W-T	C-GT	C-GRV
(C) Allocation methods		SE	SE	SE	SE	SE	SE	—	SE	En	EC
(D) Production pathway		BC	BC	BC	BC	BC	BC	BC	BC	BC	BC
(E) Ref.		208	209	209	210	209	209	211	212	213	214

[a] Reported in CTUh (Comparative Toxic Unit for humans). [b] Reported in kg NMVOC-eq. per kg bioethanol (NMVOC: Non-Methane Volatile Organic Content equivalent). [c] Reported in MJ deprived. [d] Reported in kg deprived. [e] 1 kg U^{235} = 80 011 kBq U^{235}.

Table 5 Comprehensive life cycle impact assessment of bioethanol production from second-generation feedstocks (functional unit = 1 kg of bioethanol). C-GT: cradle to gate; C-GRV: cradle to grave; SE: system expansion; En: energy; BC: biochemical conversion; TC: thermochemical conversion; eq.: equivalent; MSW: municipal solid waste

(A) Environmental impact category		Wheat straw	Switchgrass	Corn stover	Forest residue	MSW	Poplar			Bagasse
Blend		E100	E100	E100	E100	E100	E10	E85	E100	E100
(A1) Ecosystem quality										
GWP (kg CO_2-eq.)	Short term	0.87	0.84	1.14	0.23	0.14	0.246	0.125	0.096	0.24
	Long term	0.85	0.81	1.10	0.22	0.09	—	—	—	—
Acidification potential	Freshwater	7.98×10^{-9}	3.36×10^{-8}	3.97×10^{-8}	1.68×10^{-8}	1.27×10^{-8}	1.13×10^{-3}	5.3×10^{-3}	6.58×10^{-3}	7.09×10^{-3}
(kg SO_2-eq.)	Terrestrial	8.06×10^{-6}	3.64×10^{-5}	4.70×10^{-5}	1.42×10^{-5}	1.80×10^{-5}				
Eutrophication potential	Freshwater (kg PO_4-eq.)	2.99×10^{-5}	1.08×10^{-5}	1.76×10^{-5}	8.86×10^{-6}	-3.75×10^{-5}	1.63×10^{-4}	1.09×10^{-3}	1.38×10^{-3}	2.03×10^{-5}
	Marine (kg N-eq.)	7.95×10^{-5}	3.44×10^{-4}	4.95×10^{-4}	1.14×10^{-4}	2.57×10^{-4}	—	—	—	1.65×10^{-3}
Photochemical oxidant formation (kg NMVOC-eq.)		2.31×10^{-3}	8.14×10^{-3}	9.24×10^{-3}	9.67×10^{-3}	2.33×10^{-3}	0.166[e]	0.252[e]	0.273[e]	4.43×10^{-3}
Ozone layer depletion (kg CFC-11-eq.)		6.88×10^{-8}	5.73×10^{-8}	9.56×10^{-8}	5.47×10^{-8}	8.76×10^{-8}	3.07×10^{-8}	2.22×10^{-8}	2.00×10^{-8}	7.97×10^{-9}
Ionizing radiation (kg U^{235} eq.)		3.68×10^{-5}	3.24×10^{-5}	4.79×10^{-5}	2.17×10^{-5}	3.18×10^{-5}	—	—	—	2.21×10^{-7}
Land (m^2 year arable)	Transformation, biodiversity	1.50×10^{-4}	-5.99×10^{-3}	-2.06×10^{-3}	7.45×10^{-5}	-5.40×10^{-3}	—	—	—	—
	Occupation, biodiversity	0.11	0.06	0.04	0.01	−0.63				
Water scarcity (m^3 world eq.)		8.46	0.65	0.69	0.26	3.06	—	—	—	—
(A2) Human health										
Freshwater ecotoxicity (kg 1,4-DB eq.)		15 062.92[b]	15 069.82[b]	15 620.41[b]	6288.05[b]	6204.06[b]	2.43×10^{-3}	3.27×10^{-3}	3.55×10^{-3}	—
Human toxicity potential	Cancer	1.16×10^{-7}[a]	6.52×10^{-8}[a]	7.16×10^{-8}[a]	2.68×10^{-8}[a]	3.93×10^{-8}[a]	1.40×10^{-2}	1.90×10^{-2}	2.10×10^{-2}	—
(kg 1,4 DB eq.)	Non-cancer	2.83×10^{-7}[a]	1.59×10^{-7}[a]	1.66×10^{-7}[a]	2.09×10^{-7}[a]	6.79×10^{-8}[a]				
Particulate matter formation (kg PM 2.5 eq.)		3.01×10^{-4}	5.53×10^{-3}	5.71×10^{-3}	2.06×10^{-3}	1.81×10^{-3}	—	—	—	2.41×10^{-4}
(A3) Resources										
Abiotic depletion (kg Sb eq.)	Fossil and nuclear energy use	3.74[c]	7.84[c]	11.53[c]	3.87[c]	12.73[c]	1.58×10^{-3}	7.21×10^{-4}	4.55×10^{-4}	1.64×10^{-5}
	Mineral resources use	1.73×10^{-2}[d]	2.10×10^{-2}[d]	2.40×10^{-2}[d]	7.28×10^{-3}[d]	1.32×10^{-2}[d]				
(B) System boundaries		C-GT	C-GT	C-GT	C-GT	C-GT	C-GRV	C-GRV	C-GRV	C-GRV
(C) Allocation methods		SE	SE	SE	SE	SE	SE	SE	SE	En
(D) Production pathway		BC	BC	BC	TC	BC	BC	BC	BC	BC
(E) Ref.		208	208	208	208	208	215	215	215	213

[a] Reported in CTUh (Comparative Toxic Unit for humans). [b] Reported in CTUe (Comparative Toxic Unit for ecosystem). [c] Reported in MJ deprived. [d] Reported in kg deprived. [e] Reported in g ethylene eq. per kg bioethanol.

Table 6 Comparative analysis of different feedstocks.[256–266] GM: genetically modified; MSW: municipal solid waste

Severity	Low to negative	Low	Low to moderate	Moderate	High
Colour scheme					

Feedstock	Bioethanol yield (kL ha^{-1})	GHG emissions	Energy consumption	Water usage	Land use	Ref.
First-generation						
Sugarcane	5.9–9.9					227 and 256
Corn	3.8–4.2					227, 257 and 258
Second-generation						
Syngas	Variable[a]					3 and 227
Lignocellulosic biomass	1–11					32, 33, 227 and 259–261
MSW[c]	—					227 and 259
Third-generation						
Algae[f]	47–141					33, 227 and 262
Fourth-generation						
GM feedstock	Variable[d]					263
Non-traditional						
Effluent gases	Variable[b]					264
Glycerol[e]	Variable[b]					265
Synthetic biology approaches	Variable[b]					266

[a] Depends on feedstock and gasification efficiency. [b] Depends on microbes/process involved based on their conversion efficiency. [c] Energy consumption is high due to additional sorting step. [d] Due to variable carbohydrate content. [e] Byproduct of oil crop to biodiesel production. [f] GHG emissions can vary significantly as shown in Fig. 4, but mainly it lies on the lower to negative side.

health, and resources. The occupational land use is significantly higher for first-generation feedstocks used in bioethanol production compared to second-generation feedstocks. Corn, first-generation feedstocks require 3.72 m^2 year of arable land per kilogram of bioethanol, which is more than twice that of sugarcane (Table 4). This is consistent with the fact that bioethanol yield from corn is almost half that of sugarcane (Table 6), making sugarcane more efficient in terms of arable land use for bioethanol production. However, the global warming potential (GWP) is higher for sugarcane-based bioethanol than corn-based bioethanol (Table 4). GWP, measured in CO_2 equivalents, reflects the potential of gases to cause global warming over a specified period, typically 100 years.[221] As shown in Tables 4 and 5, GWP is generally higher for first-generation feedstocks than second-generation feedstocks. Nevertheless, certain food-based feedstocks have exceptionally high bioethanol yields and thus exhibit a lower GWP, such as 0.21 kg CO_2-equivalent per kilogram of bioethanol from corn,[209] which is significantly lower than corn stover's 1.4 kg CO_2-equivalent.[208] While the short-term effects of switching from conventional gasoline to renewable bioethanol are immediately noticeable within a decade, long-term GWP considers impacts over 100 years or more. Over the long term, renewable resources exhibit lower GWP and can contribute to environmental mitigation by reducing carbon emissions.[222]

The acidification potential from synthesizing one kilogram of bioethanol is higher with first-generation feedstocks, primarily due to the use of fertilizers and pesticides during crop cultivation.[38] This potential is measured in SO_2 equivalents, reflecting the cumulative effect of all acids released as if they were specific amounts of SO_2, detailed in Tables 4 and 5. Similarly, the eutrophication potential, which denotes nutrient overloading in water bodies causing excessive growth of aquatic plants and algae, ranges from 10^{-5} to 10^{-1} kg PO_4-eq. (phosphate equivalent) for freshwater and kg N-eq. (nitrogen equivalent) for marine water.[213] Alongside these, environmental impact indicators like photochemical oxidant formation potential (measured in kg NMVOC-eq. or kg ethylene-eq.), ionizing radiation potential (measured in kg U^{235} eq.), and ozone layer depletion potential (measured in kg CFC-11-eq.) also vary between first and second-generation bioethanol (Tables 4 and 5). These impacts are more pronounced in first-generation feedstocks due to the larger agricultural inputs required, contributing significantly to acidification and eutrophication. Nitrogen-based fertilizers, in particular, can lead to nutrient loading in water bodies.[223] First-generation bioethanol production involves energy-intensive methods, often relying on fossil fuels for heat and power, leading to higher emissions of pollutants such as SO_2, NO_x, and VOCs, contributing to ground-level ozone formation.[224] Additionally, the expansion of agriculture for first-generation feedstock can lead to LUCs, including deforestation, impacting air quality, biodiversity, and carbon emissions.[219] Conversely, second-generation bioethanol technologies, such as enzymatic hydrolysis and fermentation of LCB, are more efficient and have lower energy requirements.[57] They often use marginal lands or agricultural residues, reducing competition with food crops and minimizing environmental impacts.[225] The transition from first to second-generation bioethanol production aims to mitigate these impacts while ensuring sustainable biofuel production. Moreover, cultivating high water-intensive crops like sugarcane and corn for first-generation bioethanol can exacerbate water scarcity, affecting ecosystem quality.[226]

Human health is also a significant consideration in bioethanol production from various feedstocks. Each feedstock involves processing units that use chemicals or produce by-products impacting the ecosystem, leading to freshwater ecotoxicity and human toxicity, ranging from 10^{-3} kg to 10^{-1} kg, and 10^{-8} kg to 10^{-1} kg 1,4-dichlorobenzene equivalents, respectively (Tables 4 and 5). Additionally, particulate matter (PM-2.5) emissions, ranging from 10^{-4} to 10^{-1} kg PM-2.5-equivalent per kg of bioethanol produced, pose risks, especially during the production of first-generation feedstocks, engaging transportation, ploughing, and harvesting.[213] Moreover, the production process affects abiotic resources (non-living natural resources), including minerals and energy resources like nuclear and fossil fuels, typically expressed in kilograms of antimony (Sb) equivalent per kilogram of bioethanol produced.[208] This category considers the extraction and depletion of various minerals and metals used in production processes, required energy generation, and bioethanol-related infrastructure. Abiotic depletion potential (ADP) is generally higher in first-generation bioethanol due to the intensive use of non-renewable resources such as fossil fuels, fertilizers, and minerals during feedstock cultivation, processing, and infrastructure development (Tables 4 and 5). In contrast, second-generation bioethanol, focusing on non-food biomass and advanced production technologies, tends to have a lower ADP by minimizing the depletion of abiotic resources and promoting sustainable resource management practices.

Furthermore, there are concerns about the actual environmental benefits of dedicated feedstocks. For example, an LCA study found that China's corn bioethanol and soybean biodiesel GWP was 40% and 20% higher than fossil petrol and diesel, respectively. This difference is mainly due to heavy fertilizer use, high energy consumption during processing, and China's reliance on coal-based energy.[227] However, using renewable energy for processing and adopting sustainable farming practices, like no-till farming and crop rotation, can help reduce emissions.[228] Additionally, higher-yielding crops can reduce the land needed for the same bioethanol production.[229] Non-traditional feedstocks, such as glycerol, industrial waste gases, and GM crops, possess significant potential for reducing GHG emissions.[230,231] Thus, the improved efficiency of the production processes and the co-product utilization can offset emissions and improve overall sustainability.

A comprehensive LCA study by Muñoz *et al.*[232] compared bioethanol production from various feedstocks, including sugarcane, maize, sugar beet, and wheat, across different regions. The cradle-to-gate approach had much lower GHG emissions of 0.7 to 1.5 kg CO_2-eq. per kg of bioethanol compared to both cradle-to-grave of 1.3 to 2 kg CO_2-eq. and fossil-based ethanol of 1.3–3.7 kg CO_2-eq. Moreover, maize stover in the USA (GWP: 1.25) and sugar beet in France (GWP: 1.27) were found to have the lowest impact from a GHG emission perspective, although when other impact categories were considered, trade-offs were encountered. Jeswani *et al.*[227] carried out an in-depth analysis of the environmental impact of producing different types of liquid biofuels, including bioethanol. Their findings indicated that, when LUC is excluded, first-generation biofuels generally emit fewer GHGs than conventional fossil fuels.[227] However, for the majority of feedstocks, the achieved emission reductions did not meet the 60% GHG savings threshold required by the European Union's Renewable Energy Directive (RED).[227,233] In contrast, second- and third-generation biofuels demonstrated a stronger capability to cut emissions, provided that no LUC takes place. The authors also emphasized that reductions in GHG emissions are frequently offset by increase in the other environmental impacts such as acidification, eutrophication, depletion of water resources, and loss of biodiversity.[227] For first-generation bioethanol, the GWP without accounting for LUC was found to range between 0.08 and 4.4 kg CO_2 eq. per kg of bioethanol produced (Fig. 4(a)). Among all the feedstocks analyzed, only sugarcane-based bioethanol achieved the 60% GHG reduction target set by the RED compared to fossil fuels (4.3 kg CO_2 eq.). This superior performance arises from sugarcane's relatively high crop yield, lower dependency on chemical fertilizers and pesticides, and the additional carbon credits gained from co-generated electricity within integrated biorefineries.[227] Nevertheless, when LUC impacts were considered, none of the first-generation pathways achieved the RED target.[227] In contrast, the second-generation pathways revealed a wider spectrum of GWP values (−3.1 to 4.7 kg CO_2 eq.), depending heavily on both the feedstock used and the processing technology applied (Fig. 4(a)). These advanced systems often utilise lignin byproducts as a source of electricity or as value-added products, which helps offset GHG emissions, sometimes even resulting in carbon-negative balances (Fig. 4(b)). For third-generation biofuels, the variability was even more pronounced, with reported

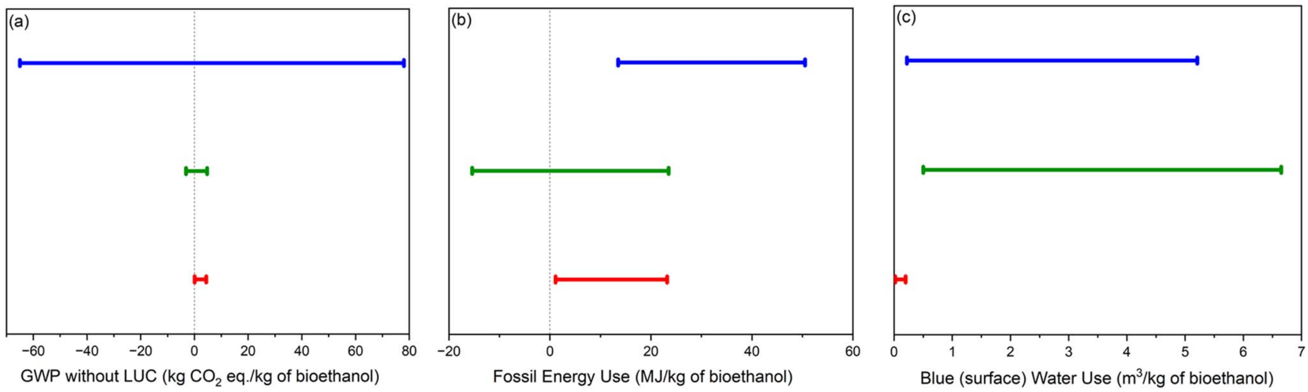

Fig. 4 Comparative life cycle impact ranges for (a) first-generation (red), (b) second-generation (green), and (c) third-generation (blue). Functional unit: 1 kg of bioethanol (this figure was drawn based on data provided in ref. 227). GWP: global warming potential; LUC: land-use change.

GWP values ranging from −65 to 78 kg CO_2 eq. (Fig. 4(a)). This broad variation stems largely from inconsistent methodological boundaries, differences in feedstock cultivation assumptions, nutrient inputs, and treatment of co-products across studies.[227]

Although second- and third-generation bioethanol pathways generally exhibit lower GWP than fossil fuels, their production is substantially more water-intensive, requiring approximately 55 to 246 times more water than fossil fuel production Fig. 4(c), which typically consumes about 3.5–8.5 liters per kilogram of gasoline.[234,235] Water use in bioethanol production varies widely with regional climatic conditions and irrigation practices, ranging from as low as 20 to 200 liters per kilogram of first-generation bioethanol in rain-fed systems Fig. 4(c). In contrast, corn-based bioethanol produced under intensive irrigation conditions, such as in Portugal, can require exceptionally high water inputs of around 2320 liters per kilogram of bioethanol.[235] Bioethanol production, regardless of generation (first to fourth), also poses significant threats to biodiversity. Large-scale cultivation of biofuel crops can cause habitat loss, soil and water pollution through nutrient runoff, and, in some cases, promote invasive species.[236–238] Intensive agricultural practices and heavy agrochemical use for first-generation feedstocks represent direct hazards to local flora and fauna.[236,239,240] The conversion of forests or other ecosystems into croplands for biofuel production further amplifies biodiversity loss by destroying wildlife habitats.[227,241] Compared to first-generation fuels, second-generation biofuels generally exhibit fewer negative ecological effects and may, under specific conditions, even enhance biodiversity.[1,227] Lignocellulosic crops, which typically require minimal fertilizers and pesticides and grow over longer cycles, can promote more sustainable land use, especially when cultivated on degraded or marginal land.[242–244] Utilizing agricultural residues or forestry byproducts as biofuel feedstocks generally causes less disturbance to ecosystems; however, excessive removal of such residues may deplete organic matter, disturb wildlife habitats, and increase herbicide use by encouraging weed proliferation.[245–247] The ecological consequences of third-generation (algal) biofuels are still uncertain. Algal cultivation could pose serious threats to coastal biodiversity by introducing invasive algal species into sensitive ecosystems such as mangroves, coral reefs, seagrass beds, and mudflats.[227] Accurately quantifying biodiversity loss remains difficult due to the absence of standardized methods for assessing biofuel-related ecological changes. Overall, although biofuels can substantially reduce GHG emissions relative to fossil-based fuels, these benefits are often counterbalanced by other environmental drawbacks. For instance, first-generation bioethanol has been shown to possess up to three times greater acidification potential and between three and twenty times higher eutrophication potential than fossil fuels.[227]

Neto *et al.*[248] highlighted several industrial initiatives that convert effluent gases into bioethanol *via* fermentation, with LanzaTech emerging as a key leader. Large-scale facilities producing approximately 46 000 and 125 000 tons of bioethanol annually have been established in China and Europe, respectively, utilizing steel mill off-gases as carbon sources.[248] LCA studies indicate that the environmental performance of syngas fermentation is highly dependent on both the feedstock origin and the extent of process integration.[249,250] Comparative studies suggest that when syngas is derived from waste gases or biomass residues, and when energy recovery systems are incorporated, the overall impacts can be comparable or even superior to conventional biomass-to-biofuel pathways.[251,252] For MFCs and APS, LCAs consistently identify the electricity mix and the choice of reactor materials (such as electrodes and membranes) as the most influential factors. Under scenarios using renewable electricity and optimized system design, these technologies can achieve significantly reduced or even net-negative GHG emissions for certain products.[253,254] In contrast, reliance on grid electricity and current pilot-scale materials often results in higher impacts than traditional production methods.[255] Moreover, pilot-scale assessments emphasize that unrecovered off-gases and inefficient resource utilization can substantially increase environmental burdens unless effective capture or reuse strategies are implemented.[254]

After thoroughly examining the environmental impact parameters in Tables 4 and 5, Table 6 presents an in-depth comparative analysis of diverse feedstocks used in bioethanol production. This analysis considers the yield and environmental effects to assess their sustainability. As shown in Table 6, the bioethanol yield is high in the case of first-generation feedstocks. Still, it has significant environmental impacts due to intensive agricultural practices and high water and energy consumption, leading to high GHG emissions. Second-generation feedstock utilizes waste materials and non-food crops, lowering environmental impacts compared to first-generation feedstocks. Third-generation also has higher yield potential with minimal land use requirements. The algal feedstocks possess tremendous potential for future scalability with advancements in cultivation and processing technologies. Fourth-generation feedstocks utilize advanced biotechnological approaches to improve efficiency and sustainability. The yield and environmental impacts vary significantly depending on specific genetic modifications and synthetic biology strategies. These are in early-stage development, having TRL 2, with the potential for significant future advancements.[1] Lastly, the fermentation of non-traditional industrial effluents offers solutions to cut down GHG emissions by sequestrating carbon right at its source, producing bioethanol. It lowers environmental impacts by utilizing GHGs as a feedstock. Integrating it with the iron and steel industries can help in significant ecological mitigation.

4. Economic and policy considerations

The global push towards sustainable energy solutions has brought bioethanol to the forefront of renewable fuel alternatives, influenced by economical, technological, policy framework, and environmental factors.[267,268] Feedstock availability and cost are crucial determinants of its economic feasibility. First-generation feedstocks, such as corn and sugarcane, dominate bioethanol production due to their high fermentable sugar content.[269] Corn, with costs typically ranging from 130 to 350 US$ per ton,[270] accounts for approximately 95% of bioethanol production in the United States.[271] However, their use raises concerns about food competition and environmental impacts.[272] Second-generation feedstocks derived from LCB offer a more sustainable option, although production costs remain high, *i.e.*, ~1.5 US$ per liter of bioethanol.[28] Technological advancements have significantly enhanced the efficiency and cost-effectiveness of bioethanol production. Innovations in pretreatment, enzymatic hydrolysis, and consolidated bioprocessing have improved conversion efficiency and reduced costs (up to 25%).[57,268,273] Genetic engineering of microbial strains has further boosted bioethanol yields and tolerance, making bioethanol production more commercially viable.[274]

The economic viability of bioethanol is tied to market dynamics such as fluctuating oil prices, government subsidies, and renewable fuel demand.[275] Policy instruments like the U.S. Renewable Fuel Standard have increased demand,[272,276] contributing to a growing global market, projected to expand from US$ 83.4 billion in 2023 to US$ 114.7 billion by 2028.[277] However, oil price volatility and inconsistent policies (such as changes in the U.S. biofuel policy) remain a challenge.[278,279] Thus, policy frameworks play a pivotal role in the bioethanol industry. Initiatives like the EU's Renewable Energy Directive (RED II) set ambitious renewable energy targets (aiming for a 14% share by 2030 (ref. 280)), while tax incentives and subsidies encourage investment. However, inconsistencies in policies, particularly in emerging economies like India and China, pose challenges. For example, the consumption of fuel ethanol in these countries remains considerably lower than that of gasoline. To illustrate, in 2022, the market penetration of fuel ethanol in India was approximately 5.1 billion liters, with a forecast to reach around 6.2 billion liters in 2023. In contrast, the gasoline market penetration was projected to increase to 53 billion liters in the same year, nearly ten times higher than fuel ethanol.[281] This disparity underscores the need for targeted policies to expand bioethanol consumption in these regions.

Supportive public policies have been key to boosting bioethanol's cost competitiveness. The Proálcool program, launched in Brazil in 1975 to promote energy self-reliance, combined blending mandates, concessional financing, and infrastructure investments that encouraged large-scale bioethanol production.[282,283] Productivity increased dramatically (from ~2.4 to ~5 kL ha^{-1}) through improved crop varieties, efficient field management, and the reuse of stillage as fertilizer, leading to an average cost reduction of 3.5% per year between 1976 and 1994.[282] Goldemberg[284,285] estimated that combined savings from both agricultural and industrial improvements could further reduce bioethanol costs by 23%.[282] However, the withdrawal of public investment and subsidies in 1984 caused bioethanol-powered car sales to fall sharply from 94.4% to 51% of total vehicle sales.[282] In response, the government introduced new incentives to revive production, and by 1991, annual bioethanol vehicle output had doubled from 0.7 million to 1.4 million cars, reaffirming Brazil's global leadership in bioethanol development.[282] Chen *et al.*[286] found that technological improvements reduced overall bioethanol costs from sugarcane by 67% with a reduction of >70% in processing cost, stressing that factors like market competitiveness, economies of scale, and learning-by-doing are significantly shaped by policy measures.

In the U.S., the Renewable Fuel Standard (RFS) and accompanying tax credits spurred capacity expansion and process improvements, boosting bioethanol production and consumption nearly tenfold between 2002 and 2019.[287] Annual blending mandates and tradable Renewable Identification Numbers (RINs) reduced market uncertainty, attracting private investment, while learning-by-doing improved efficiency despite corn price fluctuations.[288–290] McPhail *et al.*[291] found that eliminating U.S. federal tax credits and tariffs would reduce bioethanol production by 18.6% and lower corn prices by 14.5%, underscoring that policy support rather than market forces alone has been a key driver of price and production dynamics of bioethanol. However, when gasoline prices exceed $3 per gallon, bioethanol production remains profitable without policy support, allowing output to rise from 6.5 to 14 billion gallons and corn prices to stabilize near $4 per bushel.[291] Timilsina and Shrestha[292] assessed the impacts of biofuel expansion on global

Table 7 Bioethanol policies: year, provisions, impact[a]

Nations	Policy	Year	Provisions/features	Impact	Remarks	Ref.
USA	Renewable Fuel Standards (RFS)	2007	Mandated annual renewable fuel volumes and blending; tradable RINs; tax credits	Increased bioethanol production and private investors	Updated annually	272, 276, 287–290 and 302
Brazil	Proálcool	1975	Energy self-reliance; blending mandates; concessional financing; infrastructure investments	Rapid industry build-out; cost-cutting due to improved farming; ethanol-based vehicles	Reduced oil import; long legacy as frontier in bioethanol	282 and 283
Brazil	RenovaBio	2017	Market for carbon-intensity certificates; efficiency certification for producers	Attracted investment; incentivised low-carbon bioethanol	Improved sustainability metrics	303 and 304
EU	Renewable Energy Directive	2009	Binding renewable energy targets; tax incentives; subsidies	Increased investment in low-carbon fuels; higher research funding for advanced and waste-derived bioethanol	Proactive updates on targets and ILUC rules	280 and 294–298
China	Bioethanol policy	2001	Pilot E10 rollouts; fuel-grade bioethanol standards; production and quality regulation	Scale-up of pilot plants; regional blending trials	Still in place	305
India	National Policy on Biofuels (NPB)	2018	Bioethanol from surplus/damaged grains; blending targets; stopped import and export of biofuels	Rapid blending growth; spurred 2G biorefinery growth in integration with petroleum refineries	Government procurement and support	1 and 306

[a] RIN: renewable identification numbers; ILUC: indirect land use change.

food prices, summarizing studies that projected increases of 23–72% for maize, 8–30% for wheat, 18–76% for oilseeds, and 11.5–66% for sugar under planned biofuel expansion scenarios by 2020. They further noted that the 2007–2008 food crisis was partly driven by the rapid growth of first-generation biofuel production.[292] In 2008, Rosegrant *et al.*[293] concluded that restricting biofuel production from food-based feedstocks could lower maize prices by 6% by 2010 and 14% by 2015, with smaller reductions for other crops, while a global moratorium could further decrease prices of maize, cassava, sugar, and wheat by 20%, 14%, 11%, and 8%, respectively. In the EU, RED II enhanced cost competitiveness through sustainability certification and technology differentiation, granting compliance credits and preferential market access to low-carbon fuels.[294–297] This boosted investor confidence and funding for advanced and waste-derived bioethanol.[298] Emerging economies like India and China adopt hybrid models with blending targets (E10–E20), concessional financing, subsidies, and infrastructure grants, and raising rural incomes *via* agricultural residues.[299–301] These examples show how early-stage policy interventions can offset high capital costs and accelerate industry development. Table 7 provides a consolidated overview of the various policies along with their corresponding summaries.

So in a nutshell, policy frameworks have made bioethanol economically viable through three synergistic mechanisms: (i) demand creation, (ii) cost mitigation, and (iii) market differentiation. Demand was driven by blending mandates and volume targets, ensuring stable markets, lowering investor risk, and encouraging capacity growth. Cost reduction involved subsidies, concessional loans, and R&D support to foster technological learning and economies of scale. Market differentiation rewarded renewable markets *via* sustainability certifications like RED II and RFS.[307,308] Together, these measures have closed the cost gap with fossil fuels while delivering social and environmental benefits, including rural employment and lower import dependence.[60] Thus, the sustainability of bioethanol production is shaped by a complex interplay of factors, including feedstock availability, technological advances, economic viability, policy support, and environmental considerations. Overcoming the challenges in feedstock costs and efficiency through innovation, such as utilizing waste streams and advanced microbial technologies, holds promise for improving the competitiveness of bioethanol. Stable, transparent, and socially inclusive policy frameworks, supported by certification schemes ensuring environmental and economic integrity, will be essential to secure bioethanol's long-term viability as a cornerstone of the global renewable energy transition.

5. Potential improvements and future directions

A comprehensive summary of the four generations of bioethanol production is provided in Table 8, offering a holistic analysis that includes decision support, TRL, policies, and overall environmental impacts in terms of carbon emissions and GHG potential. As we progress from the first to the fourth generation, there is a noticeable increase in sustainability,

Table 8 Summary of bioethanol production from four generations of feedstock

Generation	Carbon emissions[a]	GHG reduction potential[b]	Holistic perspective	Technology readiness level (TRL)	Decision support	Policy and regulation	Ref.
First	0.08 to 4.4	Moderate to high[c]	Food-versus-fuel conflict, minimal environmental benefits	9	Established infrastructure, widely adopted	U.S. Renewable fuel standard supported blending in gasoline	225, 227, 272, 276, 309 and 314
Second	−3.1 to 4.7	High	Non-food-based feedstock offers higher sustainability	8–9	Costly pretreatment improving with R&D	EU renewable energy directive supported 2G bioethanol using incentives	1, 227, 311, 315 and 316
Third	−65 to 78	High	High yield per hectare; grow on non-arable land; reduces land-use impacts	4–5	Scale-up challenge, higher sustainability	Emerging technologies, limited policies, research funding and incentives required	1, 227 and 317
Fourth	—	Very high	Carbon-neutral/negative	2	Early-stage technology; can revolutionize sustainability	Currently speculative; require new regulatory frameworks	1

[a] kg CO_2-eq. per kg of bioethanol produced. [b] Compared to gasoline (94 g CO_2 eq. per MJ). [c] Data not well-established; sometimes even higher than gasoline.

reduced land use, and a shift toward carbon neutrality.[225,309] First-generation bioethanol sometimes has higher carbon emissions compared to gasoline.[310] Each generation presents evolving technologies and challenges, with later generations showing more promise but requiring continued research and development. Policies supporting bioethanol production have evolved, laying the foundation for more sustainable and environmental friendly alternatives. Notable policies, like the U.S. Renewable Fuel Standard (RFS),[272,276] the EU's Renewable Energy Directive (RED II),[311] Brazil's RenovaBio,[303] and others in China and India,[300,306] aim to reduce carbon emissions through the promotion of advanced biofuels. However, inconsistent regulations and policy uncertainties can hinder market stability, affecting long-term investments and planning.[312,313]

Recent innovations in bioethanol production have radically transformed the bioenergy landscape. For example, Artificial Photosynthesis systems, which harness sunlight directly,[187] significantly reduce external energy input and can be integrated with other renewable energy sources like solar or wind to build a more resilient energy infrastructure. Microbial Fuel Cells, generating both bioethanol and electricity, offer a novel approach to sustainable energy production.[175] Furthermore, advances in materials science, biotechnology, and process engineering are essential for overcoming current limitations. Biomass gasification and fermentation processes provide versatility, as syngas can be used as feedstock for multiple biofuels and chemicals,[318] offering greater efficiency and feedstock flexibility than conventional bioethanol production. Challenges remain, including the operational complexity of maintaining precise temperature, pressure, and gas composition conditions, as well as capital investment in specialized equipment.[319] Catalytic synthesis is also a promising avenue for reducing carbon footprints in bioethanol production, although it faces hurdles such as catalyst performance and process integration.[320]

Consolidated bioprocessing, a key breakthrough, integrates enzyme production, biomass hydrolysis, and fermentation into a single step, eliminating the need for additional enzymes and pretreatment processes.[321] This innovation reduces both costs and process complexity. Additionally, continuous fermentation systems, which maintain optimal conditions for microbial growth, can enhance productivity and overall process efficiency.[92,322,323] Nanotechnology improves enzyme stability and reusability, particularly in biomass pretreatment and enzyme immobilization, making bioethanol production more cost-effective and sustainable.[57] Beyond its role as a biofuel, bioethanol is becoming an increasingly versatile chemical with applications in various downstream industries (discussed in SI). In synthetic biology, engineered microorganisms convert bioethanol into high-value chemicals and pharmaceuticals, reducing dependence on petrochemical routes.[324] This expands bioethanol's role as a sustainable carbon source for biomanufacturing.

Food-based, first-generation bioethanol has been produced for several decades, with Brazil and the United States leading global output through the use of sugarcane and corn as primary feedstocks, respectively.[325] This technology is fully mature and operates at a TRL of 9, with numerous commercial-scale plants established worldwide.[1] In contrast, large agricultural nations such as India and China are currently accelerating efforts to advance second-generation bioethanol technologies toward full commercialization (TRL 9), leveraging their abundant supplies of agricultural residues and other lignocellulosic feedstocks. In India, companies such as Praj Industries Limited[326] and Nuberg

Green Energy[327] have already developed and demonstrated technologies capable of converting these residues into bioethanol and are operating at TRL 9. Similarly, in Brazil, firms like GranBio and Raízen are pursuing second-generation bioethanol production and have achieved TRLs in the range of 8 to 9, reflecting near-commercial maturity.[328] Meanwhile, in the United States, companies including Mascoma Corporation[329] and Qteros Inc.[330] remain at comparatively earlier stages of technological deployment, operating at TRLs between 6 and 7, as their projects are still at the pilot or early demonstration level. Jain and Kumar[1] reported the TRL of 7–8 for bioethanol production *via* gas fermentation, with LanzaTech emerging as the leading industrial developer in this field. Algal-based third-generation bioethanol is still limited to the laboratory or pilot scale, corresponding to TRLs between 4 and 6.[1] Algenol Biofuels (USA), which demonstrated a semi-commercial photobioreactor system for bioethanol production, achieving a TRL of around 6 before scaling back operations due to economic constraints.[331] The European initiative under the EU Horizon framework, such as the BIOFAT, has reached similar pilot-scale advancements.[332] Lastly, fourth-generation bioethanol technologies remain predominantly at the research and laboratory scale, reflecting low TRL typically between 2 and 3.[1]

The central discussion ultimately revolves around identifying which type of biomass is most suitable for sustainable bioethanol production. There is, however, no universal answer, as the selection must be region-specific and guided by the availability of local resources, climatic conditions, and socioeconomic context. Such decisions should be supported by detailed life cycle and techno-economic analyses to ensure environmental sustainability and economic feasibility. Food-based first-generation feedstocks are generally less suitable due to their high agricultural input requirements and the ongoing food-versus-fuel debate.[1,219] Hence, alternative non-food biomass should be prioritised. Second-generation lignocellulosic residues hold strong potential for countries such as Brazil, China, and India, where vast amounts of agricultural residues are produced annually.[333,334] These lignocellulosic feedstocks can be efficiently utilized in decentralized biorefineries, which would minimize transportation costs and ensure a steady biomass supply by taking advantage of the abundant crop residues generated from multiple seasonal harvests throughout the year.[60,335] Also, it will help generate employment in the rural and remote areas.[60] In contrast, third-generation algal feedstocks may be impractical in regions with limited sunlight, as their cultivation in photobioreactors can demand significant energy inputs that compromise sustainability, particularly if derived from non-renewable sources. Even if renewable energy is used to produce algal biomass, subsequently converting that biomass back into bioethanol for energy use may not be carbon-intensive, but it represents a redundant and inefficient pathway. Fourth-generation and other advanced bioethanol technologies demonstrate promise at the laboratory scale but often face scalability and biosafety challenges, especially those involving GM organisms, necessitating rigorous protocols prior to deployment.[336–338] Despite this, bioethanol production also raises social and ethical concerns, particularly the "food *vs.* fuel" debate,[339] as large-scale production from food crops can exacerbate food insecurity and drive up prices.[340] Additionally, land-use changes can displace communities and harm biodiversity.[341] Balancing energy needs with food security and social equity is essential. Environmentally, bioethanol offers potential GHG reductions compared to fossil fuels, with cellulosic bioethanol providing greater benefits (∼86% GHG reduction) than first-generation corn (∼52% GHG reduction).[342] However, land-use changes can offset these gains,[341] emphasizing the need for sustainable land management and feedstock selection to maximize environmental advantages.

Continued research and development efforts are required to ensure complete resource utilization and to make the process economical both in terms of "atoms" and "capital." Jain *et al.*[343,344] proposed the complete valorization of LCB, and suggested converting holocellulose into bioethanol or bio-oil, inorganic ash into high-purity silica for applications such as catalysis or adsorption, and lignin into bio-oil for potential material uses, including biopolymers. Comprehensive techno-economic and life cycle assessments can further guide the identification of best practices for specific regions while considering system boundaries at a global scale. Prior feedstock characterization is essential for selecting the most suitable biomass for bioethanol production. For instance, second-generation feedstocks with high lignin content or third-generation feedstocks with high lipid content may not be suitable for standalone bioethanol production. However, these materials can be integrated with other processing units to achieve complete feedstock utilization and higher atom efficiency. Statistical tools like response surface methodology can optimize pretreatment conditions, minimize inhibitors, and improve process scalability. Ultimately, the successful scale-up of carbon-negative and integrative bioethanol technologies could offer the most sustainable route for future biofuel production.

A promising direction for bioethanol production involves integrating carbon capture and utilization (CCU) technologies, where CO_2 produced during fermentation is captured and repurposed for other industrial uses, creating a closed carbon loop.[345] However, unsustainable agricultural practices, deforestation, and land use changes can offset the environmental benefits of bioethanol production.[346] In the transportation sector, vehicle electrification is on the rise, but bioethanol still offers a viable alternative for powering electric vehicles. Technologies like solid oxide fuel cells that convert ethanol into electricity have demonstrated superior energy efficiency and sustainability compared to battery-powered electric vehicles (BEVs).[347] For instance, with its higher energy density, sugarcane bioethanol results in lower GHG emissions than BEVs, which in Brazil emit 65 grams of CO_2 per kilometer, compared to the 58 grams emitted by ethanol-powered flex-fuel vehicles.[348] In contrast, hybrid electric vehicles using bioethanol, already available in the Brazilian market, emit just 29 grams of CO_2 per kilometer.[348] Direct Ethanol Fuel Cells, still in the research phase, also hold promise for portable and stationary power applications, offering high energy density and low emissions.[347,349]

Fluctuations in fossil fuel prices affect the economic competitiveness of bioethanol, making it less attractive when oil prices drop. Therefore, supportive policies, subsidies, and incentives are necessary to drive the growth of the bioethanol industry. Genetic engineering in fourth-generation feedstocks, along with innovations in enzyme technology and process integration, holds the potential for significant advancements in production efficiency and sustainability. Additionally, future approaches, such as optimizing local biomass mixtures for improved lignin extraction and hydrolysis, can address challenges in feedstock collection and transportation.[60] Decentralized biorefineries and Industry 4.0 technologies can streamline the bioethanol value chain, improving operational viability.[335,350] Advanced research, such as molecular modeling and machine learning to optimize pretreatment processes, will drive further improvements in bioethanol production.[57] Life cycle and techno-economic assessments are essential to balance costs, energy use, and environmental impacts, guiding the development of more sustainable and economical biofuel solutions. As the technologies evolve, they promise the future of renewable energy and the bioeconomy.

6. Conclusion

The Circular Bio-society 2050 vision (Bio-based Industries Consortium, 2018) highlights a promising future where sustainable energy, food, and products are sourced through circular bioeconomy principles. This review underscores bioethanol production potential from diverse feedstocks, particularly from lignin-rich biomass, which has traditionally been a challenging material. However, recent breakthroughs in biotechnology and chemical processes have opened new pathways for efficiently converting lignin into bioethanol. The review also calls for more transparency in biorefinery life cycle assessments, emphasizing the need to evaluate the entire value chain to understand the full impact and benefits, including biogenic carbon storage. While fluctuations in fossil fuel prices can affect the economic feasibility of bioethanol, government support, subsidies, and incentives are essential to fostering growth in the bioethanol sector. Integrating bioethanol production into biorefineries and aligning it with green chemistry and the circular economy can further strengthen its role in the bioeconomy. Moreover, conducting detailed LCAs of first- and second-generation bioethanol enables the identification of environmental trade-offs and hotspots, providing critical insights to guide policy and technology development. Incorporating emerging metrics such as resource efficiency and socio-environmental benefits into LCAs can enhance decision-making and support the transition to sustainable biofuels. The continued advancement in genetic engineering, enzyme technology, and process integration is expected to significantly improve bioethanol production's efficiency and sustainability. As these innovations progress, they hold the potential to shape a more sustainable and renewable energy future, offering long-term benefits for both the biofuel industry and the broader bioeconomy.

Author contributions

Sanyam Jain: writing – original draft, visualization, validation, software, methodology, investigation, formal analysis, data curation, conceptualization. Shushil Kumar: writing – review & editing, visualization, validation, supervision, software, resources, project administration, methodology, investigation, funding acquisition, formal analysis, conceptualization.

Conflicts of interest

The authors have no relevant financial or non-financial interests to disclose.

Abbreviations

LCA	Life cycle assessment
DDG	Dry distillers' grains
LCB	Lignocellulosic biomass
MSW	Municipal solid waste
MFCs	Microbial fuel cells
APS	Artificial photosynthetic systems
PECs	Photoelectrochemical cells
GHG	Greenhouse gas
TRL	Technology readiness level
GM	Genetically modified
GWP	Global warming potential
LUC	Land-use change

Data availability

No primary research results, software, or code have been included, and no new data were generated or analyzed as part of this review.

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References

1 S. Jain and S. Kumar, A comprehensive review of bioethanol production from diverse feedstocks: current advancements and economic perspectives, *Energy*, 2024, **296**, 131130.
2 J. R. Melendez, B. Mátyás, S. Hena, D. A. Lowy and A. El Salous, Perspectives in the production of bioethanol: a review of sustainable methods, technologies, and bioprocesses, *Renewable Sustainable Energy Rev.*, 2022, **160**, 112260.
3 R. M. Handler, D. R. Shonnard, E. M. Griffing, A. Lai and I. Palou-Rivera, Life Cycle Assessments of Ethanol Production via Gas Fermentation: Anticipated Greenhouse Gas Emissions for Cellulosic and Waste Gas Feedstocks, *Ind. Eng. Chem. Res.*, 2016, **55**, 3253–3261.
4 N. Vikromvarasiri, T. Laothanachareon, V. Champreda and N. Pisutpaisal, Bioethanol production from glycerol by mixed culture system, *Energy Procedia*, 2014, **61**, 1213–1218.

5 E. Bertrand and C.-G. Dussap, First Generation Bioethanol: Fundamentals—Definition, History, Global Production, Evolution, in *Liquid Biofuels: Bioethanol*, ed. C. R. Soccol, G. Amarante Guimarães Pereira, C.-G. Dussap and L. de Souza Vandenberghe, Springer International Publishing, Cham, 2022, pp. 1–12, DOI: 10.1007/978-3-031-01241-9_1.
6 F. Da Silva Fernandes, et al., Current Ethanol Production Requirements for the Yeast Saccharomyces cerevisiae, *Int. J. Microbiol.*, 2022, **2022**, 7878830.
7 K. Malik, et al., Lignocellulosic biomass for bioethanol: Insight into the advanced pretreatment and fermentation approaches, *Ind. Crops Prod.*, 2022, **188**, 115569.
8 O. Onu Olughu, et al., Technoeconomic analysis of a fungal pretreatment-based cellulosic ethanol production, *Results Eng.*, 2023, **19**, 101259.
9 A. Kasaeian, L. Fereidooni, A. Ahmadbeigi, S. Kahedi and M. Shavali, Review on Bioethanol Production from Fruit Peels Washed Solid Fraction of Pomegranate Peel Liquid Fraction of Pomegranate Peel Whole Slurry of Pomegranate Peel, *Waste Biomass Valorization*, 2025, **16**, 2669–2691.
10 J. Serate, et al., Controlling microbial contamination during hydrolysis of AFEX-pretreated corn stover and switchgrass: effects on hydrolysate composition, microbial response and fermentation, *Biotechnol. Biofuels*, 2015, **8**, 1–17.
11 Y. Zhang, et al., Diverse lignocellulosic feedstocks can achieve high field-scale ethanol yields while providing flexibility for the biorefinery and landscape-level environmental benefits, *GCB Bioenergy*, 2018, **10**, 825–840.
12 L. P. Cruz, et al., Morpho-physiological bases of biomass production by energy cane and sugarcane: a comparative study, *Ind. Crops Prod.*, 2021, **171**, 113884.
13 N. Saba, et al., Potential of bioenergy production from industrial kenaf (Hibiscus cannabinus L.) based on Malaysian perspective, *Renewable Sustainable Energy Rev.*, 2015, **42**, 446–459.
14 O. E. V. Charles, Bioethanol production from Jatropha seed cake via dilute acid hydrolysis and fermentation by Saccharomyces cerevisiae, *GSC Biol. Pharm. Sci.*, 2021, **15**, 049–054.
15 G. Dida, Biotechnology towards energy crops, *CABI Agric. Biosci.*, 2024, **5**, 45.
16 D. Hebbale and T. V. Ramachandra, Third-generation bioethanol: status, scope, and challenges, in *Handbook of Biofuels*, ed. S. Sahay, Academic Press, 2021, pp. 295–312.
17 M. Choudhary, A. Singh, M. Gupta and S. Rakshit, Enabling technologies for utilization of maize as a bioenergy feedstock, *Biofuels, Bioprod. Biorefin.*, 2020, **14**, 402–416.
18 B. Abdullah, et al., Fourth generation biofuel: a review on risks and mitigation strategies, *Renewable Sustainable Energy Rev.*, 2019, **107**, 37–50.
19 J. Hall, *Disposal of Genetically Modified Organisms, Risk Group 2 Microorganisms & Biohazardous Waste*, 2021, https://staff.flinders.edu.au/content/dam/staff/research/ebi/biosafety/sops/sop-disposal-of-gmos-risk-group-2-microorganisms-biohazardous-waste.pdf.
20 A. Althuri and S. Venkata Mohan, Emerging innovations for sustainable production of bioethanol and other mercantile products from circular economy perspective, *Bioresour. Technol.*, 2022, **363**, 128013.
21 H. Y. Leong, et al., Waste biorefinery towards a sustainable circular bioeconomy: a solution to global issues, *Biotechnol. Biofuels*, 2021, **14**, 1–15.
22 D. Paul, et al., Life cycle assessment of lithium-based batteries: review of sustainability dimensions, *Renewable Sustainable Energy Rev.*, 2024, **206**, 114860.
23 S. Kim and B. E. Dale, Life cycle assessment of various cropping systems utilized for producing biofuels: bioethanol and biodiesel, *Biomass Bioenergy*, 2005, **29**, 426–439.
24 F. Cherubini and A. H. Strømman, Life cycle assessment of bioenergy systems: state of the art and future challenges, *Bioresour. Technol.*, 2011, **102**, 437–451.
25 N. Liu, et al., Road life-cycle carbon dioxide emissions and emission reduction technologies: a review, *J. Traffic Transp. Eng., Engl. Ed.*, 2022, **9**, 532–555.
26 O. C. Nwufo, C. F. Nwaiwu, J. O. Igbokwe and O. M. I. Nwafor, Production and characterisation of bio-ethanol from various Nigerian feedstocks, *Int. J. Ambient Energy*, 2016, **37**, 469–473.
27 R. J. Bothast and M. A. Schlicher, Biotechnological processes for conversion of corn into ethanol, *Appl. Microbiol. Biotechnol.*, 2005, **67**, 19–25.
28 A. McAloon, et al., *Determining the Cost of Producing Ethanol from Corn Starch and Lignocellulosic Feedstocks*, 2000, NREL/TP-580-28893, https://www.nrel.gov/docs/fy01osti/28893.pdf#page=1.00&gsr=0.
29 D. M. d. Carvalho, O. Sevastyanova, J. H. d. Queiroz and J. L. Colodette, Cold alkaline extraction as a pretreatment for bioethanol production from eucalyptus, sugarcane bagasse and sugarcane straw, *Energy Convers. Manage.*, 2016, **124**, 315–324.
30 D. Hebbale, R. Bhargavi and T. V. Ramachandra, Saccharification of macroalgal polysaccharides through prioritized cellulase producing bacteria, *Heliyon*, 2019, **5**, e01372.
31 R. Harun and M. K. Danquah, Influence of acid pre-treatment on microalgal biomass for bioethanol production, *Process Biochem.*, 2011, **46**, 304–309.
32 A. Ameen, C. Tang, J. Liu, L. Han and G. H. Xie, Switchgrass as forage and biofuel feedstock: effect of nitrogen fertilization rate on the quality of biomass harvested in late summer and early fall, *Field Crops Res.*, 2019, **235**, 154–162.
33 D. Özçimen and B. Inan, An Overview of Bioethanol Production from Algae, in *Biofuels - Status and Perspective*, ed. K. Biernat, IntechOpen, 2015, p. 582, DOI: 10.5772/59305.
34 J. L. Moreno Alzate, et al., Physicochemical characterization of special cassava starches and their application for bio-ethanol production through no-cook technology at very high gravity, *Ind. Crops Prod.*, 2024, **219**, 119095.

35 A. A. Fathima, M. Sanitha, L. Tripathi and S. Muiruri, Cassava (Manihot esculenta) dual use for food and bioenergy: a review, *Food Energy Secur.*, 2023, **12**, 1–26.
36 R. I. Nazli, et al., Assessment of Sweet Sorghum Genotypes for Bioethanol Production Potential and Bagasse Combustion Characteristics in a Semi-Arid Mediterranean Climate, *Agronomy*, 2024, **14**, 2626.
37 S. Uppalapati, et al., Environmental impact and energy balance assessment in ethanol production from sugarcane molasses: a life cycle analysis in southern India, *Renewable Sustainable Energy Rev.*, 2024, **204**, 114807.
38 A. I. Osman, et al., Life cycle assessment and techno-economic analysis of sustainable bioenergy production: a review, *Environ. Chem. Lett.*, 2024, **22**, 1115–1154.
39 L. Zhan, et al., Life cycle assessment of optimized cassava ethanol production process based on operating data from Guangxi factory in China, *Biomass Convers. Biorefin.*, 2022, **14**, 26535–26552.
40 A. Bernstad Saraiva, System boundary setting in life cycle assessment of biorefineries: a review, *Int. J. Environ. Sci. Technol.*, 2017, **14**, 435–452.
41 Y. Liu, et al., Review of waste biorefinery development towards a circular economy: from the perspective of a life cycle assessment, *Renewable Sustainable Energy Rev.*, 2021, **139**, 110716.
42 P. Das and K. K. K. Singh, Wastewater Remediation: Emerging Technologies and Future Prospects, in *Environmental Degradation: Challenges and Strategies for Mitigation*, ed. V. P. Singh, S. Yadav, K. K. Yadav and R. N. Yadava, Springer International Publishing, Cham, 2022, pp. 227–250, DOI: 10.1007/978-3-030-95542-7_11.
43 R. S. V. Ganesh, R. P. Devi, D. Ramesh, S. Karthikeyan and D. Murugananthi, A Step into Future Fuel Industrial Effluents into Bioethanol: A Review, *Int. J. Environ. Clim. Change*, 2023, **13**, 3633–3640.
44 M. R. Singh and A. T. Bell, Design of an artificial photosynthetic system for production of alcohols in high concentration from CO_2, *Energy Environ. Sci.*, 2016, **9**, 193–199.
45 I. G. Hakeem, et al., Techno-economic analysis of biochemical conversion of biomass to biofuels and platform chemicals, *Biofuels, Bioprod. Biorefin.*, 2023, **17**, 718–750.
46 L. V. Dos Santos, et al., Second-Generation Ethanol: The Need Is Becoming a Reality, *Ind. Biotechnol.*, 2016, **12**, 40–57.
47 K. A. Selim, D. E. El-Ghwas, S. M. Easa and M. I. Abdelwahab Hassan, Bioethanol a Microbial Biofuel Metabolite; New Insights of Yeasts Metabolic Engineering, *Fermentation*, 2018, **4**, 16.
48 E. C. Ramírez, D. B. Johnston, A. J. Mcaloon and V. Singh, Enzymatic corn wet milling: engineering process and cost model, *Biotechnol. Biofuels*, 2009, **2**, 2.
49 K. Naidu, V. Singh, D. B. Johnston, K. D. Rausch and M. E. Tumbleson, Effects of Ground Corn Particle Size on Ethanol Yield and Thin Stillage Soluble Solids, *Cereal Chem.*, 2007, **84**(1), 6–9.
50 G. S. Murthy, V. Singh, D. B. Johnston, K. D. Rausch and M. E. Tumbleson, Evaluation and Strategies to Improve Fermentation Characteristics of Modified Dry-Grind Corn Processes, *Cereal Chem.*, 2006, **83**(5), 455–459.
51 A. Iram, D. Cekmecelioglu and A. Demirci, Distillers' dried grains with solubles (DDGS) and its potential as fermentation feedstock, *Appl. Microbiol. Biotechnol.*, 2020, **104**, 6115–6128.
52 H.-B. Seo, S. Kim, H.-Y. Lee and K.-H. Jung, Improved Bioethanol Production Using Activated Carbon-treated Acid Hydrolysate from Corn Hull in Pachysolen tannophilus, *Mycobiology*, 2009, **37**, 133–140.
53 R. M. E. Buenavista, K. Siliveru and Y. Zheng, Utilization of Distiller's dried grains with solubles: a review, *J. Agric. Food Res.*, 2021, **5**, 100195.
54 V. B. Veljković, et al., Biodiesel production from corn oil: a review, *Renewable Sustainable Energy Rev.*, 2018, **91**, 531–548.
55 M. Elsayed, et al., Sustainable valorization of waste glycerol into bioethanol and biodiesel through biocircular approaches: a review, *Environ. Chem. Lett.*, 2024, **22**, 609–634.
56 N. F. Ruslan, et al., Sustainable bioethanol production by solid-state fermentation: a systematic review, in *Environmental Science and Pollution Research*, Springer Berlin Heidelberg, 2024, vol. 2024.
57 S. Jain and S. Kumar, Advances and challenges in pretreatment technologies for bioethanol production: a comprehensive review, *Sustain. Chem. Clim. Action*, 2024, **5**, 100053.
58 S. Rezania, et al., Different pretreatment technologies of lignocellulosic biomass for bioethanol production: an overview, *Energy*, 2020, **199**, 117457.
59 P. Alvira, E. Tomás-Pejó, M. Ballesteros and M. J. Negro, Pretreatment technologies for an efficient bioethanol production process based on enzymatic hydrolysis: a review, *Bioresour. Technol.*, 2010, **101**, 4851–4861.
60 S. Jain and H. Mahalingam, Pretreatment of lignocellulosic biomass waste mixtures using a low-cost ionic liquid, *Sustain. Chem. Clim. Action*, 2024, **5**, 100052.
61 E. Palmqvist and B. Hahn-Hägerdal, Fermentation of lignocellulosic hydrolysates. II: Inhibitors and mechanisms of inhibition, *Bioresour. Technol.*, 2000, **74**, 25–33.
62 S. R. Chaves, et al., Regulation of cell death induced by acetic acid in yeasts, *Front. Cell Dev. Biol.*, 2021, **9**, 642375.
63 N. K. Aggarwal, N. Kumar and M. Mittal, Valorization of Organic Fraction of MSW for Bioethanol Production, in *Bioethanol Production: Past and Present*, Springer International Publishing, Cham, 2022, pp. 73–88, DOI: 10.1007/978-3-031-05091-6_6.
64 B. Thapa, S. K. Patidar, N. R. Khatiwada, A. K. KC and A. Ghimire, Production of Ethanol from Municipal Solid Waste of India and Nepal, in *7th International Conference on Solid Waste Management*, Singapore, 2017.

65 B. Sharma, C. Larroche and C. G. Dussap, Comprehensive assessment of 2G bioethanol production, *Bioresour. Technol.*, 2020, **313**, 123630.
66 M. J. Taherzadeh and K. Karimi, Acid-based hydrolysis processes for ethanol from lignocellulosic materials: a review, *Bioresources*, 2007, **2**, 472–499.
67 A. P. de Sousa Oliveira, P. Assemany, L. Covell and M. L. Calijuri, Copper multifaceted interferences during swine wastewater treatment in high-rate algal ponds: alterations on nutrient removal, biomass composition and resource recovery, *Environ. Pollut.*, 2023, **324**, 121364.
68 J. H. Yun, et al., Hybrid operation of photobioreactor and wastewater-fed open raceway ponds enhances the dominance of target algal species and algal biomass production, *Algal Res.*, 2018, **29**, 319–329.
69 P. Choudhary, et al., A review of biochemical and thermochemical energy conversion routes of wastewater grown algal biomass, *Sci. Total Environ.*, 2020, **726**, 137961.
70 L. Rocha-Meneses, et al., Genetic modification of cereal plants: a strategy to enhance bioethanol yields from agricultural waste, *Ind. Crops Prod.*, 2020, **150**, 112408.
71 M. B. Sticklen, Plant genetic engineering for biofuel production: towards affordable cellulosic ethanol, *Nat. Rev. Genet.*, 2008, **9**, 433–443.
72 V. d. S. Sobrinho, V. C. F. d. Silva and M. P. Cereda, Fermentation of sugar cane juice (Sacharum officinarum) cultivar RB 7515 by wild yeasts resistant to UVC, *J. Biotechnol. Biodiversity*, 2011, **2**, 13–21.
73 A. Tesfaw, E. T. Oner and F. Assefa, Optimization of ethanol production using newly isolated ethanologenic yeasts, *Biochem. Biophys. Rep.*, 2021, **25**, 100886.
74 H. Biebl, Fermentation of glycerol by Clostridium pasteurianum - batch and continuous culture studies, *J. Ind. Microbiol. Biotechnol.*, 2001, **27**, 18–26.
75 M. Rastogi and S. Shrivastava, Current Methodologies and Advances in Bio-ethanol Production, *Journal of Biotechnology & Bioresearch*, 2018, **1**, 1–8.
76 J. Söderström, M. Galbe and G. Zacchi, Separate versus simultaneous saccharification and fermentation of two-step steam pretreated softwood for ethanol production, *J. Wood Chem. Technol.*, 2005, **25**, 187–202.
77 G. S. Jouzani and M. J. Taherzadeh, Advances in consolidated bioprocessing systems for bioethanol and butanol production from biomass: a comprehensive review, *Biofuel Res. J.*, 2015, **2**, 152–195.
78 S. S. M. D. Tavva, et al., Bioethanol production through separate hydrolysis and fermentation of Parthenium hysterophorus biomass, *Renewable Energy*, 2016, **86**, 1317–1323.
79 I. S. Tan and K. T. Lee, Enzymatic hydrolysis and fermentation of seaweed solid wastes for bioethanol production: an optimization study, *Energy*, 2014, **78**, 53–62.
80 C. da Costa Nogueira, et al., Pressurized pretreatment and simultaneous saccharification and fermentation with in situ detoxification to increase bioethanol production from green coconut fibers, *Ind. Crops Prod.*, 2019, **130**, 259–266.
81 T. Siriwong, et al., Cold hydrolysis of cassava pulp and its use in simultaneous saccharification and fermentation (SSF) process for ethanol fermentation, *J. Biotechnol.*, 2019, **292**, 57–63.
82 K. Sakimoto, M. Kanna and Y. Matsumura, Kinetic model of cellulose degradation using simultaneous saccharification and fermentation, *Biomass Bioenergy*, 2017, **99**, 116–121.
83 C. A. Barcelos, R. N. Maeda, L. Maria, M. S. Anna and N. Pereira, Sweet sorghum as a whole-crop feedstock for ethanol production, *Biomass Bioenergy*, 2016, **94**, 46–56.
84 X. Jin, J. Ma, J. Song and G. Q. Liu, Promoted bioethanol production through fed-batch semisimultaneous saccharification and fermentation at a high biomass load of sodium carbonate-pretreated rice straw, *Energy*, 2021, **226**, 120353.
85 G. E. Ortiz, et al., A Comparative Study of New Aspergillus Strains for Proteolytic Enzymes Production by Solid State Fermentation, *Enzym. Res.*, 2016, **2016**, 3016149.
86 M. Marín, A. Sánchez and A. Artola, Production and recovery of cellulases through solid-state fermentation of selected lignocellulosic wastes, *J. Clean. Prod.*, 2019, **209**, 937–946.
87 G. S. B. Salomão, et al., Production of cellulases by solid state fermentation using natural and pretreated sugarcane bagasse with different fungi, *Biocatal. Agric. Biotechnol.*, 2019, **17**, 1–6.
88 A. Romaní, G. Garrote and J. C. Parajó, Bioethanol production from autohydrolyzed Eucalyptus globulus by simultaneous saccharification and fermentation operating at high solids loading, *Fuel*, 2012, **94**, 305–312.
89 V. Sóti, S. Lenaerts and I. Cornet, Of enzyme use in cost-effective high solid simultaneous saccharification and fermentation processes, *J. Biotechnol.*, 2018, **270**, 70–76.
90 K. Olofsson, B. Palmqvist and G. Lidén, Improving simultaneous saccharification and co-fermentation of pretreated wheat straw using both enzyme and substrate feeding, *Biotechnol. Biofuels*, 2010, **3**, 1–9.
91 P. Kotter and M. Ciriacy, Xylose fermentation by Saccharomyces cerevisiae, *Appl. Microbiol. Biotechnol.*, 1993, **38**, 776–783.
92 Y. Ying and S. Ma, *A Beginner's Guide to Bioprocess Modes – Batch, FedBatch, and Continuous Fermentation*, 2021, https://www.eppendorf.com/product-media/doc/en/763594/Fermentors-Bioreactors_Application-Note_408_BioBLU-f-Single-Vessel_A-Beginner%E2%80%99s-Guide-Bioprocess-Modes-Batch_Fed-Batch-Continuous-Fermentation.pdf.
93 R. Koppram, et al., Simultaneous saccharification and co-fermentation for bioethanol production using corncobs at lab, PDU and demo scales, *Biotechnol. Biofuels*, 2013, **6**, 2–11.
94 M. M. Ishola, A. Jahandideh, B. Haidarian, T. Brandberg and M. J. Taherzadeh, Simultaneous saccharification, filtration and fermentation (SSFF): a novel method for bioethanol production from lignocellulosic biomass, *Bioresour. Technol.*, 2013, **133**, 68–73.

95 F. Maleki, et al., Consolidated bioprocessing for bioethanol production by metabolically engineered Bacillus subtilis strains, *Sci. Rep.*, 2021, **11**, 1–13.
96 R. Mazzoli, C. Lamberti and E. Pessione, Engineering new metabolic capabilities in bacteria: lessons from recombinant cellulolytic strategies, *Trends Biotechnol.*, 2012, **30**, 111–119.
97 V. Parisutham, T. H. Kim and S. K. Lee, Feasibilities of consolidated bioprocessing microbes: from pretreatment to biofuel production, *Bioresour. Technol.*, 2014, **161**, 431–440.
98 S. H. Mohd Azhar, et al., Yeasts in sustainable bioethanol production: a review, *Biochem. Biophys. Rep.*, 2017, **10**, 52–61.
99 D. Gomes, et al., Very high gravity bioethanol revisited: main challenges and advances, *Fermentation*, 2021, **7**, 1–18.
100 F. W. Bai, W. A. Anderson and M. Moo-Young, Ethanol fermentation technologies from sugar and starch feedstocks, *Biotechnol. Adv.*, 2008, **26**, 89–105.
101 O. Deesuth, P. Laopaiboon, P. Klanrit and L. Laopaiboon, Improvement of ethanol production from sweet sorghum juice under high gravity and very high gravity conditions: effects of nutrient supplementation and aeration, *Ind. Crops Prod.*, 2015, **74**, 95–102.
102 P. Puligundla, D. Smogrovicova, V. S. R. Obulam and S. Ko, Very high gravity (VHG) ethanolic brewing and fermentation: a research update, *J. Ind. Microbiol. Biotechnol.*, 2011, **38**, 1133–1144.
103 S. Ishmayana, R. P. Learmonth and U. J. Kennedy, Fermentation performance of the yeast Saccharomyces cerevisiae in media with high sugar concentration, presented as part in *2nd International Seminar on Chemistry*, Jatinangor, 2011.
104 X. Sun, H. K. Atiyeh, R. L. Huhnke and R. S. Tanner, Syngas fermentation process development for production of biofuels and chemicals: a review, *Bioresour. Technol. Rep.*, 2019, **7**, 100279.
105 H. Richter, M. E. Martin and L. T. Angenent, A two-stage continuous fermentation system for conversion of syngas into ethanol, *Energies*, 2013, **6**, 3987–4000.
106 H. N. Abubackar, M. C. Veiga and C. Kennes, Biological conversion of carbon monoxide: rich syngas or waste gases to bioethanol, *Biofuels, Bioprod. Biorefin.*, 2011, **5**, 93–114.
107 R. M. Worden, M. D. Bredwell and A. J. Grethlein, Engineering Issues in Synthesis-Gas Fermentations, in *Fuels and Chemicals from Biomass*, ed. B. C. Saha and J. Woodward, American Chemical Society, 1997, ch. 18, pp. 320–335, DOI: 10.1021/bk-1997-0666.ch018.
108 A. M. Henstra, J. Sipma, A. Rinzema and A. J. Stams, Microbiology of synthesis gas fermentation for biofuel production, *Curr. Opin. Biotechnol.*, 2007, **18**, 200–206.
109 Y. Sudiyani, D. Dahnum, D. Burhani and A. M. H. Putri, Evaluation and comparison between simultaneous saccharification and fermentation and separated hydrolysis and fermentation process, *Second and Third Generation of Feedstocks*, ed. A. Basile and F. Dalena, Elsevier, 2019, ch. 10, pp. 273–290, DOI: 10.1016/B978-0-12-815162-4.00010-0.
110 N. I. Basir, C. W. X. Xiang, A. Syukor and Z. Ahmad, Feedforward Artificial Neural Networks-Model Prediction Control (FANN-MPC) for Semi-Simultaneous Saccharification and Fermentation (SSSF) Bioethanol Process, *ASEAN Journal of Process Control*, 2022, **1**, 1–22.
111 M. Toor, et al., An overview on bioethanol production from lignocellulosic feedstocks, *Chemosphere*, 2020, **242**, 125080.
112 M. Loizidou, et al., Pilot Scale System of Two Horizontal Rotating Bioreactors for Bioethanol Production from Household Food Waste at High Solid Concentrations, *Waste Biomass Valorization*, 2017, **8**, 1709–1719.
113 C. J. D. Neto, L. A. J. Letti, S. G. Karp, F. M. D. Vítola and C. R. Soccol, Production of Biofuels from Algae Biomass by Fast Pyrolysis, in *Biofuels from Algae*, Elsevier B.V., 2019, DOI: 10.1016/b978-0-444-64192-2.00018-4.
114 G. R. Sahana, et al., A review on ethanol tolerance mechanisms in yeast: current knowledge in biotechnological applications and future directions, *Process Biochem.*, 2024, **138**, 1–13.
115 N. R. Divate, G. H. Chen, R. D. Divate, B. R. Ou and Y. C. Chung, Metabolic engineering of Saccharomyces cerevisiae for improvement in stresses tolerance, *Bioengineered*, 2017, **8**, 524–535.
116 S. Aslanzadeh, M. M. Ishola, T. Richards and M. J. Taherzadeh, An Overview of Existing Individual Unit Operations, in *Biorefineries: Integrated Biochemical Processes for Liquid Biofuels*, Elsevier B.V., 2014, DOI: 10.1016/B978-0-444-59498-3.00001-4.
117 E. H. Silva, et al., Bioethanol Production Using Mixtures of Sorghum Juice and Sugarcane Molasses: Experimental Data and Kinetic Modeling, *Sugar Tech*, 2024, **26**, 799–808.
118 M. ShakilaBegam, E. A. Boorani, P. Akilandeswari and B. V. Pradeep, Bioethanol Production from Water Hyacinth (Eichhornia crassipes) using Different Microbial Inoculants, *J. Pure Appl. Microbiol.*, 2024, **18**, 323–331.
119 D. Khumsupan, et al., Creating a robust and reusable cell immobilization system for bioethanol production by thermotolerant yeast using 3D printing and soybean waste, *Ind. Crops Prod.*, 2025, **224**, 120434.
120 E. Audibert, et al., Determination of trade-offs between 2G bioethanol production yields and pretreatment costs for industrially steam exploded woody biomass, *Appl. Energy*, 2025, **380**.
121 S. R. Akbari, A. S. Javanmard, M. Ghaedi and M. Bagherinasab, Application of phosphoric acid plus hydrogen peroxide pretreatment and Aspergillus species enzymatic decomposition on rice straw for bioethanol production, *Biofuels*, 2025, **16**, 688–696.
122 P. Singh, P. Gangwar, N. Kumar and S. Ghosh, Continuous bioethanol production from glucose-rich hydrolysate derived from wheat straw using a unique fed-batch cultivation method in a bioreactor, *Process Saf. Environ. Prot.*, 2025, **193**, 74–86.

123 S. Xu, et al., Upcycling from chitin-waste biomass into bioethanol and mushroom via solid-state fermentation with Pleurotus ostreatus, *Fuel*, 2022, **326**, 125061.
124 N. Vikromvarasiri, S. Haosagul, S. Boonyawanich and N. Pisutpaisal, Microbial dynamics in ethanol fermentation from glycerol, *Int. J. Hydrogen Energy*, 2016, **41**, 15667–15673.
125 Sulfahri, S. Mushlihah, D. R. Husain, A. Langford and A. C. M. A. R. Tassakka, Fungal pretreatment as a sustainable and low cost option for bioethanol production from marine algae, *J. Clean. Prod.*, 2020, **265**, 121763.
126 Z. Hu, et al., Integrating genetic-engineered cellulose nanofibrils of rice straw with mild chemical treatments for enhanced bioethanol conversion and bioaerogels production, *Ind. Crops Prod.*, 2023, **202**, 117044.
127 S. Poornima, S. Manikandan, R. Prakash and M. Govarthanan, Biofuel and biochemical production through biomass transformation using advanced thermochemical and biochemical processes – a review, *Fuel*, 2024, **372**, 132204.
128 D. M. Kennes-Veiga, R. Robles-Iglesias, M. C. Veiga and C. Kennes, 6 - Syngas fermentation platforms: alcohols from syngas and CO_2, in *Higher Alcohols Production Platforms*, ed. H. Amiri, M. Tabatabaei and A.-S. Nizami, Academic Press, 2024, pp. 157–181, DOI: 10.1016/B978-0-323-91756-8.00009-8.
129 J.-L. Zheng, et al., Life cycle assessment and techno-economic analysis of fuel ethanol production via bio-oil fermentation based on a centralized-distribution model, *Renewable Sustainable Energy Rev.*, 2022, **167**, 112714.
130 V. Volli, A. R. K. Gollakota, M. K. Purkait and C.-M. Shu, Conversion of Waste Biomass to Bio-oils and Upgradation by Hydrothermal Liquefaction, Gasification, and Hydrodeoxygenation, in *Biorefinery of Alternative Resources: Targeting Green Fuels and Platform Chemicals*, ed. S. Nanda, D.-V. N. Vo and P. K. Sarangi, Springer Singapore, Singapore, 2020, pp. 285–315, DOI: 10.1007/978-981-15-1804-1_13.
131 S. Mishra and R. K. Upadhyay, Review on biomass gasification: Gasifiers, gasifying mediums, and operational parameters, *Mater. Sci. Energy Technol.*, 2021, **4**, 329–340.
132 C. Mihalcea, F. Burton, R. Conrado and S. Simpson, R&D&I and Industry Examples: LanzaTech's Gas Fermentation, in *CO_2 and CO as Feedstock: Sustainable Carbon Sources for the Circular Economy*, Springer International Publishing, Cham, 2023, pp. 333–343, DOI: 10.1007/978-3-031-27811-2_27.
133 S. Wan, et al., Recent progress in engineering Clostridium autoethanogenum to synthesize the biochemicals and biocommodities, *Synth. Syst. Biotechnol.*, 2024, **9**, 19–25.
134 C. Benevenuti, et al., Residual gas for ethanol production by clostridium carboxidivorans in a dual impeller stirred tank bioreactor (Stbr), *Fermentation*, 2021, **7**, 199.
135 S. Kumar, R. M. Dineshkumar, M. A. Vinayakaselvi and A. Ramanathan, Bio-ethanol production from syngas-derived biomass: a review, *Mater. Today Proc.*, 2021, **46**, 9989–9993.
136 H. Khalid, et al., Syngas conversion to biofuels and biochemicals: a review of process engineering and mechanisms, *Sustain. Energy Fuels*, 2024, **8**, 9–28.
137 M. E. Dry, The Fischer-Tropsch process: 1950-2000, *Catal. Today*, 2002, **71**, 227–241.
138 H. Yue, X. Ma and J. Gong, An alternative synthetic approach for efficient catalytic conversion of syngas to ethanol, *Acc. Chem. Res.*, 2014, **47**, 1483–1492.
139 X. Li, D. Griffin, X. Li and M. A. Henson, Incorporating Hydrodynamics into Spatiotemporal Metabolic Models of Bubble Column Gas Fermentation, *Biotechnol. Bioeng.*, 2019, **116**.
140 A. Dave, G. Kishore, G. Monoj and K. Mondal, Study on thermal degradation characteristics, kinetics, thermodynamic, and reaction mechanism analysis of Arachis hypogaea shell pyrolysis for its bioenergy potential, *Biomass Convers. Biorefin.*, 2023, **13**, 9289–9304.
141 H. Shahbeik, et al., Using nanocatalysts to upgrade pyrolysis bio-oil: a critical review, *J. Clean. Prod.*, 2023, **413**, 137473.
142 S. Kumar, J. P. Lange, G. Van Rossum and S. R. A. Kersten, Liquefaction of Lignocellulose in Fluid Catalytic Cracker Feed: A Process Concept Study, *ChemSusChem*, 2015, **8**, 4086–4094.
143 R. K. Mishra, V. Kumar, P. Kumar and K. Mohanty, Hydrothermal liquefaction of biomass for bio-crude production: a review on feedstocks, chemical compositions, operating parameters, reaction kinetics, techno-economic study, and life cycle assessment, *Fuel*, 2022, **316**, 123377.
144 G. Calvaruso, M. T. Clough, M. D. K. Rechulski and R. Rinaldi, On the Meaning and Origins of Lignin Recalcitrance: A Critical Analysis of the Catalytic Upgrading of Lignins Obtained from Mechanocatalytic Biorefining and Organosolv Pulping, *ChemCatChem*, 2017, **9**, 2691–2700.
145 Y. Y. Liong, R. Halis, O. M. Lai and R. Mohamed, Conversion of lignocellulosic biomass from grass to bioethanol using materials pretreated with alkali and the white rot fungus, Phanerochaete chrysosporium, *Bioresources*, 2012, **7**, 5500–5513.
146 R. L. Kudahettige, M. Holmgren, P. Imerzeel and A. Sellstedt, Characterization of bioethanol production from hexoses and xylose by the white rot fungus Trametes versicolor, *Bioenergy Res.*, 2012, **5**, 277–285.
147 D. Salvachúa, E. M. Karp, C. T. Nimlos, D. R. Vardon and G. T. Beckham, Towards lignin consolidated bioprocessing: simultaneous lignin depolymerization and product generation by bacteria, *Green Chem.*, 2015, **17**, 4951–4967.
148 J. G. Linger, et al., Lignin valorization through integrated biological funneling and chemical catalysis, *Proc. Natl. Acad. Sci. U. S. A.*, 2014, **111**, 12013–12018.
149 G. T. Beckham, C. W. Johnson, E. M. Karp, D. Salvachúa and D. R. Vardon, Opportunities and challenges in

biological lignin valorization, *Curr. Opin. Biotechnol.*, 2016, **42**, 40–53.

150 M. P. McLeod, et al., The complete genome of Rhodococcus sp. RHA1 provides insights into a catabolic powerhouse, *Proc. Natl. Acad. Sci. U. S. A.*, 2006, **103**, 15582–15587.

151 M. Kosa and A. J. Ragauskas, Lignin to lipid bioconversion by oleaginous Rhodococci, *Green Chem.*, 2013, **15**, 2070–2074.

152 C. Brunschwig, W. Moussavou and J. Blin, Use of bioethanol for biodiesel production, *Prog. Energy Combust. Sci.*, 2012, **38**, 283–301.

153 C. Gancedo, J. M. Gancedo and A. Sols, Glycerol Metabolism in Yeasts: Pathways of Utilization and Production, *Eur. J. Biochem.*, 1968, **5**, 165–172.

154 V. Barbe, et al., Unique features revealed by the genome sequence of Acinetobacter sp. ADP1, a versatile and naturally transformation competent bacterium, *Nucleic Acids Res.*, 2004, **32**, 5766–5779.

155 C. Zhao, et al., Synergistic enzymatic and microbial lignin conversion, *Green Chem.*, 2016, **18**, 1306–1312.

156 M. A. Ali and A. Abutaleb, An Updated Comprehensive Literature Review of Phenol Hydrogenation Studies, *Catal. Lett.*, 2022, **152**, 1555–1581.

157 A. Sreenavya, A. Sahu and A. Sakthivel, Hydrogenation of Lignin-Derived Phenolic Compound Eugenol over Ruthenium-Containing Nickel Hydrotalcite-Type Materials, *Ind. Eng. Chem. Res.*, 2020, **59**, 11979–11990.

158 M. Lang and H. Li, Toward Value-Added Arenes from Lignin-Derived Phenolic Compounds via Catalytic Hydrodeoxygenation, *ACS Sustain. Chem. Eng.*, 2022, **10**, 13208–13243.

159 D. D. Laskar, B. Yang, H. Wang and J. Lee, Pathways for biomass-derived lignin to hydrocarbon fuels, *Biofuels, Bioprod. Biorefin.*, 2013, **7**, 602–626.

160 S. Abikusna and B. Sugiarto, Study on the utilization of low-grade bioethanol on SI gasoline engine as a mixture of pure gasoline fuel or with the addition of oxygenated additives to improve performance and reduce emissions, *IOP Conf. Ser. Earth Environ. Sci.*, 2021, **753**.

161 B. Sugiarto, C. Simanjuntak, A. P. Adrian, N. Farisa and N. A. Nubli, Comparative study on the use of oxigenated additive at low grade bioethanol for spark ignition engine, *AIP Conf. Proc.*, 2021, **2376**, 070006.

162 M. N. Aftab, I. Iqbal, F. Riaz, A. Karadag and M. Tabatabaei, Different Pretreatment Methods of Lignocellulosic Biomass for Use in Biofuel Production, in *Biomass for Bioenergy - Recent Trends and Future Challenges*, ed. A. E.-F. Abomohra, IntechOpen, 2019, p. 208, DOI: 10.5772/intechopen.84995.

163 C. J. A. Mota, B. P. Pinto and A. L. d. Lima, *Glycerol: A Versatile Renewable Feedstock for the Chemical Industry*, Springer Cham, 2017, DOI: 10.1007/978-3-319-59375-3.

164 A. Chatzifragkou and S. Papanikolaou, Effect of impurities in biodiesel-derived waste glycerol on the performance and feasibility of biotechnological processes, *Appl. Microbiol. Biotechnol.*, 2012, **95**, 13–27.

165 A. Y. Hernández Almanza, N. Balagurusamy, H. R. Leza and C. N. Aguilar, *Bioethanol: Biochemistry and Biotechnological Advances*, Apple Academic Press, New York, 2022, DOI: 10.1201/9781003277132.

166 C. T. Trinh and F. Srienc, Metabolic engineering of Escherichia coli for efficient conversion of glycerol to ethanol, *Appl. Environ. Microbiol.*, 2009, **75**, 6696–6705.

167 V. Kumar and S. Park, Potential and limitations of Klebsiella pneumoniae as a microbial cell factory utilizing glycerol as the carbon source, *Biotechnol. Adv.*, 2018, **36**, 150–167.

168 K. O. Yu, S. W. Kim and S. O. Han, Engineering of glycerol utilization pathway for ethanol production by Saccharomyces cerevisiae, *Bioresour. Technol.*, 2010, **101**, 4157–4161.

169 B. Zhang, et al., Glycerol uptake and synthesis systems contribute to the osmotic tolerance of Kluyveromyces marxianus, *Enzyme Microb. Technol.*, 2020, **140**, 109641.

170 S. Tang, L. Boehme, H. Lam and Z. Zhang, Pichia pastoris fermentation for phytase production using crude glycerol from biodiesel production as the sole carbon source, *Biochem. Eng. J.*, 2009, **43**, 157–162.

171 N. A. A. Adnan, S. N. Suhaimi, S. Abd-Aziz, M. A. Hassan and L. Y. Phang, Optimization of bioethanol production from glycerol by Escherichia coli SS1, *Renewable Energy*, 2014, **66**, 625–633.

172 G. P. da Silva, M. Mack and J. Contiero, Glycerol: a promising and abundant carbon source for industrial microbiology, *Biotechnol. Adv.*, 2009, **27**, 30–39.

173 X. Liu, P. R. Jensen and M. Workman, Bioconversion of crude glycerol feedstocks into ethanol by Pachysolen tannophilus, *Bioresour. Technol.*, 2012, **104**, 579–586.

174 S. M. R. Khattab and T. Watanabe, Production the industrial levels of bioethanol from glycerol by engineered yeast 'Bioethanol-4 generation, *bioRxiv*, 2020, preprint, DOI: 10.1101/2020.06.04.132589.

175 R. S. Pandya, T. Kaur, R. Bhattacharya, D. Bose and D. Saraf, Harnessing microorganisms for bioenergy with Microbial Fuel Cells: powering the future, *Water Energy Nexus*, 2024, **7**, 1–12.

176 R. K. Srivastava, Bio-energy production by contribution of effective and suitable microbial system, *Mater. Sci. Energy Technol.*, 2019, **2**, 308–318.

177 J. Yuan, H. Huang, S. G. Chatterjee, Z. Wang and S. Wang, Effective factors for the performance of a co-generation system for bioethanol and electricity production via microbial fuel cell technology, *Biochem. Eng. J.*, 2022, **178**, 108309.

178 A. Rusdin, *et al.*, Production of Electricity and Bioethanol with Microbial Fuel Cell (MFC) Technology on Molasses Substrate, presented as part in *9th International Conference of the Indonasian Chemical Society ICICS 2021: Toward a Meaningful Society*, Indonesia, 2024.

179 S. Angioni, et al., Photosynthetic microbial fuel cell with polybenzimidazole membrane: synergy between bacteria and algae for wastewater removal and biorefinery, *Heliyon*, 2018, **4**, e00560.

180 H. Akinosho, T. Rydzak, A. Borole, A. Ragauskas and D. Close, Toxicological challenges to microbial bioethanol production and strategies for improved tolerance, *Ecotoxicology*, 2015, **24**, 2156–2174.
181 J. M. Sonawane, R. Mahadevan, A. Pandey and J. Greener, Recent progress in microbial fuel cells using substrates from diverse sources, *Heliyon*, 2022, **8**, e12353.
182 A. Shrivastava and R. K. Sharma, Lignocellulosic biomass based microbial fuel cells: performance and applications, *J. Clean. Prod.*, 2022, **361**, 132269.
183 Y. Sharma and B. Li, The variation of power generation with organic substrates in single-chamber microbial fuel cells (SCMFCs), *Bioresour. Technol.*, 2010, **101**, 1844–1850.
184 S. S. S. Garimella, S. V. Rachakonda, S. S. Pratapa, G. D. Mannem and G. Mahidhara, From cells to power cells: harnessing bacterial electron transport for microbial fuel cells (MFCs), *Ann. Microbiol.*, 2024, **74**, 19.
185 E. Durna Pişkin, Microbial fuel cells in electricity generation with waste treatment: alternative electron acceptors, *Sigma J. Eng. Nat. Sci.*, 2024, **42**, 273–285.
186 D. Ucar, Y. Zhang and I. Angelidaki, An overview of electron acceptors in microbial fuel cells, *Front. Microbiol.*, 2017, **8**, 1–14.
187 S. D. Pandit, Towards Artificial Photosynthesis: Yeast-Inorganic Hybrid System, PhD thesis, Massachusetts Institute of Technology, 2022.
188 D. K. Dogutan and D. G. Nocera, Artificial Photosynthesis at Efficiencies Greatly Exceeding That of Natural Photosynthesis, *Acc. Chem. Res.*, 2019, **52**, 3143–3148.
189 F. Tavella, *Development of Catalytic Electrodes and Cell Design for Solar Fuel Generation*, University of Messina, 2018.
190 A. Machín, M. Cotto, J. Ducongé and F. Márquez, Artificial Photosynthesis: Current Advancements and Future Prospects, *Biomimetics*, 2023, **8**, 298.
191 P. Chinna Ayya Swamy, et al., Near Infrared (NIR) absorbing dyes as promising photosensitizer for photo dynamic therapy, *Coord. Chem. Rev.*, 2020, **411**, 213233.
192 L. Wang, Recent Advances in Metal-Based Molecular Photosensitizers for Artificial Photosynthesis, *Catalysts*, 2022, **12**, 919.
193 J. Li and T. Chen, Transition metal complexes as photosensitizers for integrated cancer theranostic applications, *Coord. Chem. Rev.*, 2020, **418**, 213355.
194 A. R. Nihmiya, R. M. H. H. Jayarathne and A. H. L. R. Nilmini, Recent Advancement in CO_2 Capturing: An Electrochemical Approach, *Asian J. Chem.*, 2023, **35**, 2031–2047.
195 R. K. Yadav, et al., A photocatalyst-enzyme coupled artificial photosynthesis system for solar energy in production of formic acid from CO_2, *J. Am. Chem. Soc.*, 2012, **134**, 11455–11461.
196 T. T. Zhao, et al., Artificial bioconversion of carbon dioxide, *Chin. J. Catal.*, 2019, **40**, 1421–1437.
197 L. Braud, K. McDonnell and F. Murphy, Environmental life cycle assessment of algae systems: critical review of modelling approaches, *Renewable Sustainable Energy Rev.*, 2023, **179**, 113218.
198 M. Aresta, A. Dibenedetto and G. Barberio, Utilization of macro-algae for enhanced CO_2 fixation and biofuels production: development of a computing software for an LCA study, *Fuel Process. Technol.*, 2005, **86**, 1679–1693.
199 A. Chamkalani, S. Zendehboudi, N. Rezaei and K. Hawboldt, A critical review on life cycle analysis of algae biodiesel: current challenges and future prospects, *Renewable Sustainable Energy Rev.*, 2020, **134**, 110143.
200 G. Jafari and F. Naseri-moghanlou, Investigating the role of life cycle assessment of biodiesel production from algae, *Journal of Environmental Science Studies*, 2024, **9**, 8202–8206.
201 K. Sander and G. S. Murthy, Life cycle analysis of algae biodiesel, *Int. J. Life Cycle Assess.*, 2010, **15**, 704–714.
202 A. Laveglia, N. Ukrainczyk, N. De Belie and E. Koenders, Cradle-to-grave environmental and economic sustainability of lime-based plasters manufactured with upcycled materials, *J. Clean. Prod.*, 2024, **452**, 142088.
203 K. M. Hoang and A. Böckel, Cradle-to-cradle business model tool: innovating circular business models for startups, *J. Clean. Prod.*, 2024, **467**, 142949.
204 I. M. Peters, J. Hauch and C. Brabec, Cradle-to-cradle recycling in terawatt photovoltaics: a vision of perpetual utility, *Joule*, 2024, **8**, 899–912.
205 Y. A. Adenle, S. Haideri and I. Sandouka, Understanding the best practices of cradle to cradle in furnishings, carpet, and textile industries–a case studies analysis and conceptual model, *Cleaner and Circular Bioeconomy*, 2024, **8**, 100088.
206 A. S. Butt, I. Ali and K. Govindan, The role of reverse logistics in a circular economy for achieving sustainable development goals: a multiple case study of retail firms, *Prod. Plann. Control*, 2024, **35**, 1490–1502.
207 N. Fulop, *Sustainable and Natural Techniques in Model Making and Other Industries Thesis Declaration of Originality*, Institute of Art, Design + Technology, 2024.
208 N. Shakelly, et al., Comparative Life Cycle Assessment of Bioethanol Production from Different Generations of Biomass and Waste Feedstocks, *Proced. CIRP*, 2023, **116**, 630–635.
209 A. Sanni, A. S. Olawale, Y. M. Sani and S. Kheawhom, Sustainability analysis of bioethanol production from grain and tuber starchy feedstocks, *Sci. Rep.*, 2022, **12**, 1–15.
210 T. Numjuncharoen, S. Papong, P. Malakul and T. Mungcharoen, Life-Cycle GHG Emissions of Cassava-Based Bioethanol Production, *Energy Procedia*, 2015, **79**, 265–271.
211 S. Foteinis, V. Kouloumpis and T. Tsoutsos, Life cycle analysis for bioethanol production from sugar beet crops in Greece, *Energy Policy*, 2011, **39**, 4834–4841.
212 P. Gallejones, G. Pardo, A. Aizpurua and A. del Prado, Life cycle assessment of first-generation biofuels using a nitrogen crop model, *Sci. Total Environ.*, 2015, **505**, 1191–1201.

213 D. Maga, et al., Comparative life cycle assessment of first- and second-generation ethanol from sugarcane in Brazil, *Int. J. Life Cycle Assess.*, 2019, **24**, 266–280.
214 O. Cavalett, M. F. Chagas, J. E. A. Seabra and A. Bonomi, Comparative LCA of ethanol versus gasoline in Brazil using different LCIA methods, *Int. J. Life Cycle Assess.*, 2013, **18**, 647–658.
215 S. González-García, et al., Environmental profile of ethanol from poplar biomass as transport fuel in Southern Europe, *Renewable Energy*, 2010, **35**, 1014–1023.
216 H. Wei, et al., Direct vegetation response to recent CO_2 rise shows limited effect on global streamflow, *Nat. Commun.*, 2024, **15**, 9423.
217 P. Dłuzewski, K. Wiatrowska and S. Kuśmierz, The Role of Stand Age in Soil Carbon Dynamics in Afforested Post-Agricultural Ecosystems: The Case of Scots Pine Forests in Dfb-Climate Zone, *Forests*, 2024, **15**, 2127.
218 W. Y. Lam, et al., Estimating greenhouse gas emissions from direct land use change due to crop production in multiple countries, *Sci. Total Environ.*, 2021, **755**, 143338.
219 P. Mounica, N. Karuppiah, S. Tamilselvi and T. Jarin, Feasibility and possibility of biofuel-based electric vehicles in the electric vehicle market, in *Renewable Energy for Plug-In Electric Vehicles*, Elsevier, 2024, pp. 111–127, DOI: 10.1016/B978-0-443-28955-2.00008-1.
220 H. Priadi, S. Awad, A. Villot, Y. Andres and W. W. Purwanto, Techno-enviro-economic analysis of second-generation bioethanol at plant-scale by different pre-treatments of biomass from palm oil waste, *Energy Convers. Manage.:X*, 2024, **21**, 100522.
221 J. Lynch, M. Cain, R. Pierrehumbert and M. Allen, Demonstrating GWP: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants, *Environ. Res. Lett.*, 2020, **15**, 044023.
222 M. A. Mac Kinnon, J. Brouwer and S. Samuelsen, The role of natural gas and its infrastructure in mitigating greenhouse gas emissions, improving regional air quality, and renewable resource integration, *Prog. Energy Combust. Sci.*, 2018, **64**, 62–92.
223 E.-M. Ursache and C. Bradu, Nitrogen-Based Nutrient Pollution of Water Bodies: Impact on the Aquatic Ecosystems and Human Health, *Publishing House of the Romanian Academy*, 2024, **26**, 37–45.
224 I. W. Kularathne, C. A. Gunathilake, A. C. Rathneweera, C. S. Kalpage and S. Rajapakse, The effect of use of biofuels on environmental pollution-a review, *International Journal of Renewable Energy Research*, 2019, **9**, 1355–1367.
225 C. M. Igwebuike, S. Awad and Y. Andrès, Renewable Energy Potential: Second-Generation Biomass as Feedstock for Bioethanol Production, *Molecules*, 2024, **29**, 1619.
226 A. Fatima, S. Yadav and D. Srivastava, Sustainable millet-based ethanol production in India: a comprehensive analysis of water footprint and environmental impact, *Discov. Water*, 2024, **4**, 65.
227 H. K. Jeswani, A. Chilvers and A. Azapagic, Environmental sustainability of biofuels: a review, *Proc. R. Soc. A*, 2020, **476**, 20200351.
228 M. Aghabeygi, V. Strauss, L. Bayer, C. Paul and K. Helming, Sustainable soil management practices provide additional benefit for energy use efficiency, *Heliyon*, 2024, **10**, e39417.
229 R. H. Mumm, P. D. Goldsmith, K. D. Rausch and H. H. Stein, Land usage attributed to corn ethanol production in the United States: sensitivity to technological advances in corn grain yield, ethanol conversion, and co-product utilization, in *Fuel Production from Non-Food Biomass: Corn Stover*, 2015, pp. 245–280, DOI: 10.1201/b18437.
230 C. R. Chilakamarry, A. M. M. Sakinah, A. W. Zularisam and A. Pandey, Glycerol waste to value added products and its potential applications, *Syst. Microbiol. Biomanuf.*, 2021, **1**, 378–396.
231 E. Kovak, D. Blaustein-Rejto and M. Qaim, Genetically modified crops support climate change mitigation, *Trends Plant Sci.*, 2022, **27**, 627–629.
232 I. Muñoz, et al., Life cycle assessment of bio-based ethanol produced from different agricultural feedstocks, *Int. J. Life Cycle Assess.*, 2014, **19**, 109–119.
233 S. Searle, N. Pavlenko, S. El Takriti and K. Bitnere, *Potential Greenhouse Gas Savings from a 2030 Greenhouse Gas Reduction Target with Indirect Emissions Accounting for the European Union*, 2017, https://theicct.org/publications/potential-greenhouse-gas-savings-2030-greenhouse-gas-reduction-target-indirect.
234 M. Wu, M. Mintz, M. Wang and S. Arora, Water consumption in the production of ethanol and petroleum gasoline, *Environ. Manag.*, 2009, **44**, 981–997.
235 M. Berger, S. Pfister, V. Bach and M. Finkbeiner, Saving the planet's climate or water resources? The trade-off between carbon and water footprints of European biofuels, *Sustain*, 2015, **7**, 6665–6683.
236 P. Chowdhury, N. A. Mahi, R. Yeassin, N. U. R. Chowdhury and O. Farrok, Biomass to biofuel: impacts and mitigation of environmental, health, and socioeconomic challenges, *Energy Convers. Manage.:X*, 2025, **25**, 100889.
237 T. Gomiero, Large-scale biofuels production: a possible threat to soil conservation and environmental services, *Appl. Soil Ecol.*, 2018, **123**, 729–736.
238 C. G. Chimera, C. E. Buddenhagen and P. M. Clifford, Biofuels: the risks and dangers of introducing invasive species, *Biofuels*, 2010, **1**, 785–796.
239 S. Desai, M. Singh, A. Chavan, N. S. Wagh and J. Lakkakula, 11 - Micro- and nanoencapsulation techniques in agriculture, in *Agricultural Nanobiotechnology*, ed. S. Ghosh, S. Thongmee and A. Kumar, Woodhead Publishing, 2022, pp. 297–323, DOI: 10.1016/B978-0-323-91908-1.00009-2.
240 A. Gunjal and D. Bhagat, Agrochemicals and their effects on flora and fauna, *Vigyan Varta*, 2021, **2**, 5–11.
241 S. J. Tudge, A. Purvis and A. De Palma, The impacts of biofuel crops on local biodiversity: a global synthesis, *Biodivers. Conserv.*, 2021, **30**, 2863–2883.

242 E. Maletta and C. H. Díaz-Ambrona, Lignocellulosic Crops as Sustainable Raw Materials for Bioenergy, in *Green Energy to Sustainability: Strategies for Global Industries*, 2020, DOI: 10.1002/9781119152057.ch20.
243 I. Vera, R. Hoefnagels, M. Junginger and F. van der Hilst, Supply potential of lignocellulosic energy crops grown on marginal land and greenhouse gas footprint of advanced biofuels—a spatially explicit assessment under the sustainability criteria of the Renewable Energy Directive Recast, *GCB Bioenergy*, 2021, **13**, 1425–1447.
244 J. Valentine, et al., Food vs. fuel: the use of land for lignocellulosic 'next generation' energy crops that minimize competition with primary food production, *GCB Bioenergy*, 2012, **4**, 1–19.
245 R. Mohd Ghazi, et al., Health effects of herbicides and its current removal strategies, *Bioengineered*, 2023, **14**, 2259526.
246 A. Parven, I. M. Meftaul, K. Venkateswarlu and M. Megharaj, Herbicides in modern sustainable agriculture: environmental fate, ecological implications, and human health concerns, *Int. J. Environ. Sci. Technol.*, 2025, **22**, 1181–1202.
247 J. Whalen, et al., Sustainable biofuel production from forestry, agricultural and waste biomass feedstocks, *Appl. Energy*, 2017, **198**, 281–283.
248 A. S. Neto, S. Wainaina, K. Chandolias, P. Piatek and M. J. Taherzadeh, Exploring the Potential of Syngas Fermentation for Recovery of High - Value Resources: A Comprehensive Review, *Curr. Pollut. Rep.*, 2025, **11**, 7.
249 P. Biomass, et al., Syngas from What? Comparative Life-Cycle Assessment for Syngas Production from Biomass, CO_2, and Steel Mill Off-Gases, *ACS Sustain. Chem. Eng.*, 2023, **11**, 5356–5366.
250 H. Sun, et al., Comparative life cycle assessment (LCA) of biofuel production via corn stover: fermentation to ethanol, pyrolysis to bio-oil, and gasification to jet fuel, *Biomass Convers. Biorefin.*, 2023, 12809–12821.
251 E. M. El-Fawal, A. M. A. E. Naggar, A. A. E. Zahhar, M. M. Alghandi, A. S. Morshedy, H. A. E. Sayed and A. E. M. E. Mohammed, Biofuel production from waste residuals: comprehensive insights into biomass conversion technologies and engineered biochar applications, *RSC Adv.*, 2025, **15**, 11942–11974.
252 A. I. Osman, et al., Conversion of biomass to biofuels and life cycle assessment: a review, *Environ. Chem. Lett.*, 2021, **19**, 4075–4118.
253 J. Luo, P. Mar, A. J. J. Straathof and A. Ramirez, Life cycle assessment of hexanoic acid production via microbial electrosynthesis and renewable electricity: future opportunities, *J. Environ. Chem. Eng.*, 2024, **12**, 113924.
254 S. Das, V. Ravi, S. Cheela, B. K. Dubey and M. M. Ghangrekar, Heliyon Design and operation of pilot-scale microbial electrosynthesis for the production of acetic acid from biogas with economic and environmental assessment, *Heliyon*, 2024, **10**, e39950.
255 S. Jung, L. B. Kara, Z. Nie, T. W. Simpson and K. S. Whitefoot, Is Additive Manufacturing an Environmentally and Economically Preferred Alternative for Mass Production?, *Environ. Sci. Technol.*, 2023, **57**, 6373–6386.
256 K. C. Khaire, V. S. Moholkar and A. Goyal, Bioconversion of sugarcane tops to bioethanol and other value added products: an overview, *Mater. Sci. Energy Technol.*, 2021, **4**, 54–68.
257 Sapna, et al., *Corn to Ethanol: Retrospect's and Prospects, Maize: Leading to a New Paradigm*, 2012, https://iimr.icar.gov.in/wp-content/uploads/2020/03/Corn-to-Ethanol-Retrospects-and-Prospects.pdf.
258 Corn for Biofuel Production – Farm Energy, 2019, https://farm-energy.extension.org/corn-for-biofuel-production/.
259 K. Patel and S. K. Singh, Sustainable waste management: a comprehensive life cycle assessment of bioethanol production from agricultural and municipal waste, *Environ. Sci. Pollut. Res.*, 2024, **31**, 51431–51446.
260 A. Wawro, J. Jakubowski, W. Gieparda, Z. Pilarek and A. Łacka, Potential of Pine Needle Biomass for Bioethanol Production, *Energies*, 2023, **16**, 1–10.
261 S. Bonifacino, et al., Bioethanol production using high density Eucalyptus crops in Uruguay, *Heliyon*, 2021, **7**, e06031.
262 P. Azadi, et al., The carbon footprint and non-renewable energy demand of algae-derived biodiesel, *Appl. Energy*, 2014, **113**, 1632–1644.
263 N. S. M. Aron, K. S. Khoo, K. W. Chew, P. L. Show, W. H. Chen and T. H. P. Nguyen, Sustainability of the four generations of biofuels – a review, *Int. J. Energy Res.*, 2020, **44**, 9266–9282.
264 A. Thomas Kägi and G. Roberts, *Life Cycle Assessment of Ethanol Pro-duction from BOF Gas Production in China (NXBZ)*, 2023, https://lanzatech.com/wp-content/uploads/2023/11/LCA-Ethanol-from-BOF-Gas-NXBZ-v1.3.pdf.
265 S. Cristian Galusnyak, L. Petrescu, I. L. Arpad and C. C. Cormos, Towards value-added chemicals: technical and environmental life cycle assessment evaluation of different glycerol valorisation pathways, *Sustain. Energy Technol. Assessments*, 2024, **72**, 104043.
266 N. Savla, et al., Techno-economical evaluation and life cycle assessment of microbial electrochemical systems: a review, *Curr. Res. Green Sustainable Chem.*, 2021, **4**, 100111.
267 J. Zhou and S. Yan, A Comprehensive Review of Corn Ethanol Fuel Production: From Agricultural Cultivation to Energy Application, *J. Energy Biosci.*, 2024, **15**, 208–220.
268 M. Abdul Kareem Joyia, et al., Trends and advances in sustainable bioethanol production technologies from first to fourth generation: a critical review, *Energy Convers. Manage.*, 2024, **321**, 119037.
269 S. Aghaei, M. Karimi Alavijeh, M. Shafiei and K. Karimi, A comprehensive review on bioethanol production from corn stover: worldwide potential, environmental importance, and perspectives, *Biomass Bioenergy*, 2022, **161**, 106447.
270 Maize (corn) - Daily Price - Commodity Prices - Price Charts, Data, and News, Index Mundi, https://

www.indexmundi.com/commodities/?commodity=corn&months=60.
271 T. S. Lin, H. S. Kheshgi, Y. Song, C. J. Vörösmarty and A. K. Jain, Which crop has the highest bioethanol yield in the United States?, *Front. Energy Res.*, 2023, **11**, 1070186.
272 C. Spandagos, Achieving decarbonization goals through biofuels: policy challenges and opportunities in the European Union and the United States, in *Advances in Biofuels Production, Optimization and Applications*, ed. M. Jeguirim and A. A. Zorpas, Elsevier, 2024, ch. 13, pp. 269–283, DOI: 10.1016/B978-0-323-95076-3.00003-X.
273 E. Olguin-Maciel, A. Singh, R. Chable-Villacis, R. Tapia-Tussell and H. A. Ruiz, Consolidated bioprocessing, an innovative strategy towards sustainability for biofuels production from crop residues: an overview, *Agronomy*, 2020, **10**, 1834.
274 D. Sarkar, P. B. Patil, K. Poddar and A. Sarkar, Boosting 2G bioethanol production by overexpressing dehydrogenase genes in Klebsiella sp. SWET4adh1+adhE: ANN optimization, scale-up, and economic sustainability, *Renewable Energy*, 2025, **239**, 122093.
275 J. Jezek, *Analysis of Dynamic Networks in Large Biofuels Related Financial and Economic System*, Charles University, 2024.
276 J. Miller, C. M. Clark, S. Peterson and E. Newes, Estimated attribution of the RFS program on soybean biodiesel in the U.S. using the bioenergy scenario model, *Energy Policy*, 2024, **192**, 114250.
277 Bioethanol Market Size, Industry Share Growth Forecast Report, markets and markets, https://www.marketsandmarkets.com/Market-Reports/bioethanol-market-131222570.html.
278 A. P. Saravanan, T. Mathimani, G. Deviram, K. Rajendran and A. Pugazhendhi, Biofuel policy in India: a review of policy barriers in sustainable marketing of biofuel, *J. Clean. Prod.*, 2018, **193**, 734–747.
279 A. Christensen and B. Hobbs, A model of state and federal biofuel policy: feasibility assessment of the California Low Carbon Fuel Standard, *Appl. Energy*, 2016, **169**, 799–812.
280 European Environment Agency, *Use of renewable energy for transport in Europe*, 2024, https://www.eea.europa.eu/en/analysis/indicators/use-of-renewable-energy-for.
281 India: ethanol fuel market penetration 2024 | Statista, https://www.statista.com/statistics/1321863/india-ethanol-fuel-and-gasoline-market-penetration/.
282 F. Rosillo-Calle and L. A. B. Cortez, Towards proalcool II-a review of the Brazilian bioethanol programme, *Biomass Bioenergy*, 1998, **14**, 115–124.
283 L. M. Coelho Junior, et al., Sugarcane Bioelectricity Supply in Brazil: A Regional Concentration and Structural Analysis, *Sustainability*, 2025, **17**, 1–20.
284 L. C. Monaco, I. C. Macedo and J. Goldemberg, *The Brazilian fuel-alcohol program*, United States, 1993.
285 J. Goldemberg, The evolution of ethanol costs in Brazil, *Energy Policy*, 1996, **24**, 1127–1128.
286 X. Chen, H. M. Nuñez and B. Xu, Explaining the reductions in Brazilian sugarcane ethanol production costs: importance of technological change, *GCB Bioenergy*, 2015, **7**, 468–478.
287 E. Newes, et al., Ethanol production in the United States: the roles of policy, price, and demand, *Energy Policy*, 2022, **161**, 112713.
288 J. C. Olson, *Structural Shifts in Agricultural Markets Caused by Government Mandates: Ethanol and the Renewable Fuels Standard*, Royal Agricultural College, 2009.
289 J. Vasco-Correa, S. Khanal, A. Manandhar and A. Shah, Anaerobic digestion for bioenergy production: global status, environmental and techno-economic implications, and government policies, *Bioresour. Technol.*, 2018, **247**, 1015–1026.
290 Y. H. Luh and S. E. Stefanou, Learning-by-doing and the sources of productivity growth: a dynamic model with application to U.S. agriculture, *J. Prod. Anal.*, 1993, **4**, 353–370.
291 L. L. Mcphail and B. A. Babcock, *Short-Run Price and Welfare Impacts of Federal Ethanol Policies*, CARD Working Paper, Iowa State University, 2008.
292 G. R. Timilsina and A. Shrestha, *Biofuels: Markets, Targets and Impacts*, 2010, https://download.ssrn.com/worldbank/5364.pdf?response-content-disposition=inline&X-Amz-Security-Token=IQoJb3JpZ2luX2VjEAUaCXVzLWVhc3QtMSJHMEUCIC7VcqatTvowpep%2Bi75AoL8FFSZOngkCW5dYNOWQCvm0AiEA18bBdcceLQGmxZEB6mXQ1TU2%2B809stnlDR5WkyI2Qz8qxgUIvf%2F%2F%2F%2F%2F%2F%2F%2F%2F%2FARAEGgwzMDg0NzUzMDEyNTciDAqXVv9I%2BzKMnxJWGCqaBf0pDZ5Rh4hNlz0lcG2L8xpHstFAuBiml%2FB0pmzEc1obMhEy96afKdFcxH2fjdZy6tWJxUVPiqiPeVCVU5bDc3fdtAA6UJJ1%2BW8aBQzFrQ64CszpIEI5RUIBzBPL5qIpc5kMfHbEfBLVTma3WxXMp3uy%2BPinE6bl2COy5odHoH2jhq.
293 M. Rosegrant, *Biofuels and grain prices: impacts and policy responses*, 2008.
294 A. M. Gallo and M. C. Serluca, *Corporate Social Responsibility and Stakeholders: A Systematic Literature Review*, Accounting and Taxation (IWAT2024), 2024.
295 T. Mai-Moulin, R. Hoefnagels, P. Grundmann and M. Junginger, Effective sustainability criteria for bioenergy: towards the implementation of the European renewable directive II, *Renewable Sustainable Energy Rev.*, 2021, **138**, 110645.
296 E. Webster, Transnational legal processes, the EU and RED II: strengthening the global governance of bioenergy, *Review of European, Comparative & International Environmental Law*, 2020, **29**, 86–94.
297 A. Falanga, M. Picone, F. M. Greco and A. A. Cartenì, Roadmap to Low-Carbon Freight Transport: A Review of EU Directives and Regulations, *WSEAS Trans. Power Syst.*, 2025, **20**, 114–132.
298 C. Panoutsou, et al., Advanced biofuels to decarbonise European transport by 2030: markets, challenges, and policies that impact their successful market uptake, *Energy Strategy Rev.*, 2021, **34**, 100633.

299 A. K. Chandel, R. Arora, R. Gupta, V. Narisetty and V. Kumar, Global Biofuel Alliance and Roadmap for Ethanol Blending Program in India: Analysis and Perspective, *Sugar Tech*, 2024, **26**, 1005–1015.
300 A. P. Saravanan, A. Pugazhendhi and T. Mathimani, A comprehensive assessment of biofuel policies in the BRICS nations: implementation, blending target and gaps, *Fuel*, 2020, **272**, 117635.
301 *Market Penetration Assessment of Biodiesel (B100) and Bioethanol (E100) as Road Transport Fuels in Indonesia*, 2024, https://www.eria.org/uploads/Developing-Biofuel-Based-Road-Transport-Industry.pdf.
302 Renewable Fuel Standard (RFS2): Final Rule | US EPA.
303 C. Grangeia, L. Santos and L. L. B. Lazaro, The Brazilian biofuel policy (RenovaBio) and its uncertainties: an assessment of technical, socioeconomic and institutional aspects, *Energy Convers. Manage.:X*, 2022, **13**, 100156.
304 R. S. Tiburcio, T. Rocha, D. Mac, A. Maria and P. Neto, Brazilian Biofuels Policy (RenovaBio): Overview and Generation of Decarbonization Credits by Biodiesel Production Facilities, *Energy Sustain. Dev.*, 2023, **77**, 101334.
305 X. Han, Y. Chen and X. Wang, Impacts of China's bioethanol policy on the global maize market: a partial equilibrium analysis to 2030, *Food Secur.*, 2022, 147–163.
306 S. Das, The National Policy of biofuels of India – a perspective, *Energy Policy*, 2020, **143**, 111595.
307 A. J. K. Pols, The Rationality of Biofuel Certification: A Critical Examination of EU Biofuel Policy, *J. Agric. Environ. Ethics*, 2015, **28**, 667–681.
308 T. J. Lark, et al., Environmental outcomes of the US Renewable Fuel Standard, *Proc. Natl. Acad. Sci. U. S. A.*, 2022, **119**, e2101084119.
309 R. C. Rial, Biofuels versus climate change: exploring potentials and challenges in the energy transition, *Renewable Sustainable Energy Rev.*, 2024, **196**, 114369.
310 N. S. Mat Aron, et al., Sustainability of the four generations of biofuels – a review, *Int. J. Energy Res.*, 2020, **44**, 9266–9282.
311 A. Gallucci and E. F. Bompard, *Energy interplay in the Mediterranean area in-between ecological transition and geopolitical criticalities*, Polytechnic University of Turin, 2024.
312 T. H. Ng, Y. S. Lim, Y. Z. Lim, K. H. Chan and C. T. Lye, Is economic policy uncertainty detrimental to sustainability? Evidence from Asian countries, *Environ. Dev. Sustain.*, 2024, **26**, 20885–20908.
313 A. O. Ajayi, C. P. Agupugo, C. Nwanevu and C. Chimziebere, Review of penetration and impact of utility solar installation in developing countries: policy and challenges, *Int. J. Front. Eng. Technol. Res.*, 2024, **7**(2), 11–24.
314 T. X. Do and T. A. Vu, Enhancing sustainable ethanol fuel production from cassava in Vietnam, *Energy Clim. Change*, 2024, **5**, 100136.
315 M. Safaripour, A. Ghanbari, E. Seyedabadi and G. Pourhashem, Investigation of environmental impacts of bioethanol production from wheat straw in Kermanshah, Iran, *Biomass Convers. Biorefin.*, 2023, **13**, 5931–5941.
316 R. Morales-Vera, L. Vásquez-Ibarra, F. Scott, M. Puettmann and R. Gustafson, Life Cycle Assessment of Bioethanol Production: A Case Study from Poplar Biomass Growth in the U.S. Pacific Northwest, *Fermentation*, 2022, **8**, 734.
317 J. M. Greene, J. Gulden, G. Wood, M. Huesemann and J. C. Quinn, Techno-economic analysis and global warming potential of a novel offshore macroalgae biorefinery, *Algal Res.*, 2020, **51**, 102032.
318 M. Yasin, et al., Syngas Fermentation into Biofuels and Biochemicals, in *Biomass, Biofuels, Biochemicals*, Academic Press, 2019, ch. 13, pp. 301–327, DOI: 10.1016/B978-0-12-816856-1.00013-0.
319 J. R. C. Rey, et al., A review of cleaning technologies for biomass-derived syngas, *Fuel*, 2024, **377**, 132776.
320 M. Pamei, et al., Challenges and advances in understanding the roadmap for direct hydrogenation of carbon dioxide to ethanol, *Catal. Rev.*, 2024, **68**, 44–90.
321 N. Aggarwal, et al., Microbial engineering strategies to utilize waste feedstock for sustainable bioproduction, *Nat. Rev. Bioeng.*, 2024, **2**, 155–174.
322 D. Carrillo-Nieves, et al., Current status and future trends of bioethanol production from agro-industrial wastes in Mexico, *Renewable Sustainable Energy Rev.*, 2019, **102**, 63–74.
323 C. K. Phwan, et al., Overview: comparison of pretreatment technologies and fermentation processes of bioethanol from microalgae, *Energy Convers. Manage.*, 2018, **173**, 81–94.
324 B. Long, et al., Engineering strategies to optimize lignocellulosic biorefineries, *Nat. Rev. Bioeng.*, 2024, **3**, 230–244.
325 A. Singh, et al., A Comprehensive Review of Feedstocks as Sustainable Substrates for Next-Generation Biofuels, *Bioenergy Res.*, 2023, **16**, 105–122.
326 Advanced Bioethanol - Praj Industries, https://www.praj.net/businesslines/advanced-bioethanol/.
327 Turnkey Green Energy Solutions for Hydrogen, Ammonia & Bioenergy Projects, https://nuberggreen.com/Green-Energy-Hydrogen-Transportation-Chemicals-Fertilizers.php.
328 L. P. Pinheiro, et al., Improving the Feasibility of 2G Ethanol Production from Lignocellulosic Hydrolysate Using Immobilized Recombinant Yeast: A Technical–Economic Analysis and Life Cycle Assessment, *Fermentation*, 2025, **11**, 1–27.
329 Advanced BioFuels USA – Mascoma Announces Consolidated Bioprocessing Advances, https://advancedbiofuelsusa.info/mascoma-announces-consolidated-bioprocessing-advances.
330 Qteros, Israel-based recycling company partner to produce cellulosic ethanol | Ethanol Producer Magazine, https://ethanolproducer.com/articles/qteros-israel-based-recycling-company-partner-to-produce-cellulosic-ethanol-6059.

331 P. Woods, *Algenol Biofuels's DIRECT to ETHANOLTM Technology*, 2009.

332 BIOfuel From Algae Technologies | BIOFAT | Project | Fact Sheet | FP7 | CORDIS | European Commission, https://cordis.europa.eu/project/id/268211.

333 H. Negi, D. C. Suyal, R. Soni, K. Giri and R. Goel, Indian Scenario of Biomass Availability and Its Bioenergy-Conversion Potential, *Energies*, 2023, **16**, 1–17.

334 B. F. M. L. Gomes, S. Vaz Júnior and L. V. A. Gurgel, Production of activated carbons from technical lignin as a promising pathway towards carbon emission neutrality for second-generation (2G) ethanol plants, *J. Clean. Prod.*, 2024, **450**, 141648.

335 P. O. Lemire, et al., GIS method to design and assess the transportation performance of a decentralized biorefinery supply system and comparison with a centralized system: case study in southern Quebec, Canada, *Biofuels, Bioprod. Biorefin.*, 2019, **13**, 552–567.

336 J. Yadav, H. Marwah and C. Kumar, Synthetic biology and metabolic engineering paving the way for sustainable next-gen biofuels: a comprehensive review, *Energy Adv.*, 2025, 1209–1228.

337 Z. U. D. Sheikh, et al., Overcoming limitations of second-generation bioethanol production process through advancements in strain development, *Environ. Sci. Pollut. Res.*, 2025, DOI: 10.1007/s11356-025-36623-w.

338 M. E. H. Osman, et al., Exploring the Prospects of Fermenting/Co-Fermenting Marine Biomass for Enhanced Bioethanol Production, *Fermentation*, 2023, **9**, 1–32.

339 O. Awogbemi and D. V. V. Kallon, Recent advances in the application of nanomaterials for improved biodiesel, biogas, biohydrogen, and bioethanol production, *Fuel*, 2024, **358**, 130261.

340 G. A. Aryee, I. D. Sardinha and C. Branquinho, Linking drivers of food insecurity and ecosystem services in Africa, *Front. Sustain. Food Syst.*, 2024, **8**, 1272332.

341 P. Das, C. K. Jha, S. Saxena and R. K. Ghosh, Can biofuels help achieve sustainable development goals in India? A systematic review, *Renewable Sustainable Energy Rev.*, 2024, **192**, 114246.

342 A. Aui, Y. Wang and M. Mba-Wright, Evaluating the economic feasibility of cellulosic ethanol: a meta-analysis of techno-economic analysis studies, *Renewable Sustainable Energy Rev.*, 2021, **145**, 111098.

343 S. Jain and S. Kumar, Valorization of lignin-rich byproduct from commercial bioethanol process: Production of phenolic-rich bio-oil and high-purity silica, *Biomass Bioenergy*, 2026, **207**, 108805.

344 S. Jain, N. Kasera and S. Kumar, Transforming rice straw into bio-oil and silica via fractionation and liquefaction, *ACS Sustainable Resour. Manage.*, 2025, **2**, 960–970.

345 D. Baskaran, P. Saravanan, L. Nagarajan and H. S. Byun, An overview of technologies for capturing, storing, and utilizing carbon dioxide: technology readiness, large-scale demonstration, and cost, *Chem. Eng. J.*, 2024, **491**, 151998.

346 S. Sikiru, et al., Technology projection in biofuel production using agricultural waste materials as a source of energy sustainability: a comprehensive review, *Renewable Sustainable Energy Rev.*, 2024, **200**, 114535.

347 M. Singh, et al., Advancements and challenges of fuel cell integration in electric vehicles: a comprehensive analysis, *Int. J. Hydrogen Energy*, 2024, **88**, 1386–1397.

348 A. A. C. d. Lago, *Brazil's Ethanol Journey: from 'a fuel of the future' to the 'future of fuel'*, Energyworld, 2022, https://energy.economictimes.indiatimes.com/news/oil-and-gas/brazils-ethanol-journey-from-a-fuel-of-the-future-to-the-future-of-fuel/90941877.

349 K. Bhunia, K. Serbara Bejigo and S. J. Kim, Palladium nanoparticles integrated ternary nickel cobalt iron hydroxide as an efficient bifunctional electrocatalyst for direct ethanol fuel cell, *Chem. Eng. J.*, 2024, **484**, 149306.

350 K. Pandey, M. Pandey, V. Kumar, U. Aggarwal and B. Singhal, Bioprocessing 4.0 in biomanufacturing: paving the way for sustainable bioeconomy, *Syst. Microbiol. Biomanuf.*, 2024, **4**, 407–424.