RECENT PROGRESS IN BIOETHANOL PRODUCTION FROM RENEWABLE BIOMASS AND WASTE: A CRITICAL REVIEW OF TECHNOLOGIES AND CHALLENGES

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Abstract

Increased interest in the sustainable use of bioethanol as an alternative fuel for transportation has been sparked by increasing concerns regarding climate change and carbon dioxide emissions from the transportation industry. There is an immediate need for low-carbon fuels which can be utilized within the existing fuel infrastructure. Issues of food security and sustainability have prompted research into alternative feedstocks such as agricultural wastes, food wastes, forestry wastes, and industrial organic wastes, although first-generation bioethanol produced from food crops plays a major role in global bioethanol production. This review paper critically examines the latest developments in the production of bioethanol from wastes with a focus on pretreatment, hydrolysis, fermentation, and downstream separation techniques that have been reported between the years 2020 and 2025. Literature review was conducted using scientific databases such as Scopus, Web of Science, Science Direct, and Google Scholar. Around 75 articles were selected for comparison depending on parameters such as feedstock quality, process efficiency, scalability, and techno-economic feasibility. The current analysis is focused on industrial-scale issues rather than lab-scale ethanol yield like previous studies. The production of ethanol has been made possible due to the development of physicochemical pretreatment methods and genetically engineered microorganisms that can ferment a mixture of carbohydrates. The scale-up of the process is limited by expensive enzymes, formation of inhibitors, complex process integration, and high-energy separation requirements. In general, the study shows that the production of bioethanol from waste biomass needs an integrated approach.

Keywords: Bioethanol, Renewable biomass, Waste valorization, Lignocellulosic biofuels, Techno-economic analysis.

1. INTRODUCTION

Finding sustainable alternatives to fossil-based transportation fuels has become more urgent due to the growing energy demand in the world, along with growing concerns about greenhouse gas emissions and climate change. The transport sector continues to be one of the largest contributors to carbon dioxide emissions because of its very high dependence on fuels produced from petroleum. Bioethanol has emerged as a good renewable fuel in this respect because of its high-octane number, biodegradability, and the ability to reduce net carbon emissions when produced from renewable feedstocks (Zabed *et al.,* 2021; Kumar *et al.,* 2023). The importance of bioethanol as a transitional fuel in the global energy transition is further heightened by its direct integration into existing fuel infrastructures. Generally, first-generation feedstocks such as corn, sugarcane, and other high-sugar or high-starch feedstocks have been typically utilized as the primary bioethanol sources. The large-scale utilization of first-generation feedstocks as a source of bioethanol bioenergy seems to have created major food security-related issues, coupled with other issues such as competition for arable land and ecological sustainability, despite the resulting potential to attain high yields through existing bioenergy production technology (Naik *et al.,* 2022; Mussatto, 2023). The long-term sustainability of first-generation bioethanol bioenergy has been significantly limited by the food versus fuel controversy, which highlights other sources besides foods.

Therefore, the process of biofuel production via bioethanol fermentation from waste-derived biomass feedstocks including forestry residues, industrial organic waste, and municipal organic waste has become an emerging research area in recent years. These waste-derived feedstocks are promising resources for sustainable bioethanol production using the sustainable process since they are cost-effective, environmentally friendly, and non-competitive for food crop cultivation (Bhatia *et al.,* 2021; Sindhu *et al.,* 2022). However, owing to the complexity of lignocellulose biomass, characterized particularly by higher concentration of lignin and cellulose, it is hard to metabolize this kind of substance and requires an efficient process of pretreatment, hydrolysis, fermentation, etc. (Kumar & Verma, 2024).

In spite of immense research, the viable commercial utilization of advance bioethanol technologies remains relatively low; thus, it remains hindered by high costs of enzymes, energy-intensive operation of downstream processing, and logistics (Gnansounou *et al.,* 2023; Bhatt *et al.,* 2024). There has been no critical evaluation of the current technological developments made, keeping in view techno-economic viability and scalability, much of which has been reviewed, even for bioethanol synthesized via waste- and residue-based biofuel technologies.

Because of high enzyme costs, energy consumption during downstream processing, feedstock transportation, and scaling challenges, the implementation of highly advanced bioethanol systems remains limited in spite of great advancements in the research area (Gnansounou et al., 2023; Bhatt et al., 2024). Most of the review papers published today focus on the feedstock categorization, pretreatment approaches, hydrolysis efficiency, and ethanol yield at the laboratory stage, while technological and economic feasibility, industrialization, and issues of industrial implementation of bioethanol facilities using wastes as raw material have not been discussed enough. Moreover, many earlier reviews consider separate processes without analyzing their constraints and industrial applicability.

Taking into account the process efficiency, scalability, techno-economic viability, environmental sustainability, and possibility for commercialization, the review critically discusses the advances made within bioethanol production from waste-derived and renewable biomass feedstocks in the years 2020 to 2025 (Klein-Marcuschamer et al., 2022). In comparison with the traditional reviews that were oriented toward increasing the yield of bioethanol, the current article presents the more industrial approach to waste-derived bioethanol production.

For conducting the literature search on contemporary research on bioethanol production from wastes, a structured literature review strategy was adopted. Searches on scientific databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar were conducted using keyword pairs such as “bioethanol production,” “waste biomass,” “lignocellulosic feedstock,” “food waste valorization,” “pretreatment,” “fermentation,” “techno-economic analysis,” and “advanced biofuel.” Pilot plant studies, articles published in peer-reviewed journals, and reviews relevant to the subject matter from 2020 to 2025 in English language were considered.

2. CLASSIFICATION OF RENEWABLE BIOMASS AND WASTE FEEDSTOCKS

The production of bioethanol is based on a variety of biomass feedstocks, and they are very different in terms of costs, availability, composition, and sustainability implications. Sometimes, feedstocks are also grouped according to their origin and possible competing demands on food production systems, based on their generation types. However, renewable biomass and wastes, which are generated on a massive scale around the globe, are still gaining more importance as a part of sustainable bioethanol production studies (Sönnichsen, 2024; Igwebuike *et al.,* 2024).

2.1 First, Second, and Third-Generation Feedstocks (brief)

Fruity food crops rich in carbohydrates such as sugarcane, corn, wheat, and barley are first-generation feedstocks, with direct fermentation techniques employed to produce ethanol from them. Though first-generation bioethanol production technologies have been well established, food/ethanol competition, higher food production costs, and ILUC effects pose threats to the sustainability of the technologies (Sönnichsen, 2024; Melendez *et al.,* 2022). Conversely, lignocellulose residues from urban, forest, and crop environments, which constitute second-generation biomass, are abundantly available globally and do not enter food/ethanol competition (Althuri & Venkata Mohan, 2022; Igwebuike *et al.,* 2024). Third-generation feedstocks, as implied and discussed by other researchers, mainly comprised micro and macro algae. These, although promising in terms of productivity, face the negative impact of technology and financial constraints as limitations. The move away from food crops and into alternative feedstocks which can be used to produce ethanol but not at the expense of food security can be traced through this.

2.2 Waste-Derived Feedstocks

The valorization of waste-derived feedstocks-organic materials with little to no current economic value-as substrates for bioethanol has been a key focus of recent study. Despite being produced in vast amounts, these wastes are still not fully utilized in the current biofuel markets.

Agricultural waste is one of the most significant contributors to renewable biomass. On top of over 998 million tons of agriculture waste each year around the world, rice husk, wheat straw, corn stover, and sugarcane bagasse have reported to contain a content of cellulose and hemicellulose above 35% of dry biomass. For example, corn stover plays an important role as a fuel for cellulosic bioethanol, and its global production potential has been estimated to be over 1 billion tons (Ruan *et al.,* 2019, as referenced by other literature). However, despite their availability, only a small portion of these food and other residues is currently being exploited for biofuel production because of problems associated with its scale-up for valorization to biofuel production.

The fermentable sugar and starch compounds present in food and waste, a considerable part of which comprise municipal waste, have the potential for producing alcohol, but this is hampered by factors like heterogeneity and inefficient collection methods. A biorefinery in a circular bioeconomy represents an opportunity for the fractions of lignocellulosic biomass contained in the residuals from the forestry and paper mill industries, which include waste products such as sawdust, wood chips, and pulp sludge. The possibilities include ethanol and various other bioproducts (Lignocellulosic Biomass Valorization for Bioethanol Production, 2022). The availability of such residues avoids competition with agricultural land and reduces most environmental costs linked to waste management.

Other inexpensive feedstocks are industrial organic waste from the food processing and agro-industry, among others. In employing them, there is a reduction in disposal costs and an improvement in the sustainability profile of biorefineries.

Importantly, even if trash and renewable biomass are in abundant supply, availability is not always translated to usage. Large-scale deployment remains affected by issues in pretreatment, collection of feedstock, seasonal unpredictability, and cost competitiveness (Sönnichsen, 2024; Igwebuike *et al.,* 2024). Figure 1 shows the key steps involved in bioethanol production from wastes along with their technical difficulties such as inhibitors production, enzyme inhibition, contamination issues, and high energy consumption. Table 1 summarizes the pros and cons of various feedstocks based on wastes. The main advantage of agricultural and forestry wastes is that they contain abundant biomass; however, they need extensive pretreatment due to the presence of recalcitrant lignin, while food waste is highly fermentable and needs less pretreatment despite contamination.

3. PHYSICOCHEMICAL CHARACTERISTICS INFLUENCING ETHANOL YIELD

The inherent physicochemical characteristics of the renewable biomass materials, including trash, which guide the type, extent, and cost of the required pretreatment, enzymatic hydrolysis, fermentation, as well as guiding the overall cost of the entire production process, are key factors affecting the efficiency of the bioethanol conversion process from the lignocellulosic materials, including trash, due to the inherent complexity and diversity associated with the materials (Zhang *et al.,* 2022).

3.1 Cellulose Crystallinity

The primary factor that influences the hydrolysis of ethanol is cellulose crystallinity. This is the measure of the ordered structure found within cellulose. The hydrolysis of ethanol is more difficult due to the crystalline structure of cellulose, which reduces the rate of ethanol productivity and glucose yield (Li *et al.,* 2023). Additionally, rice straw is composed of crop residues that have a higher rate of crystallinity index when producing bioethanol from agricultural waste. This requires greater pretreatment techniques to reduce the amount of hydrogen bonds found within cellulose to an amorphous structure.

Table 1. Advantages and Limitations of waste derived feedstocks

Feedstock Type	Major Carbohydrate Fraction	Typical Advantages	Major Limitations	Pretreatment Requirement	Industrial Potential
Agricultural residues	Cellulose, hemicellulose	Abundant availability, low cost, non-food biomass, high polysaccharide content	High lignin recalcitrance, seasonal availability, transportation challenges	Moderate to severe pretreatment required for lignin disruption	High potential due to large global availability
Food/kitchen waste	Sugars, starch, organic carbohydrates	High fermentability, low lignin content, rapid hydrolysis, reduced pretreatment demand	Heterogeneous composition, contamination risk, rapid microbial spoilage	Mild pretreatment generally sufficient	High potential for decentralized biorefineries
Forestry residues	Cellulose with high lignin content	Large and continuous biomass supply, high energy density	Strong biomass recalcitrance, difficult enzymatic hydrolysis	Severe pretreatment often necessary	Moderate to high potential with advanced pretreatment technologies
Paper and pulp waste	Processed cellulose fibers	Improved digestibility, partially delignified structure, lower hydrolysis resistance	High moisture content, collection and storage issues	Mild to moderate pretreatment required	Promising for integrated industrial waste valorization
Industrial organic waste	Mixed carbohydrates and organic compounds	Continuous generation, waste management benefits, low feedstock cost	Presence of inhibitory compounds, variable composition	Feedstock-specific pretreatment needed	Moderate potential depending on waste consistency

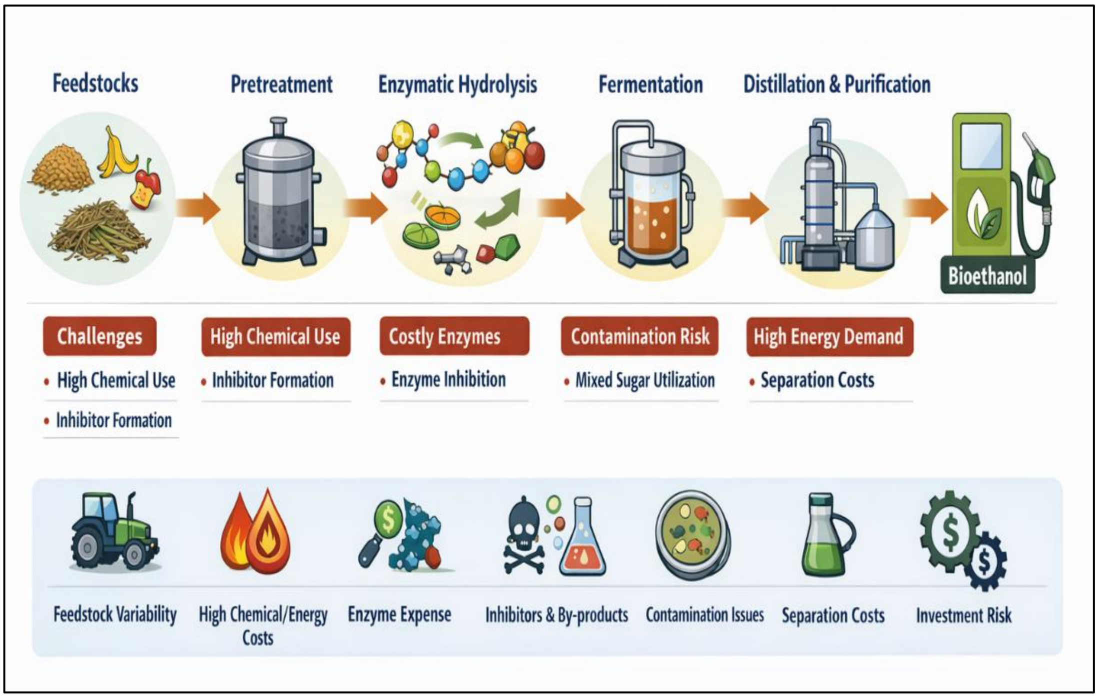

Fig 1. Bioethanol Production from Biomass and Wastes: Process and Challenges

The drawbacks of this method are the increased costs resulting from the use of higher levels of chemicals during the process (Yang *et al.,* 2024). The issue of maximizing the severity of pretreatment, which balances cost effectiveness and improving cellulose crystallinity, remains a major issue when produced bioethanol is utilized.

3.2 Lignin Content and Biomass Recalcitrance

Since the lignin levels restrict enzyme penetration as well as promote ineffective enzyme adsorption, it is one of the main considerations in defining biomass recalcitrance. When comparing biomass such as agricultural residues with small lignin levels, biomass such as forestry residues and paper mill wastes, with a greater lignin level, report lower hydrolysis efficiency and ethanol levels (Xu *et al.,* 2022). As per current investigations, partial modification of lignin instead of removing it completely enhances enzymatic hydrolysis while reducing the use and cost of chemicals (Qin *et al.,* 2023). Nonetheless, lignin remains the fundamental cause of inefficiency in second-generation bioethanol processes and a major aspect in defining process costs.

3.3 Carbon-to-Nitrogen (C/N) Ratio in Waste Substrates

The C/N ratio of the feedstock derived from wastes directly influences microbial growth, metabolic activity, and ethanol yield during fermentation. Low C/N ratios are likely to favour biomass growth over ethanol production, while substrates with a very high C/N ratio may be subjected to nitrogen limitation (Zhou *et al.,* 2023). The C/N ratio often changes for food and kitchen waste due to their diverse nature, leading to inconsistent fermentation performance. Ensuring optimum fermentation conditions sometimes requires supplementation of nutrients or blending of substrates; this increases process complexity and cost (Chen *et al.,* 2024).

3.4 Moisture and Ash Content

The levels of moisture determine the energy required for pretreatment, stability of the storage of the feedstock, and the efficiency of transportation. Food waste and bagasse are samples of wet substances that reduce drying energy input levels while increasing transportation expenditures (Wang *et al.,* 2022). The levels of ash, as seen in crop residues like rice straw, can reduce ethanol production while increasing maintenance expenditures due to chemical interference during the pretreatment process, equipment scaling, and reduced heat transfer rates (Patel *et al.,* 2023). The factors mentioned are specific examples of the need to apply specific preprocessing techniques for the improvement of economic benefits.

In general, the overall physicochemical properties of waste and biomass have a significant influence on the overall cost of production, energy efficiency, as well as ethanol yield. As such, it is evident that to maximize the scalability of ethanol production systems, it is necessary to incorporate feedstock property assessment.

4. RECENT ADVANCES IN PRETREATMENT TECHNOLOGIES (2020–2025)

Since pretreatment significantly impacts cellulose accessibility, cellulose conversion, and overall bioethanol production, it remains to be one of the most critical and costly processes involved in the production of bioethanol from lignocellulosic sources derived from biomass and waste. The major role of pretreatment process is the disruption of the lignocellulosic matrix by degrading the lignin, reducing the cellulose crystallinity, and increasing the biomass surface area. Increasing the efficiency of pretreatment process along with decreasing the chemical consumption, production of inhibitors, energy use, and environmental burden has remained a major objective for the period 2020 to 2025. From comparison of the recent studies, there is no universal pretreatment method which is superior all the time.

4.1 Conventional Pretreatment Methods

As a result of their relatively advanced level of technological feasibility and scale-up potential, traditional methods of pretreatment, such as diluted acid, alkaline, and steam explosion, remain widely studied today. Several investigations report cellulose conversion yields between 65% and 80%, varying according to the type of feedstock and acid concentration. Among these methods, diluted acid treatment displays exceptional performance in terms of hemicellulose dissolution capacity and sugar release rate. However, comparison reveals that excessively acidic conditions produce a significant number of toxic compounds, such as furfural and hydroxymethylfurfural (HMF), reducing fermentation efficiency and increasing detoxification costs (Jönsson & Martín, 2022).

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For agricultural and forestry residues, alkali pretreatment systems have proved superior at removing lignin than dilute acids. Lignin removal efficacy has been estimated at 70%, hence improving glucose recovery rates and enzyme digestibility of lignocellulose (Kim et al., 2023). The use of substantial amounts of chemicals, wastewater treatment, and alkali recovery processes, on the other hand, makes the process expensive in terms of costs and pollution. Steam explosion, on the other hand, looks promising because it uses less chemicals. Nonetheless, comparative research indicates that steam explosion gives uneven results when applied to biomass with high levels of lignin and has low lignin removal efficacies compared to the alkali system (Zhao et al., 2024).

Even with inhibitor formation, energy costs, and chemical costs still hindering the economics of conventional methods of pretreatments, they are still scalable and have been well used in the industry.

4.2 Emerging Hybrid Pretreatment Technologies

To deal with the disadvantages of conventional methods and increase the process sustainability, there is increasing attention being paid to developing novel pretreatment technologies. Based on some comparative studies, hybrid techniques involving biological, chemical, and physical methods can achieve much better performance in terms of biomass conversion efficiency and environmental impact.

IL pretreatment methods have received much attention owing to their strong potential to disrupt lignin-carbohydrate complex networks and solubilize cellulose. In optimal IL treatment conditions, research conducted recently indicates that cellulose conversion is more than 85%, together with appreciable amounts of lignin solubilization (Sun et al., 2023). IL technologies usually produce less inhibitors as well as higher enzyme digestibility compared to conventional acid and alkali pretreatment approaches. However, high solvent prices, solvent viscosities, and complicated solvent recovery operations still make IL-based technologies economically uncompetitive for industrial applications.

Deep eutectic solvents (DES) represent an alternative with better sustainability compared to ionic liquids, considering the lower toxicity, ability to degrade easily, and lower costs associated with their use. It has been reported that DES treatments are able to minimize the environmental impacts of solvent waste management while providing the same level of lignin removal as alkali systems (Zhang et al., 2024). For the pretreatment of agricultural biomass, DESs proved extremely effective, leading to increased levels of sugar yield and better enzymatic accessibility. Long processing times and lack of adequate solvent recycling represent critical issues.

Ultrasound-assisted and microwave-assisted pretreatment technologies have attracted attention as well since they are considered the ways of process intensification. In combination with moderate chemical pretreatment, microwave-assisted pretreatment increases the efficiency of heat transfer processes and disrupts biomass faster, thus resulting in higher sugar release rates. As opposed to conventional heating approaches, according to some studies, pretreatment time was cut down by nearly 50%. However, large scale microwave systems are quite expensive and energy-consuming now. By means of cavitation processes, ultrasound-assisted pretreatment improves the penetration of chemicals into the biomass structure and cell wall disruption. Although these approaches require less use of chemicals, they can be implemented on an industrial scale with some difficulty because of technical issues.

The fungi and microorganisms capable of lignin degradation are applied in biological pretreatment methods that are environmentally friendly and use relatively less energy and generate fewer inhibitors. Based on comparisons conducted, the biological processes are highly effective in the protection of carbohydrates during the pretreatment process. Nonetheless, long residence time, inefficient delignification, and slow reaction rates are still a major challenge to the application of these methods (Shirkavand et al., 2023). Biological processes have therefore shown lower productivity compared to physicochemical processes despite performing excellently in the environment.

All in all, it appears that the optimal strategy for bioethanol production through industry is that of a hybrid pre-treatment process that uses either physical or biological enhancements, coupled with gentle chemical pre-treatment. This combination optimizes sugar recovery, minimizes inhibitor formation, provides energy conservation, and improves environmental sustainability. Nevertheless, problems of solvent recovery, complexity of operations, and heavy capital investments are still barriers to commercial application. Table 2 provides a comparative assessment of the benefits and drawbacks of traditional and new pretreatment methods applied in the production of bioethanol from wastes. Dilute acid and alkali pretreatment methods are known to be highly efficient in terms of biomass breakdown, but they result in inhibitor production, generate wastewater, and are costly. New techniques like ionic liquid and deep eutectic solvent treatments are more effective at removing lignin and environmentally friendly; yet their implementation in industry is constrained due to difficulties in recycling and cost-effectiveness.

5. ADVANCES IN ENZYMATIC HYDROLYSIS AND SUGAR RECOVERY

During the process of bioethanol manufacture from wastes and renewable resource biomass, enzymatic hydrolysis represents a key process step linking pretreatment and fermentation. However, the effectiveness and cost of enzymatic conversion remain crucial barriers, especially for heterogeneous wastes, despite significant advancements observed to date in pretreatment technologies. With a focus on the sugar yield and enzyme costs, the latest research activities have been dedicated to enzyme technology, process technology, and technologies to reduce inhibitory effects.

5.1 Recent Enzyme Engineering Strategies

During the last five years, enzyme engineering has provided custom mixtures with higher activity against previously pretreated lignocellulosic substrates. Some modern formulations have been designed to increase the rates of cellulose depolymerization under milder conditions by supplementing cellulases, hemicellulases, and β-glucosidases with accessory enzymes like LPMOs (Johansen *et al.,* 2022). Enzyme genetic and protein engineering has also been done to further enhance thermostability and resistance to inhibitors commonly found in hydrolysates derived from wastes (Zhang *et al.,* 2023). Even though these modified enzymes provide increased sugar yields, their manufacturing cost prohibits widespread industrial applications.

Table 2. Evaluation of pretreatment technologies for Bioethanol Production

Pretreatment Method	Efficiency	Cost	Environmental Impact	Scalability	Major Limitation
Dilute acid	High hemicellulose removal	Moderate	Inhibitor formation and corrosion	High	Detoxification requirement
Alkaline	High lignin removal	High	Wastewater generation	Moderate	Chemical recovery complexity
Steam explosion	Moderate–high biomass disruption	Moderate	Relatively low pollution	High	Incomplete lignin removal
Ionic liquids	Very high cellulose dissolution	Very high	Low emissions but solvent recovery issues	Low	High solvent cost
DES	High lignin removal	Moderate	Biodegradable and low toxicity	Moderate	Slow solvent recycling
Microwave-assisted	High in hybrid systems	High	Reduced chemical use	Low–moderate	High energy demand
Biological (fungal)	Low–moderate lignin degradation	Low	Environmentally benign	Low	Slow processing rate

5.2 Enzyme Recycling and Immobilization Approaches

Recent research has focused on enzyme recycling and immobilization techniques aimed at prolonging enzyme use over multiple cycles of hydrolysis to reduce enzyme costs. Immobilization on solid supports such as silica, magnetic nanoparticles, and biopolymer matrices has demonstrated improved enzyme stability and reusability, particularly for hydrolysis of food waste and agricultural residues (Kumar *et al.,* 2024). However, the additional capital costs of immobilization systems along with limitations imposed by mass transfer and enzyme leakage reduce the economic viability at scale. While enzyme recycling using ultrafiltration or adsorption-desorption has shown partial success, efficiency often deteriorates due to lignin interactions and inhibitor-mediated enzyme inactivation (Ragauskas *et al.,* 2022).

5.3 Inhibition Effects on Sugar Recovery

Furthermore, the enzymatic degradation of processed biomass and trash remains impacted by inhibitors such as furfural, HMF, and phenolics. The alteration in protein structure caused by these inhibitors or the blocking of enzyme active sites have shown negative effects on enzymes (Liu *et al.,* 2023). Waste biomass feedstocks are also shown to be sensitive to changes in the amounts of inhibitors formed throughout the process, leading to inconsistencies in efficiency in the enzymatic degradation process. Even though the efficiency of processes such as overliming, biological treatments, and the use of activated carbon filters has been researched in additive processes to waste biomass enzymatic degradation processes, their applicability remains restricted by the costs involved in the processes (Moreno *et al.,* 2024).

5.4 Why Enzyme Cost Still Dominates Overall Economics

Enzyme costs still constitute a big share of the total costs associated with the production of bioethanol, even with the current improvements in technology. In waste-based processes, high enzyme dosages are regularly required to compensate for the presence of inhibitors and partial delignification, which in turn tends to increase the operational costs (Klein-Marcuschamer, *et al.,* 2022). In addition, the high costs of recalcitrance and the sensitivity to process fluctuations overshadow the importance of advanced enzymes because of their low recyclability. The need for integrated solutions is underscored by the point that the cost of enzymes still presents a major barrier to the industrial-scale production of bioethanol from renewable biomass and waste materials.

6. FERMENTATION TECHNOLOGIES AND MICROBIAL INNOVATIONS

The final biological process of ethanol production using heterogeneous waste substrates and biomass as raw material is fermentation, which holds great importance for economical processes, efficient substrate utilization, and production of bioethanol. Bioethanol fermentation for large scale commercialization using heterogeneous waste materials still poses certain challenges such as inhibition, mixed sugar fermentation, variability of the substrate and process integration even after advancements made in microbial fermentation from 2020 to 2025. The comparison of research carried out during these years highlights that many advanced fermentation processes show excellent yields of bioethanol in laboratory conditions; however, their industrial application depends upon feedstock and microbial tolerance.

6.1 Conventional Fermentation Pathways: Comparative Perspective

The three traditional methods used in fermentation to generate lignocellulosic and biowaste ethanol are SHF (separate hydrolysis and fermentation), SSF (simultaneous saccharification and fermentation), and SSCF (simultaneous saccharification and co-fermentation). Based on the findings of comparative studies carried out, there are certain strengths and weaknesses of each of the configurations depending on the feedstock used.

In contrast to HTSHF, where both enzyme hydrolysis and fermentation take place concurrently, both SHF and THF involve independent enzyme hydrolysis and fermentation steps, thus allowing for increased process flexibility. It has been proven that SHF can attain high sugar conversion yields thanks to optimization of temperature and pH conditions. Nevertheless, accumulation of fermentable sugars in hydrolysis stage frequently leads to end-product inhibition and risk of contamination, especially when using hydrolysates derived from waste sources with variable microorganisms' content (Olsson et al., 2022).

Since SSF decreases reactor size and prevents the accumulation of glucose, this method has gained much attention. From comparisons, it is evident that compared to SHF, SSF provides better ethanol production and less possibility of contamination. As simultaneous sugar utilization leads to decreased enzyme inhibition, an increase in ethanol production by 10-20% has been observed from optimal SSF process conditions (Basso et al., 2023). Nonetheless, SSF results in a compromise between the best temperatures for microbial fermentation and enzymes, and as a result, process effectiveness is reduced.

SSCF has been developed as a modern alternative that is able to ferment both pentoses and hexoses simultaneously, thereby increasing the overall carbon conversion efficiency from lignocellulose biomass. As pentose sugars such as xylose and arabinose can be fermented as well, SSCF is characterized by better ethanol yield performance theoretically than SSF and SHF methods. Nevertheless, comparative analysis of different systems demonstrates that SSCF is very susceptible to the complexity of microorganism interaction and inhibitor formation, particularly for heterogeneous waste-based hydrolysates (Zhang et al., 2024). The key problems preventing its implementation include system instability and microorganism metabolic balancing.

In general, SSF and SSCF demonstrate higher ethanol productivity and integration efficiency in comparison to SHF. However, all the described approaches are highly dependent on the specific waste material and thus pose problems for scaling up and reproducibility.

6.2 Genetically Engineered and Robust Microorganisms

The creation of robust strains of bacteria capable of fermenting a mixed stream of sugars under harsh industrial conditions is what has dominated breakthroughs in the realm of microbial engineering. Mutated variants of Saccharomyces cerevisiae have demonstrated better performance in pentose sugars fermentation, such as xylose and arabinose, compared to other microorganisms, resulting in higher production of ethanol from lignocellulosic materials (Li et al., 2023). In laboratory conditions, it has been observed that ethanol productivity levels could be about 80-90 percent of the theoretical maximum value. Nevertheless, ethanol production is hampered significantly when inhibitors like furfural, hydroxymethylfurfural (HMF), and phenols are involved in industrial settings.

Since they have been able to work under high temperatures and rigorous processing conditions, the thermotolerant bacteria and those resistant to inhibitors have equally attracted much attention. Strains such as Scheffersomyces stipitis and Kluyveromyces marxianus in pretreated biomass hydrolysates have shown improved fermentation efficiency as well as resistance to inhibiting substances. The thermotolerant strains reduce requirements of cooling and contamination risks in industrial fermentation processes according to studies made on them. Oxygen transfer limitations, variation in inhibitor concentration, and stability of microorganisms in fermenters continue to pose problems.

Alternatively, one can employ co-culture fermentations that make use of synergistic microbial communities for increasing substrate utilization efficiency and inhibitor tolerance. Recent scientific research has shown that co-culture fermentations have advantages over monoculture fermentations with respect to ethanol yield and use of mixed sugars (Chen et al., 2024). Increased inhibitor tolerance and prolonged fermentation performance under varying substrates have been noted in some research involving co-culture fermentations. Nevertheless, some technical challenges remain which hamper the application of co-culture fermentation on an industrial scale.

The main problems include maintaining microbial population balance, overcoming microbial competition and achieving reproducible performance. Overall, based on comparative results, the goal of obtaining maximal possible ethanol production in a laboratory is becoming secondary to microbial tolerance and robustness.

6.3 Laboratory Success Rarely Translates to Industrial Scale

Although there have been remarkable developments in microbial metabolism and fermentation in laboratory-based ethanol production, its commercialization remains a distant reality. One of the key reasons for the disparity lies in the fundamental difference between actual waste-based feedstocks and carefully regulated lab-based hydrolyzate, which varies widely in composition, inhibition level, and availability of nutrients (Díaz et al., 2023). Under the stress conditions encountered in an industrial environment, many highly performing microbial strains under laboratory control fail to maintain their viability and productivity levels.

Among the other challenges associated with the large-scale fermentation process include shear stresses, mass transfer limitations, the threat of contamination, non-uniform heat transfer, and the potential genetic instability of engineered microbes. The presence of these constraints means that when compared on an industrial scale, the amount of ethanol produced is usually significantly lower than reported in laboratory studies. Additionally, due to accumulation of inhibitors, continuous fermentation causes a gradual loss of microbial viability.

Consequently, future efforts in fermentation should not only focus on optimizing ethanol yield but should also consider robustness and flexibility of the process. Laboratory-adapted strains are much less likely to meet commercial success than robust systems that have high adaptability to feedstock variation and process fluctuations, as shown by comparative studies in recent pilot plant tests. Consequently, there is need for a trade-off between innovation of microorganisms and limitations set by industrial processes for successful implementation of bioethanol from waste.

7. INTEGRATED AND INTENSIFIED BIOETHANOL PRODUCTION PROCESSES

Lately, research has essentially targeted process integration and intensification strategies that reduce unit operations, power, and overall production costs, which are geared toward eliminating the operation and economic limitations of conventional techniques in bioethanol production processes. Although improved processes are efficient in mass and energy efficiencies, integrated processes involve the integration of conversion strategies in either one or related processes of bioethanol production. Implementation of these strategies on an industrial scale is currently limited despite their theoretically established processes, although they are applicable to waste-based and renewable biomass processes.

7.1 Consolidated Bioprocessing (CBP)

Enzyme production, biomass breakdown, and fermentation occur simultaneously in a single reactor via a complex technology known as consolidated bioprocessing (CBP). This technology is considered very attractive for the use of lignocellulosic and waste feedstocks since it has the chance of reducing enzyme costs considerably and the technology used might be simpler (Lynd *et al.,* 2022). Research on the utilization of genetically altered microorganisms, including bacteria and fungi, to perform different functions such as ethanol fermentation and cellulose breakdown has been done (Bayer *et al.,* 2023). However, microbial development, enzyme production, and ethanol tolerance pose a problem in achieving high ethanol levels under a process such as CBP. In addition, when the process is exposed to a range of waste materials, results show poor performance and poor robustness of the process.

7.2 Process Integration and Energy Optimization

To enhance the energy efficiency of the process in the production of bioethanol, process integration methods, including heat integration, water recycling, and combination of the pretreatment and fermentation processes, have been widely researched. There is the possibility of reducing energy consumption in the process by as much as 20-30%, as recent simulation and plant-scale studies have shown (Martín & Grossmann, 2023). The anaerobic digestion process, which valorizes residues, has also been suggested as an integrated aspect in waste-based bioethanol processes to enhance the sustainability of the overall process. In most situations, however, the process's economic advantages cannot justify the increase in the degree of process complexity, capital costs, and rigidity in operation, mainly due to the variable supply of the raw materials (Silva *et al.,* 2024).

7.3 Role of Membrane Technologies and In Situ Ethanol Removal

In view of the aforementioned, membrane-based operations for product inhibition reduction, with intensification in fermentation productivity, have been seen as an exciting means for process intensification due to their potential in the application of in situ ethanol removal (ISER), with various techniques including gas stripping, membrane distillation, or even pervaporation being depicted in the literature for the enhancement in ethanol recovery, along with the energy reduction required for the downstream distillation step (Qureshi *et al.,* 2022). On the same note, it should be noted that in applications involving wasteselective fermentation, the major challenge facing degradation operations, i.e., microbes with low ethanol tolerance, is addressed (Zhang *et al.,* 2023).

7.4 Why Integrated and Intensified Processes Are Not Yet Widely Commercialized

Despite the obvious theoretical potential of the improved bioethanol production techniques, the commercialization of these technologies is not very encouraging. It is, for instance, worth noting that the documented successes are mostly based on integrated systems in laboratory scales, which are normally controlled environments in terms of conditions and feedstock makeup. Industrial-scale integrated systems, apart from challenges related to instability in the microbes, variability in the makeup of the feedstock, levels of inhibitors, and high levels of maintenance required, particularly when the feedstocks are wastes, may also be quite challenging due to the operational risks associated with integrated technologies (Kopsahelis & Koutinas, 2024). As a result, they remain pre-commercial technologies in need of further testing, particularly in the industrial arena, despite the overwhelming scholarly interest in integrated bioethanol production technologies.

8. DOWNSTREAM PROCESSING AND DEHYDRATION TECHNOLOGIES

One of the most energy-intensive operations involved in the production of bioethanol using waste and other forms of renewable energy resources is downstream processing, which entails ethanol separation and dehydration processes. While there has been a lot of attention given to increasing the efficiency of upstream operations in bioethanol production, the processes involved in downstream operations still consume a considerable part of the total energy and operational cost required. The recent developments in ethanol recovery and dehydration processes (2020-2025) are critically discussed in this section, with due emphasis on the disadvantages involved.

8.1 Limitations of Conventional Distillation

Due to its robustness, conventional distillation is applied most widely to separate ethanol. However, by its nature, distillation uses a considerable amount of energy, especially so in cases involving low concentrated ethanol, which is normally found in wasted materials. This is due to the ethanol/water azeotrope, which makes further drying stages necessary, hence increasing the need for steam significantly (Goh *et al.,* 2022). Up to 40% of the whole process's energy is wasted in the actual process of distillation, especially in the use of lignocellulose wastes, which, just like in first-generation processes, have lower ethanol titers (Morales *et al.,* 2023).

8.2 Molecular Sieves for Ethanol Dehydration

Due to its high product purity and operational reliability, molecular sieve adsorption has often been applied for the dehydration of ethanol above the azeotropic limit. Recent studies have reported that ethanol purities of more than 99.5% v/v can be achieved with the use of zeolite-based molecular sieves, while a relatively stable performance is maintained. Despite such advantages, molecular sieve systems are sensitive to contaminants commonly encountered in waste-derived ethanol streams. A large amount of energy is also required for the regeneration process of adsorbent. Fouling and/or reduced adsorption efficiency over prolonged operation remains an issue, especially during the processing of fermentation broths obtained from different biomass feedstocks.

8.3 Membrane-Based Separation Technologies

Pervaporation and membrane distillation are two membrane-based separation processes that have been identified as potential alternatives to conventional dehydration techniques. These separation processes have the potential to reduce the overall energy requirement while achieving selective ethanol separation through more `kinder' working conditions (Dong *et al.,* 2024). Waste-based bioethanol processes are attracted to pervaporation processes due to the effective separation of ethanol from fermented broths. However, large-scale application of these two processes has been hindered by the issue of membrane fouling. In addition, the presence of suspended materials in the bioethanol process often negatively influences membrane performance, hence rendering membrane-based processes less reliable in such processes (Zhou *et al.,* 2023).

8.4 Energy Consumption Comparison and Hidden Bottlenecks

Although the availability of alternate separation technologies may decrease the energy intensity of downstream processing in comparison with conventional distillation, the absence of a beneficial impact in industrial operations remains a common conclusion of all comparative investigations of various downstream processing technologies. However, even though various hybrid configurations involving membrane dehydration and conventional distillation may indicate a beneficial scope, they also introduce additional process complexity and capital costs (Ravindran & Sekhar, 2024). Hence, currently, downstream energy absorption remains a hidden constraint against the beneficial impacts of upstream process improvement.

9. TECHNO-ECONOMIC AND ENVIRONMENTAL ASSESSMENT

Technical feasibility and sustainability potential for production of bioethanol from waste biomass require techno-economic and environmental analysis. Techno-economic feasibility and environmental benefits associated with waste biomass-based bioethanol production are still limited because of relatively high operational cost, lack of successful process integration, and poor economic feasibility even with considerable improvements achieved at lab and pilot scales. Effectiveness of pretreatment technology, enzymatic process, biomass transportation, and energy consumption downstream are highly influential on techno-economic feasibility of bioethanol from waste biomass, according to comparative analysis carried out between 2020 and 2025.

9.1 Cost Drivers in Waste-Based Bioethanol Production

Several interrelated factors lead to higher costs associated with the production of bioethanol made from waste materials. The raw materials used in making the bioethanol are cheap when compared to those obtained from food crops; however, because of variability and low bulk density, the cost of handling the biomass may still be high (Kumar et al., 2023). Based on comparisons in several studies, the logistics of the feedstocks can constitute about 20 to 30 percent of the total production costs.

However, in most bioethanol production plants, pretreatment and enzymatic hydrolysis remain the major obstacles. The combined costs incurred by pretreatment and enzymatic hydrolysis remain relatively high at approximately 50-60%, owing to the extensive use of energy, chemicals, and enzymes in these two steps (Humbird et al., 2022). Even though pretreatment using ionic liquids and deep eutectic solvents is efficient in terms of sugar recovery efficiency, its associated solvent recovery significantly escalates costs. Conversely, steam explosion and diluted acid pretreatment techniques may not incur many costs but are associated with inhibitor formation issues.

These two processes of distillation and dehydration belong to the more energy-consuming separation methods and contribute to the significant growth of operational costs. The energy required for bioethanol purification alone may make up 30-40% of the total energy consumption in conventional production systems according to some research. Besides, during laboratory evaluations, the cost of treating water and disposing of wastes is always overlooked; however, on an industrial scale, this becomes important from the economic point of view. Overall, because of process complexity, heavy investments in equipment, and process instability, the minimal ethanol price for waste bioethanol remains higher than that of petroleum gasoline irrespective of technical improvements. Thus, enhancement of enzymes, milder pretreatment conditions, and energy recovery technologies remain key issues for bioethanol commercialization.

9.2 Life Cycle Assessment (LCA) Insights

Bioethanol produced from wastes can provide substantial environmental advantages relative to conventional fuel based on LCA performed in the last five years; nonetheless, results may differ significantly based on the boundary conditions, assumptions about allocation, and energy integration schemes. Based on comparative LCAs, most of the environmental burden of bioethanol production systems can be attributed to energy used for upstream processes like pretreatment, hydrolysis, and distillation (Cherubini et al., 2022).

The research that includes renewable electricity, energy capture from waste heat, and residue use demonstrates that the environmental performance is better and the level of greenhouse gas emissions is lower in comparison with systems that depend on fossil energy in processes. It means that the biorefineries, which utilize lignocellulosic residues for generating energy internally, require less usage of fossil resources and produce fewer amounts of carbon dioxide. However, according to comparative research, a system that uses large amounts of fossil energy can hardly outperform gasoline-based transportation systems environmentally (Zang et al., 2024).

Feedstock choice and its implications to the environment have also recently been pointed out in scientific investigations. The wastes coming from agriculture and food processing industries usually make less impact to the environment because they are not subject to land-use changes just like those crops produced solely for energy generation. Nevertheless, inefficient logistics might negate some aspects of sustainability due to the highly logistical nature of garbage collection operations.

Overall, data based on life cycle assessment reveal that process integration and energy use become increasingly important for the environmental sustainability of bioethanol generated from wastes rather than ethanol production.

9.3 Greenhouse Gas Emission Reduction Potential

Compared with fossil-based fuels, waste-based bioethanol has a lot of potential in lowering GHG emissions in comparison to other alternatives. The recent comparative studies demonstrate that based on the feedstock source, effectiveness of pre-treatment, energy integration approach, and system size, GHG reductions of between 40% and over 80% can be achieved (Lopes et al., 2023). This is since such systems will not only avoid methane releases but will also provide GHG reductions.

Furthermore, results from comparative analysis indicate that renewable energy biorefineries exhibit better performance with respect to reducing carbon emissions. Conversely, energy-intensive downstream processing, excessive enzyme use, and poor ethanol yields are likely to significantly diminish environmental benefits. Despite high ethanol production capability at laboratory scale, some studies suggest that inefficiencies in process integration may result in insufficient reductions in GHG emissions.

In summary, it is evident that merely focusing on enhancing ethanol yields alone does not lead to substantial GHG reductions. Rather, process integration about feedstock, energy requirements during pre-treatment, fermentation capabilities, and downstream processes are required. As shown in Fig. 2, there are several key factors that contribute to the costs associated with large-scale production of ethanol from waste. Enzymes and distillation account for the largest proportion of production costs due to the high enzyme dosage required as well as energy costs associated with separation processes. Pretreatment also accounts for a large proportion of costs due to chemicals and energy costs. Feedstock variability and contamination also influence the process.

9.4 Comparison with Fossil Fuels and Reasons for Pilot-Scale Failure

Even though waste bioethanol has proven itself to be environmentally friendly, its high cost compared to gasoline, resulting from the rising cost of production and operation, remains an obstacle in the market. Considering that laboratory conditions' assumptions do not work out easily in the industrial process, comparative analysis reveals that most pilot plants cannot become successful (IEA Bioenergy, 2023).

One of the major causes behind pilot failure is inconsistency in the feedstock. The variation in terms of moisture level, lignin content, sugar composition, and inhibitor production in industrial waste biomass results in poor fermentation performance and inconsistent ethanol productivity, compared to laboratory feedstock. In addition to that, the problems associated with scale up include mass transfer limitations, fouling of equipment, contamination risks, and higher maintenance costs.

Inadequate consideration of the complexity involved in implementing the steps of pretreatment, hydrolysis, fermentation, and separation as part of an ongoing process was evident in most pilot studies, according to economic evaluations. The unrealistic commercial projections were often brought about by overly optimistic ethanol yields and efficiencies. Besides, the fluctuating market, uncertain price levels of crude oil, and uncoordinated government policies served to undermine investor confidence and deter further industrial implementation of such technologies.

Analysis shows that apart from technological enhancement, other factors including supply chain efficiency, energy management, favourable policies, and proper scale up are required to achieve the commercialization of waste-to-bioethanol technology.

10. SCALE-UP AND COMMERCIALIZATION CHALLENGES

Despite the continuous development in science and several pilot scale experiments, large scale commercialization of bioethanol production from renewable biomass and waste materials is yet to be achieved. Several challenges related to technology, finance, logistics, and policies that have largely been disregarded by academic works are identified once the project is moved from optimizing in laboratory scale to implementing in an industry. Commercial viability is not solely reliant on ethanol production efficiency, but rather, it also involves feedstock availability, process integration, process efficiency,

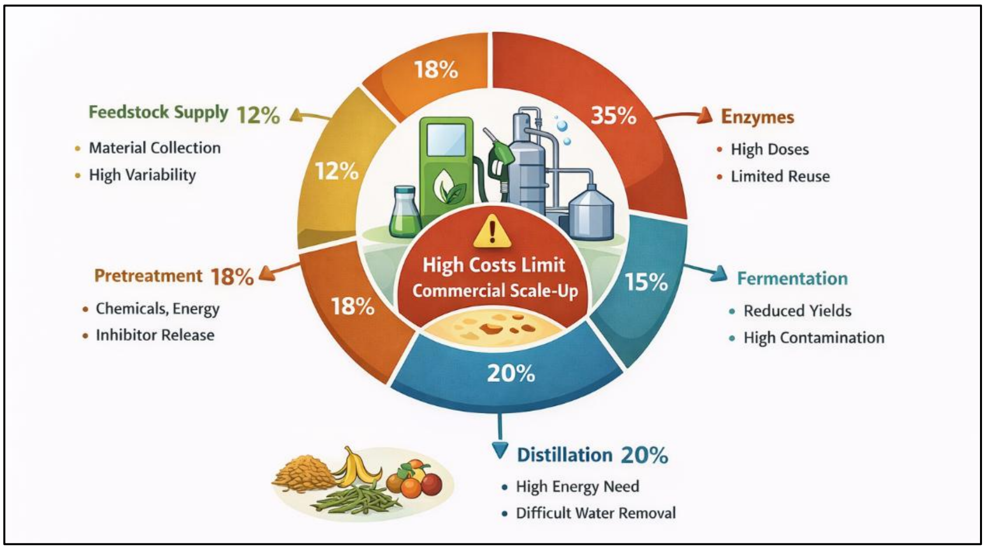

Fig 2. Cost Breakdown of Industrial Bioethanol production

and economic feasibility, based on comparative studies between running and non-running pilot plants. This chapter identifies the most critical challenges hindering the industrialization of waste-to-bioethanol process.

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10.1 Feedstock Logistics and Seasonal Availability

One of the most daunting problems facing the production of bioethanol at an industrial level is the establishment of a stable and constant supply chain of raw materials. Large scale systems must cope with heterogeneity issues regarding composition, moisture, and seasonality unlike small scale tests which employ standardized biomass. Collection, transportation, and storage have been found to be quite complex due to high levels of spatial variation and carbohydrate composition of waste materials from urban areas and agricultural residues.

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Table 3. Laboratory versus industrial challenges in bioethanol commercialization

Area	Laboratory Expectation	Industrial Reality	Commercial Impact	Key Challenge
Feedstock quality	Uniform composition	Highly variable composition	Frequent process adjustment	Supply inconsistency
Pretreatment	High conversion efficiency	Inhibitor formation and corrosion	Increased detoxification cost	Process instability
Enzyme performance	High enzymatic activity	Activity loss due to lignin and inhibitors	Higher enzyme loading cost	Reduced hydrolysis efficiency
Microbial strains	Stable flask performance	Stress and contamination issues	Lower ethanol yield	Poor industrial robustness
Process integration	Energy-efficient operation	Operational complexity	Downtime and maintenance risk	Scale-up difficulty
Economics	Favourable modelled projections	Market and policy volatility	Investor hesitation	Poor economic competitiveness

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Transportation cost of the biomass feedstock is another major operational constraint, especially in distributed biorefineries that utilize multiple sources of waste biomass having low density. Many techno-economic analyses have indicated that storage and transport costs can have a considerable effect on the total cost of the feedstock especially where transport costs exceed economically feasible levels. Moreover, longer period storage leads to reduction in dry matter, microbiological degradation and less availability of fermentable sugars affecting ethanol production adversely.

Failure to secure long-term feedstock supply deals at reasonable prices was another reason for failure in many pilot plants as per comparative industry analysis. There could be variation in plant utilization, fermentation, and pretreatment efficiencies due to the inconsistent or variable nature of feedstock supplied to the facility. For waste streams where inherent heterogeneity of feedstock is inherently higher compared to energy crops, this problem is more challenging. In general, it seems that logistics and feedstock supply chain management remain some of the key issues concerning production of ethanol from waste.

10.2 Enzyme Cost and Capital Investment Constraints

One of the biggest challenges facing the commercialization of lignocellulosic bioethanol production is the issue of enzyme economics. Research suggests that while enzyme engineering techniques have increased the efficiency of hydrolysis and reduced the use of enzymes, enzyme hydrolysis remains among the costliest operations in the commercial production of bioethanol. This is because the nature of the feedstock obtained from wastes tends to be complex, and thus, custom enzymes are required for specific cases, increasing costs and limiting process standardization (Goldemberg et al., 2023).

Inhibitor accumulation, variations in substrate, and changing operating conditions are also observed through comparative pilot scale tests to be the reasons why it is often difficult to maintain enzyme activity levels achieved during laboratory experiments under long-term industrial operations. Low enzyme effectiveness usually results in partial hydrolysis, thereby reducing ethanol output, which ultimately increases the overall cost of production.

High capital expenditure demands are also known to greatly hinder commercialization processes. Large investments are required for reactors, distillation equipment, wastewater management facilities, and energy management structures. Pretreatment and separation processes require relatively large amounts of energy and corrosion resistant materials. Hence, among all of them, pretreatment and separation equipment are the most capital intensive. According to an industrial survey conducted by Balan, equipment fouling, corrosion, unplanned shutdowns, and maintenance complexity are also known to cause overspending (Balan., 2024). Consequently, comparative evidence suggests that reducing enzyme dependency, simplifying pretreatment operations, and improving process integration are essential for improving economic competitiveness with fossil fuel-based systems.

10.3 Policy, Market, and Infrastructure Gaps

Despite technological advancements made in waste-based ethanol processes, one of the external influences encouraging the commercialization of advanced biofuels is policy support. It can be seen from comparative international studies that nations with effective policies on carbon reductions, renewable fuel use, and financial inducements tend to have greater deployment of advanced bioethanol production technologies compared to regions with inconsistent regulatory environments (Carriquiry et al., 2022).

Nonetheless, the changing incentive structure of governments, unclear carbon pricing mechanism, and subsidization of fossil fuels continue to lead to limited confidence among investors for such bioethanol ventures. The competitiveness of waste-based bioethanol production process may also be affected by economic instabilities caused by fluctuating crude oil prices.

There is a problem regarding infrastructure development in this regard. Ethanol blending, storage, and distribution are currently unable to benefit from the infrastructure for fuel supply existing in various locations. According to comparative analyses, there is a serious delay in industrial adoption due to inefficient interactions between energy infrastructure, waste management systems, and climate change policies. In addition, investment planning processes are complicated by lack of coordinated efforts in waste valorization and production of transport biofuels.

10.4 Case Studies of Failed or Stalled Bioethanol Plants

Generally, policy frameworks should include energy security, waste management, and GHG emissions reduction objectives in comparison with separate biofuel programs.

Examples of projects which have not succeeded or even failed include several lignocellulosic bioethanol schemes in North America and Europe where, amongst other factors, low than expected ethanol yields, inconsistent quality of feedstock used, operational instability, and much greater costs of operation than predicted are amongst common problems identified during comparative analysis of these plants (Searle and Malins, 2023).

to the dependence on subsidies by the government and premature commercialization before maturation of technology.

But despite being incomplete, these projects can provide lessons that will help in future endeavours. A realistic techno-economic analysis, feedstock flexibility, a staged scale-up strategy, and proper integration of process engineering, logistics and policy frameworks are required to make the commercialization efforts successful. The large difference between the results obtained at laboratory scale and those at industrial scale for ethanol production is shown in Fig. 3. Even though laboratory-scale production yields efficient conversion rates of materials, several difficulties are encountered at industrial scale, such as the use of variable feedstock, inhibitors, unstable enzymes, corrosion, and high production costs. All these contribute greatly to lower the expected ethanol yield.

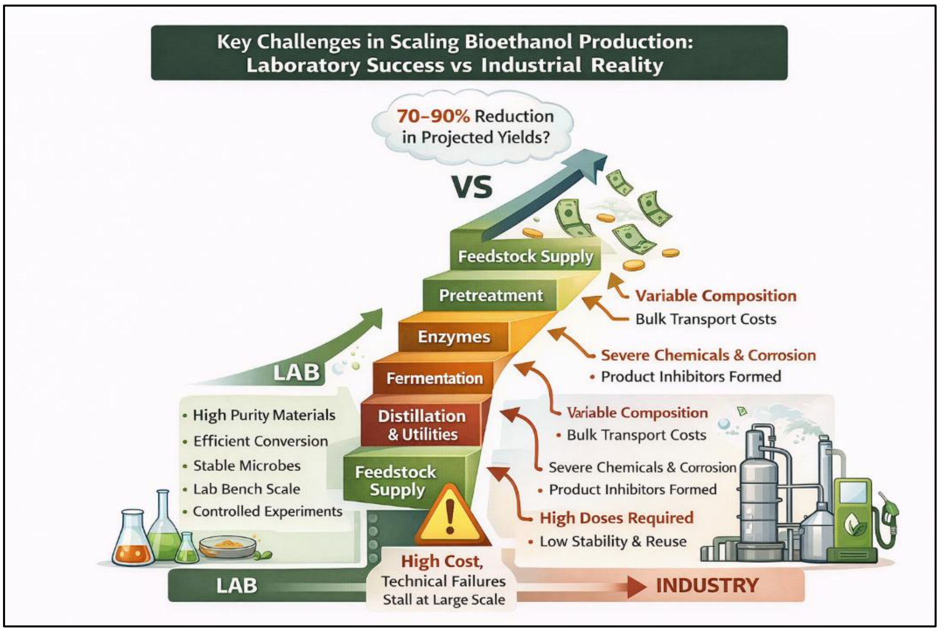

Fig 3. Key Challenges in scaling Bioethanol Production: Laboratory Success Vs Industrial Reality

Without the necessary pilot scale testing in actual industrial environment, most facilities based their expectations primarily on successful results obtained at laboratory scale. In this way, problems related to unexpected poor heat and mass transfer, severe equipment fouling, inhibitors and unstable microorganism performance have been revealed. In several cases, the performance of the plant and its financial stability have been negatively influenced by difficulties in obtaining consistent feedstock supplies.

In comparative studies, it is found that many initiatives have been failures due to erroneous expectations concerning the technical difficulty of achieving a continuous process, involving pretreatment, hydrolysis, fermentation, and purification, that could prove economically feasible. The financial aspects were further compounded due

11. ROLE OF BIOETHANOL IN THE ENERGY TRANSITION AND CIRCULAR ECONOMY

Apart from being a renewable energy source, bioethanol derived from waste and other biomass is gaining importance as a component of the overall frameworks for the implementation of a circular economy and energy shift. In fact, as policy and system-level study find, a vital consideration at this point is that the benefits of bioethanol extend beyond greenhouse gas reduction. This includes a critical evaluation of bioethanol functions along with their circumstances under which it is considered to play a vital role.

11.1 Waste Valorization and Resource Circularity

Since food scraps, industrial organic wastes, and agricultural leftovers have been converted into valuable energy forms, it directly promotes the concept of the circular economy theory. These wastes are redirected or diverted into bioethanol production channels rather than dumping them or burning them, which helps in efficient use and reduction of wastes and their associated impacts on the environment (Geissdoerfer *et al.,* 2022). According to recent studies, particularly in regions that are very agricultural, the production of bioethanol and wastes would significantly minimize the costs associated with wastes and their impacts, especially with regards to the environment (Velenturf & Purnell, 2023). However, feedstock supply, logistics, and collaboration between wastes providers and bioethanol plants are requirements for the successful valorization of wastes.

11.2 Role of Rural Biorefineries in Regional Development

Rural and decentralized biorefineries have been proposed as tools to provide employment opportunities in the rural region, boost the rural energy production business, and reduce carbon emissions through reduced transportation costs. Rural biorefineries can support the economic growth of the region and ensure energy security through the utilization of available biomass and trash in the region (Batidzirai *et al.,* 2022). The problem in the operation of small businesses is the high production costs per unit, lack of skilled labor, and inability to access capital. The biorefineries are unable to compete with the use of fossil fuels because of the lack of supply chain and government support systems, thereby hindering their extensive use.

11.3 Integration with Existing Fuel Infrastructure

One of the major advantages of bioethanol in the climate change mitigation process, which will bring about a transition in the present energy mix, is the compatibility of bioethanol with the existing energy infrastructure for energy supply and blending (Hamelin *et al.,* 2024). Bioethanol blending into gasoline at various degrees necessitates no major changes in the infrastructure, and this energizing prospect will increasingly lead towards a climate-friendly future. In this direction, it was found that waste-derived bioethanol emerges as an even more formidable alternative because of its contribution in realizing emission reduction targets while circumventing conflicts between food and fuel production. However, there are challenges still in integrating it into the existing infrastructure on a high scale, mainly because of variations in fuel standards in different regions, blending incompatibilities, and engine compatibility problems at higher concentrations.

Considering all these factors, the bioethanol made from waste and biomass material has the potential to play an important role in the circular economy. In the end, technical progress must go hand in hand with systemic factors like waste management plans, infrastructural preparedness, and government policies.

12. RESEARCH GAPS AND FUTURE PERSPECTIVES

Even though progress has been made in the production of bioethanol from waste and biomass, the largescale implementation and sustainability of the process remain limited and restricted by several research needs. This calls for a departure from the conventional concept of technological optimization and moving into the realm of integrated strategies that consider the reality of real-world industrial and socio-economic conditions.

12.1 Key Research Gaps in Current Studies

The overdependence on results obtained during experimentation to measure performance at lab-scale, where such measurements often utilize a model substrate or a synthetic hydrolysate not reflective of actual waste-derived materials, is a major drawback of current research in the field. Factors critical to performance at industrial levels, such as feedstock variation, inhibitor development, and microbial stability, along with downtime, are usually ignored in studies that report economically viable levels of ethanol produced (Moncada *et al.,* 2022). Downstream processing, such as fermentation and enzymatic hydrolysis, is carried out separately, and such a system is not necessarily optimal.

There is a lack of a standardized life cycle assessment and techno-economic framework, which has been a substantial issue. It is very challenging to examine the studies' results, as there are often inconsistencies in the system boundary, assumptions, and functional units. This makes generalization about positive economic and environmental results too favorable (Jeswani *et al.,* 2023). There has been little focus on supply chain, policy, and market issues, all of which play a major role in the economic viability of the process but are still underrepresented in the context of research studies.

12.2 Realistic Future Research Directions

The research effort in the future should be directed towards feedstock-flexible technologies, capable of diverse and seasonally changing waste streams with a minimum level of preprocessing. According to de Jong et al. (2024), this involves the development of resilient microbial consortia, flexible process management methods, and modular designs for biorefineries that would adapt to changes in feedstock availability. Besides, co-product valorization, better utilization of residues, and integration with renewable energy resources should also form areas of emphasis toward reducing enzyme and energy intensity.

To bridge this gap between success in a laboratory and industrial deployment, there is an urgent requirement for long-term pilot and demonstration studies under real operational conditions. Besides peak performance, such studies should include information about operating stability, maintenance needs, and economic sensitivity regarding changes in input costs.

12.3 Need for System-Level Optimization and Policy Integration

Ultimately, to successfully optimize the system from various technological, economic, and environmental viewpoints, there is a need for sustainable bioethanol production from renewable biomass and trash. More accurate system performance can be achieved using advanced modeling approaches that involve various system optimization, sustainability assessment, and simulation (Papadopoulos & Zabaniotou, 2022). Bioethanol production must follow various waste management practices, climate change, and rural development strategies.

13. CONCLUSION

Emphasizing advancements in science, economics, and hurdles of commercialization, this assessment process critically examined and analyzed advancements in 2020-2025, in relation to the manufacturing of bioethanol from renewable resources and trash. Though there have been advancements in the utilization of feedstock, efficiency of pretreatment, advancements in enzymes, improvements in fermentation, and integrated processing, there has not been a significant move towards taking lab-scale results to industrial-scale results in the methods employed in the manufacture of bioethanol from renewable resources of energy. From such a critical assessment, it has been clear that there is a restriction in place in relation to the synthesis of bioethanol from trash, not in terms of a barrier but a mix of several restrictions.

Some new technologies having promising capabilities to increase conversion efficiency and sustainability include membrane-assisted separation, consolidated and intensified bioprocesses, sophisticated pretreatment, and robust microbial systems. However, high capital costs, operational complexity, and the lack of validation under practical industrial circumstances stand in the way of their wide commercialization. According to techno-economic and life cycle assessments, environmental benefits and greenhouse gas reductions are extremely sensitive to system design decisions and energy integration and process scale. This underpins that optimistic performance promises should be interpreted with care.

It is apparent that in the coming days, enhancements in developing bioethanol from wastes will rely more on system optimization than on making incremental improvements to the operation of individual units within a system. Long-term pilot-scale and demonstration-scale research, flexible feedstocks within a process, energy management, and policy drivers regarding wastes and climate protection need to be further considered and focused on if a prominent and potentially important contribution to a global energy and resource diversion shift, as represented by bioethanol produced from renewable resources and wastes, is to emerge as a viability, as well as a necessity, within technological, financial, and policy drivers.

REFERENCES

Al-Asheh, S., Banat, F., & Qtaishat, M. R. (2021). Molecular sieve dehydration of ethanol: Performance evaluation and industrial challenges. *Separation and Purification Technology, 270*, 118770. https://doi.org/10.1016/j.seppur.2021.118770

Althuri, S., & Venkata Mohan, S. (2022). Classification of bioethanol feedstocks and implications for sustainable biofuel production. *Renewable and Sustainable Energy Reviews, 158*, 112145. https://doi.org/10.1016/j.rser.2022.112145

Balan, V. (2024). Challenges in scaling up lignocellulosic biofuel production: Lessons from demonstration plants. *Biotechnology for Biofuels and Bioproducts, 17*, 21. https://doi.org/10.1186/s13068-024-02401-3

Basso, T. P., de Farias, D., & Basso, L. C. (2023). Strategies for efficient fermentation of lignocellulosic hydrolysates: A comparative analysis of SHF and SSF. *Biotechnology for Biofuels and Bioproducts, 16*, 88. https://doi.org/10.1186/s13068-023-02289-7

Batidzirai, B., Smeets, E., & Faaij, A. (2022). Bioenergy supply from agricultural residues: Regional development and sustainability implications. *Renewable and Sustainable Energy Reviews, 156*, 111962. https://doi.org/10.1016/j.rser.2021.111962

Bayer, E. A., Moraïs, S., & Lamed, R. (2023). Consolidated bioprocessing for biofuel production: Advances and challenges. *Current Opinion in Biotechnology, 79*, 102840. https://doi.org/10.1016/j.copbio.2022.102840

Bhatia, S. K., Jagtap, S. S., Bedekar, A. A., Bhatia, R. K., Patel, A. K., Pant, D., & Yang, Y. H. (2021). Recent developments in pretreatment technologies on lignocellulosic biomass: Effect of key parameters, technological improvements, and challenges. *Bioresource Technology, 300*, 122724. https://doi.org/10.1016/j.biortech.2019.122724

Bhatt, A. H., Ren, Z. J., & Tao, L. (2024). Techno-economic assessment of lignocellulosic bioethanol production pathways: Bottlenecks and opportunities. *Renewable and Sustainable Energy Reviews, 189*, 113816. https://doi.org/10.1016/j.rser.2023.113816

Carriquiry, M. A., Du, X., & Timilsina, G. R. (2022). Advanced biofuels: Policy incentives and market barriers. *Energy Policy, 165*, 112987. https://doi.org/10.1016/j.enpol.2022.112987

Chen, Y., Liu, J., Wang, X., & Zhao, G. (2024). Effect of carbon-to-nitrogen ratio on ethanol fermentation performance using food waste substrates. *Bioresource Technology Reports, 25*, 101628. https://doi.org/10.1016/j.biteb.2023.101628

Chen, Y., Zhao, Z., Liu, J., & Huang, H. (2024). Co-culture fermentation strategies for improved bioethanol production from lignocellulosic biomass. *Bioresource Technology, 387*, 129567. https://doi.org/10.1016/j.biortech.2023.129567

Cherubini, F., Zang, G., & Strømman, A. H. (2022). Life cycle assessment of bioenergy systems: State of the art and future challenges. *Renewable and Sustainable Energy Reviews, 154*, 111816. https://doi.org/10.1016/j.rser.2021.111816

de Jong, E., Jungmeier, G., & Posada, J. (2024). Bio-based production systems: From pilot to commercial scale. *Biofuels, Bioproducts and Biorefining, 18*(2), 355–370. https://doi.org/10.1002/bbb.2591

Díaz, A. B., de Souza Moretti, M. M., & Ballesteros, M. (2023). Challenges in scaling up lignocellulosic ethanol fermentation: From laboratory to industry. *Renewable and Sustainable Energy Reviews, 181*, 113387. https://doi.org/10.1016/j.rser.2023.113387

Dong, Y., Li, P., & Wang, Z. (2024). Advances in membrane-based ethanol separation for biofuel production. *Progress in Energy and Combustion Science, 99*, 101092. https://doi.org/10.1016/j.pecs.2023.101092

Encyclopedia of Bioethanol. (2023). Bioethanol feedstock classification and characteristics. *Encyclopedia, 3*(2), 245–261. https://doi.org/10.3390/encyclopedia3020018

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2022). The circular economy: A new sustainability paradigm? *Journal of Cleaner Production, 365*, 132752. https://doi.org/10.1016/j.jclepro.2022.132752

Gnansounou, E., Dauriat, A., & Villegas, J. D. (2023). Bioethanol production from lignocellulosic biomass: Status, challenges, and perspectives. *Renewable Energy, 216*, 1192–1206. https://doi.org/10.1016/j.renene.2023.06.041

Goldemberg, J., Coelho, S. T., & Guardabassi, P. (2023). Bioethanol production costs and commercialization challenges. *Energy Policy, 172*, 113300. https://doi.org/10.1016/j.enpol.2022.113300

Goh, K., Setiawan, L., & Bae, T. H. (2022). Energy-efficient separation technologies for bioethanol purification. *Energy & Environmental Science, 15*(6), 2321–2340. https://doi.org/10.1039/D2EE00312K

Hamelin, L., Borzęcka, M., & Wenzel, H. (2024). Biofuels in future energy systems: Infrastructure compatibility and sustainability trade-offs. *Energy Conversion and Management, 295*, 117541. https://doi.org/10.1016/j.enconman.2023.117541

Humbird, D., Davis, R., & Tao, L. (2022). Economic impact of feedstock and enzyme costs in cellulosic biofuel production. *Biofuels, Bioproducts and Biorefining, 16*(4), 789–802. https://doi.org/10.1002/bbb.2379

IEA Bioenergy. (2023). *Status and challenges of advanced biofuel commercialization*. IEA Bioenergy Task 39.

Igwebuike, C. M., Awad, S., & Andrès, Y. (2024). Renewable energy potential: Second-generation biomass as feedstock for bioethanol production. *Molecules, 29*(7), 1619. https://doi.org/10.3390/molecules29071619

International Energy Agency. (2023). *Renewables 2023: Analysis and forecast to 2028*. IEA.

Jeswani, H. K., Chilvers, A., & Azapagic, A. (2023). Environmental sustainability of biofuels: A critical review of life cycle assessment studies. *Renewable and Sustainable Energy Reviews, 172*, 113037. https://doi.org/10.1016/j.rser.2022.113037

Johansen, K. S., Lærke, P. E., & Felby, C. (2022). Enzyme technology for lignocellulosic biomass conversion: Recent advances and future perspectives. *Biotechnology Advances, 54*, 107823. https://doi.org/10.1016/j.biotechadv.2021.107823

Jönsson, L. J., & Martín, C. (2022). Pretreatment of lignocellulose: Formation of inhibitory by-products and strategies for minimizing their effects. *Bioresource Technology, 356*, 127259. https://doi.org/10.1016/j.biortech.2022.127259

Kim, J. S., Lee, Y. Y., & Kim, T. H. (2023). A review on alkaline pretreatment technology for bioconversion of lignocellulosic biomass. *Bioresource Technology, 349*, 126850. https://doi.org/10.1016/j.biortech.2022.126850

Kiss, A. A., & Ignat, R. M. (2022). Energy-efficient bioethanol dehydration by adsorption-based processes. *Chemical Engineering and Processing: Process Intensification, 173*, 108806. https://doi.org/10.1016/j.cep.2022.108806

Klein-Marcuschamer, D., Oleskowicz-Popiel, P., Simmons, B. A., & Blanch, H. W. (2022). Technoeconomic analysis of biofuels: A critical update on enzyme costs. *Biofuels, Bioproducts and Biorefining, 16*(1), 8–21. https://doi.org/10.1002/bbb.2301

Kopsahelis, N., & Koutinas, A. A. (2024). Process integration and intensification in biorefineries: Barriers to industrial implementation. *Trends in Biotechnology, 42*(3), 310–323. https://doi.org/10.1016/j.tibtech.2023.10.004

Kumar, A., Murthy, G. S., & Patel, S. K. (2023). Economic challenges of lignocellulosic bioethanol production from waste biomass. *Renewable Energy, 205*, 1083–1094. https://doi.org/10.1016/j.renene.2023.01.067

Kumar, D., & Verma, P. (2024). Recent progress in lignocellulosic bioethanol production: Pretreatment, hydrolysis, and fermentation strategies. *Biotechnology Advances, 69*, 108229. https://doi.org/10.1016/j.biotechadv.2023.108229

Kumar, R., Singh, R., & Pandey, A. (2024). Immobilized enzyme systems for enhanced hydrolysis of lignocellulosic biomass. *Bioresource Technology Reports, 26*, 101728. https://doi.org/10.1016/j.biteb.2024.101728

Kumar, R., Singh, S., & Singh, O. V. (2023). Bioconversion of lignocellulosic biomass: Biochemical and molecular perspectives. *Journal of Cleaner Production, 389*, 136117. https://doi.org/10.1016/j.jclepro.2023.136117

Lamers, P., Junginger, M., & Faaij, A. (2022). Supply chain logistics of agricultural residues for bioenergy applications. *Biomass and Bioenergy, 158*, 106334. https://doi.org/10.1016/j.biombioe.2022.106334

Li, H., Zhang, Y., Sun, J., & Liu, S. (2023). Impact of cellulose crystallinity on enzymatic hydrolysis of lignocellulosic biomass. *Carbohydrate Polymers, 305*, 120530. https://doi.org/10.1016/j.carbpol.2023.120530

Li, X., Chen, Y., Nielsen, J., & Li, Z. (2023). Engineering *Saccharomyces cerevisiae* for efficient pentose fermentation: Progress and limitations. *Metabolic Engineering, 75*, 1–12. https://doi.org/10.1016/j.ymben.2022.12.004

Liu, Y., Wang, J., & Xu, F. (2022). Microwave-assisted pretreatment of lignocellulosic biomass for bioethanol production: Mechanisms and challenges. *Renewable Energy, 195*, 1225–1237. https://doi.org/10.1016/j.renene.2022.06.081

Liu, Z., Chen, H., & Wang, X. (2023). Inhibitory effects of furfural and phenolic compounds on enzymatic hydrolysis of lignocellulosic biomass. *Fuel, 340*, 127493. https://doi.org/10.1016/j.fuel.2023.127493

Lopes, M. L., Paulillo, S. C. L., & Godoy, A. (2023). Greenhouse gas emissions of bioethanol production systems: A comparative assessment. *Energy Policy, 176*, 113531. https://doi.org/10.1016/j.enpol.2023.113531

Lynd, L. R., Guss, A. M., & Himmel, M. E. (2022). Making consolidated bioprocessing a reality for lignocellulosic biofuels. *Nature Biotechnology, 40*(11), 1612–1620. https://doi.org/10.1038/s41587-022-01409-9

Martín, M., & Grossmann, I. E. (2023). Energy optimization of bioethanol production processes using process integration techniques. *Energy, 263*, 125567. https://doi.org/10.1016/j.energy.2023.125567

Melendez, M. F., Sawarkar, R., & Offei, S. (2022). Classification of biofuel feedstocks: First to third generation. *Energy Reports, 8*, 1234–1248. https://doi.org/10.1016/j.egyr.2022.01.045

Moncada, J., Aristizábal, V., & Cardona, C. A. (2022). Design and analysis of biorefineries based on lignocellulosic biomass: Gaps and challenges. *Bioresource Technology, 344*, 126257. https://doi.org/10.1016/j.biortech.2021.126257

Morales, M., Dávila, J. A., & Ballesteros,M. (2023). Energy analysis of lignocellulosic ethanol production: Role of downstream processing. *Renewable Energy, 209*, 1245–1256. https://doi.org/10.1016/j.renene.2023.02.036

Moreno, A. D., Ibarra, D., & Ballesteros, M. (2024). Detoxification strategies for lignocellulosic hydrolysates: Impact on enzymatic saccharification and fermentation. *Renewable and Sustainable Energy Reviews, 186*, 113654. https://doi.org/10.1016/j.rser.2023.113654

Mussatto, S. I. (2023). Challenges in bioethanol production from first- and second-generation feedstocks. *Biomass and Bioenergy, 170*, 106679. https://doi.org/10.1016/j.biombioe.2023.106679

Naik, S. N., Goud, V. V., Rout, P. K., & Dalai, A. K. (2022). Production of first- and second-generation biofuels: A comprehensive review. *Renewable and Sustainable Energy Reviews, 165*, 112529. https://doi.org/10.1016/j.rser.2022.112529

Lynd, L. R., Guss, A. M., & Himmel, M. E. (2022). Making consolidated bioprocessing a reality for lignocellulosic biofuels. Nature Biotechnology, 40(11), 1612–1620. https://doi.org/10.1038/s41587-022-01409-9

Martín, M., & Grossmann, I. E. (2023). Energy optimization of bioethanol production processes using process integration techniques. Energy, 263, 125567. https://doi.org/10.1016/j.energy.2023.125567

Qureshi, N., Saha, B. C., & Cotta, M. A. (2022). In situ product recovery techniques for bioethanol fermentation: A review. Renewable Energy, 191, 768–781. https://doi.org/10.1016/j.renene.2022.04.048

Silva, C. F. L., Mussatto, S. I., & Roberto, I. C. (2024). Integrated biorefinery concepts for sustainable bioethanol production from waste biomass. Journal of Cleaner Production, 421, 138508. https://doi.org/10.1016/j.jclepro.2023.138508

Zhang, Y., Wang, X., & Li, J. (2023). Challenges of membrane-based ethanol separation in integrated bioprocesses. Separation and Purification Technology, 315, 123678. https://doi.org/10.1016/j.seppur.2023.123678

Al-Asheh, S., Banat, F., & Qtaishat, M. R. (2021). Molecular sieve dehydration of ethanol: Performance evaluation and industrial challenges. Separation and Purification Technology, 270, 118770. https://doi.org/10.1016/j.seppur.2021.118770

Dong, Y., Li, P., & Wang, Z. (2024). Advances in membrane-based ethanol separation for biofuel production. Progress in Energy and Combustion Science, 99, 101092. https://doi.org/10.1016/j.pecs.2023.101092

Goh, K., Setiawan, L., & Bae, T. H. (2022). Energy-efficient separation technologies for bioethanol purification. Energy & Environmental Science, 15(6), 2321–2340. https://doi.org/10.1039/D2EE00312K

Kiss, A. A., & Ignat, R. M. (2022). Energy-efficient bioethanol dehydration by adsorption-based processes. Chemical Engineering and Processing: Process Intensification, 173, 108806. https://doi.org/10.1016/j.cep.2022.108806

Morales, M., Dávila, J. A., & Ballesteros, M. (2023). Energy analysis of lignocellulosic ethanol production: Role of downstream processing. Renewable Energy, 209, 1245–1256. https://doi.org/10.1016/j.renene.2023.02.036

Ravindran, R., & Sekhar, S. J. (2024). Hybrid separation systems for sustainable bioethanol recovery. Journal of Cleaner Production, 418, 138127. https://doi.org/10.1016/j.jclepro.2023.138127

Zhou, J., Liu, X., & Zhang, L. (2023). Fouling behavior of pervaporation membranes in bioethanol separation. Journal of Membrane Science, 681, 121802. https://doi.org/10.1016/j.memsci.2023.121802

Cherubini, F., Zang, G., & Strømman, A. H. (2022). Life cycle assessment of bioenergy systems: State of the art and future challenges. Renewable and Sustainable Energy

Reviews, 154, 111816. https://doi.org/10.1016/j.rser.2021.111816

Humbird, D., Davis, R., & Tao, L. (2022). Economic impact of feedstock and enzyme costs in cellulosic biofuel production. Biofuels, Bioproducts and Biorefining, 16(4), 789–802. https://doi.org/10.1002/bbb.2379

IEA Bioenergy. (2023). Status and challenges of advanced biofuel commercialization. IEA Bioenergy Task 39.

Kumar, A., Murthy, G. S., & Patel, S. K. (2023). Economic challenges of lignocellulosic bioethanol production from waste biomass. Renewable Energy, 205, 1083–1094. https://doi.org/10.1016/j.renene.2023.01.067

Lopes, M. L., Paulillo, S. C. L., & Godoy, A. (2023). Greenhouse gas emissions of bioethanol production systems: A comparative assessment. Energy Policy, 176, 113531. https://doi.org/10.1016/j.enpol.2023.113531

Zang, G., Alves, C. M., & Cherubini, F. (2024). Environmental performance of advanced biofuels: Insights from life cycle assessments. Journal of Cleaner Production, 434, 140282. https://doi.org/10.1016/j.jclepro.2024.140282

Balan, V. (2024). Challenges in scaling up lignocellulosic biofuel production: Lessons from demonstration plants. Biotechnology for Biofuels and Bioproducts, 17, 21. https://doi.org/10.1186/s13068-024-02401-3

Carriquiry, M. A., Du, X., & Timilsina, G. R. (2022). Advanced biofuels: Policy incentives and market barriers. Energy Policy, 165, 112987. https://doi.org/10.1016/j.enpol.2022.112987

Goldemberg, J., Coelho, S. T., & Guardabassi, P. (2023). Bioethanol production costs and commercialization challenges. Energy Policy, 172, 113300. https://doi.org/10.1016/j.enpol.2022.113300

Lamers, P., Junginger, M., & Faaij, A. (2022). Supply chain logistics of agricultural residues for bioenergy applications. Biomass and Bioenergy, 158, 106334. https://doi.org/10.1016/j.biombioe.2022.106334

Searle, S., & Malins, C. (2023). Lessons from failed cellulosic biofuel projects. Energy Strategy Reviews, 45, 101042. https://doi.org/10.1016/j.esr.2022.101042

Thompson, J. L., & Meyer, S. (2023). Feedstock variability and its impact on biorefinery performance. Journal of Cleaner Production, 383, 135405. https://doi.org/10.1016/j.jclepro.2022.135405

Batidzirai, B., Smeets, E., & Faaij, A. (2022). Bioenergy supply from agricultural residues: Regional development and sustainability implications. Renewable and Sustainable Energy Reviews, 156, 111962. https://doi.org/10.1016/j.rser.2021.111962

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2022). The circular economy: A new sustainability paradigm? Journal of Cleaner Production, 365, 132752. https://doi.org/10.1016/j.jclepro.2022.132752

Hamelin, L., Borzęcka, M., & Wenzel, H. (2024). Biofuels in future energy systems: Infrastructure compatibility and sustainability trade-offs. Energy Conversion and Management, 295, 117541. https://doi.org/10.1016/j.enconman.2023.117541

Velenturf, A. P. M., & Purnell, P. (2023). Principles for a sustainable circular economy. Sustainable Production and Consumption, 36, 229–241. https://doi.org/10.1016/j.spc.2023.01.009

de Jong, E., Jungmeier, G., & Posada, J. (2024). Bio-based production systems: From pilot to commercial scale. Biofuels, Bioproducts and Biorefining, 18(2), 355–370. https://doi.org/10.1002/bbb.2591

Jeswani, H. K., Chilvers, A., & Azapagic, A. (2023). Environmental sustainability of biofuels: A critical review of life cycle assessment studies. Renewable and Sustainable Energy Reviews, 172, 113037. https://doi.org/10.1016/j.rser.2022.113037

Moncada, J., Aristizábal, V., & Cardona, C. A. (2022). Design and analysis of biorefineries based on lignocellulosic biomass: Gaps and challenges. Bioresource Technology, 344, 126257. https://doi.org/10.1016/j.biortech.2021.126257

Papadopoulos, K. P., & Zabaniotou, A. (2022). System-level sustainability assessment of bioenergy systems: A review. Energy Conversion and Management, 258, 115497.