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Advances in Bioethanol Production: Innovations in Feedstocks, Pretreatment, and Fermentation Technologies

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ABSTRACT
The global depletion of fossil fuel reserves, environmental degradation, and the urgent need for sustainable energy solutions have accelerated research into bioethanol as a renewable, low-carbon alternative. This review examines recent advances in feedstocks, pretreatment methods, and fermentation technologies for bioethanol production, highlighting their potential to enhance process efficiency, economic viability, and environmental sustainability. First-generation (1G) bioethanol, derived from edible sugar and starch-based crops, faces food security challenges, while second-generation (2G) lignocellulosic biomass is hindered by recalcitrance and high processing costs. Third-generation (3G) feedstocks, such as algae, offer high yields and low land competition but face cultivation and scale-up barriers. Innovations in feedstock utilization including agro-industrial wastes, pulp residues, marine macroalgae, and fruit peels, demonstrate improved conversion efficiency, reduced pretreatment severity, and enhanced coproduct valorization. Advanced pretreatment methods, such as surfactant-assisted hydrolysis, organosolv fractionation, and combined low-severity chemical and enzymatic approaches, significantly improve enzymatic digestibility, minimize inhibitor formation, and reduce chemical consumption. Fermentation advancements, from conventional Separate Hydrolysis and Fermentation (SHF) to integrated approaches like Simultaneous Saccharification and Fermentation (SSF), Simultaneous Saccharification and Co-Fermentation (SSCF), Simultaneous Saccharification, Filtration, and Fermentation (SSFF), and Direct Microbial Conversion/Consolidated Bioprocessing (DMC/CBP), enable higher ethanol yields, efficient pentose utilization, and reduced operational costs. Collectively, these technological developments pave the way for more sustainable, scalable, and economically competitive bioethanol production systems.

Keywords: Bioethanol, Feedstocks, Fermentation, Pretreatment, Technological Innovations.

I. INTRODUCTION

The pressing need for sustainable, renewable and low-carbon energy sources has deepened research into bioethanol as an alternate to fossil fuels. Worldwide fossil fuel reserves are anticipated to reduce significantly within the next forty to fifty (40–50) years, and their combustion continues to drive urban air pollution, climate change and biodiversity loss [1–4]. In 2023, global bioethanol production reached approximately 111 billion liters, with the United States, Brazil, and the European Union producing over 85% [5].As the energy demand for transportation and various industrial processing increases, impact on the environment became of paramount concern [4].

Ethanol as an energy source with high efficiency and low environmental impact has been used as fuel for ethanol flex engines or blended with gasoline for gasoline engines.The numerous advantages of ethanol include; an oxygenate, octane enhancer as well as fuel volume extender. When ethanol is blended with gasoline, it increases the octane rating as well as oxygen content of the fuel, thus resulting in more complete combustion with15% higher combustion efficiency than gasoline [6]. In addition, Reimelt et al.,[7] outlined other benefits of bioethanol as; Lower carbon dioxide emission, lower dust emission, biodegradable, and renewable. As an oxygenate source, bioethanol has the potential to reduce particulate emissions in compression-ignition engines, it also provides reasonable antiknock value, broader flammability limit, higher flame speed and higher heat of vaporization than gasoline [8,9]. These properties pave way for shorter burn time, higher compression ratio and leaner burn engine, which give a theoretical efficiency advantage over gasoline in an internal combustion engine [8]. Lower energy density (it has 66% of the energy than gasoline), corrosiveness, low flame luminosity, lower vapour pressure (making cold start difficult), miscibility with water (which cause phase separation in engines) are common disadvantages attributed to bioethanol [10,11].

Most important industrial production of bioethanol is built on the use of sugar and various starchy (1G) raw materials. These feedstocks are edible and poses a great danger on food securitytherefore, there is a need to source for non-edible starch feedstock of little or no economic value to enhance the production of bioethanol [12]. Second generation feedstock (2G) proved to be the way out however, chemical complexity of its structure hindered the bioconversion of lignocellulosic biomass to ethanol making the feedstock a challenge for ethanol production [13,14]. These challenges led to less than 10% bioethanol production from 2G biomass globally and solutions are been sourced for to overcome it and enhance biomass conversion to bioethanol [11]. A general simplified representation of the process is shown in the figure 1.

The third (3G) generationbioethanol produced from specially engineered energy crops such as algaehave been receiving a lot of attention as a new energy source of the future, sustainable, and capable to reduce use of fossil fuels [15,16]. These algae are characterized with several advantages which include; (i) they are non-food source therefore, no conflict with food crops. (ii) Grows on lands unsuitable for agriculture. (iii) Yield over 30 times more energy per unit area than other biofuels (iv) Characterized with fast growth needing only water, sunlight and carbon dioxide. (v) Consumes huge amount of carbon dioxide thus, reducing greenhouse gases significantly [15,16]. The major drawback to algae biofuel production is in the culture of the biomass.

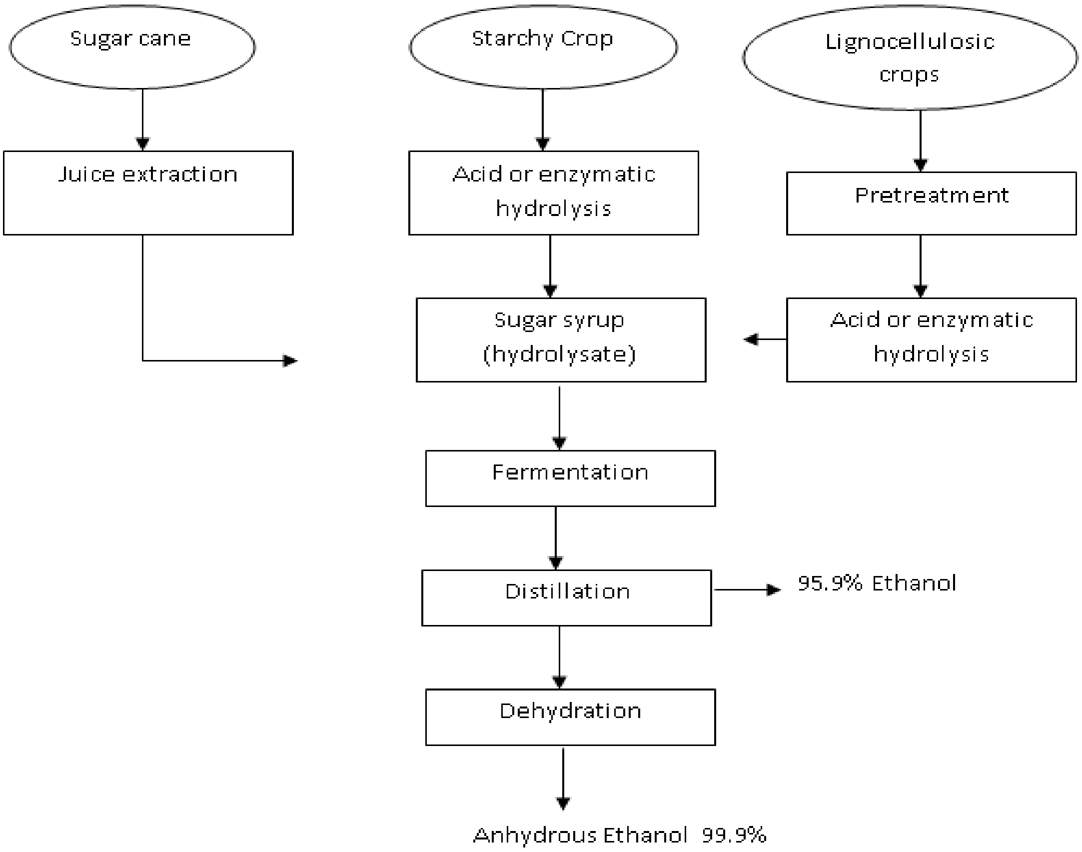

Figure 1. Overall process of bioethanol production

The open-pond system, though cheap and account for 98% of the commercial algae production is susceptible to other microbial attack which can reduce the total biofuel output [16]. The closed system is much more expensive, and suffers from operating challenges such as overheating and cannot be scaled-up beyond hundred square meters. Hence, the process of bioethanol production depends on the generation of the raw material used.

II. INNOVATIONS IN FEEDSTOCKS

Carbohydratesare the core fermentable component in a feedstock used for bioethanol production, which includes;reducing sugars (mono tooligosaccharides), starch and cellulose. Monosaccharides (for instance glucose) are the main components in sugar-based feedstocks, while amylose and amylopectinare the carbohydrates in the starchy crops. Cellulose and hemicellulose are the primary carbohydrates in lignocellulosic feedstocks [17].

Since the core challenges of 1G bioethanol is food vs fuel (food security) while those for 2G/3G bioethanol are feedstock biomass recalcitrance due to heterogeneity, incomplete pentose utilization, and cost-intensive enzymes and downstream processing. Novel, low-cost waste streams are increasingly attractive because they reduce feedstock costs and improve sustainability metrics.Recent advances to overcome the challenges especially 2G/3G feedstock processing for bioethanol production pay major emphasis on three key drivers [11]:

a. Reducing feedstock cost and competition with food
b. Improving sugar accessibility through novel physical, chemical, and biological strategies
c. Valorizing residues and wastes to improve overall process economics and environmental sustainability

Recent progresses in feedstock innovations for bioethanol production are;

2.1. Agro and dairy waste feedstocks

Acid whey: Dairy whey, a cheese and paneer production by-product, contains less than 4-5% proteins, lactose, and essential minerals. Naturally treated as a waste that poses a disposal challenges, it’s now being processed for bioethanol production. A key innovation in this is Amul’s 2025 pilot in India integrates enzymatic hydrolysis of lactose to glucose/galactose followed by fermentation with lactose-positive yeasts (Kluyveromyces marxianus) [18].

The advantage of this innovation stems from

i. Eliminates disposal costs for whey
ii. Increases revenue from bioethanol and possibly protein-rich coproducts
iii. Negligible lignin which implies that costly pretreatment procedure is not required
iv. Enhanced bioethanol recovery from 450,000 L of whey reached with approximately 4.4–8%.

This represents a scalable circular bioeconomy model where waste streams from food processing are directly converted into value-added biofuels.

2.2. Eucalyptus pulp and bark:

One of the fast-growing hardwoods used widely in the paper and pulp industry is Eucalyptus tree. It produces very large amount of bark and pulping residues rich in glucan and hemicellulose. Organosolv (ethanol, methanol) and alkaline pretreatments together with surfactant-assisted enzymatic hydrolysis are the key innovative strategies employed for their processing [19]. Surfactants like Tween 80 reduce non-productive enzyme binding to lignin, increasing saccharification efficiency.

Key advantages:

i. Generates high-purity lignin coproducts for chemicals
ii. Improves enzymatic hydrolysis yields without severe chemical conditions
iii. Potential integration with existing pulp mills
iv. Glucan recovery increased by >20%, with ethanol yields approaching theoretical maxima when coupled with SSF [19].

2.3. Sugarcane bagasse and corn stover:

These are ample, low-cost, readily available wastes from the sugar and corn industries. The residues have been pretreated using alkaline and ammonia fiber explosion (AFEX) pretreatments followed by high-solids simultaneous saccharification and co-fermentation process (SSCF) .

Key advantages;

i. High-solids fed-batch SSCF at 25–30% dry matter allows ethanol Liters>100 g/L, reducing distillation energy per liter ethanol [20, 21].
ii. Co-fermentation using engineered yeasts capable of metabolizing both glucose and xylose, increasing ethanol yield by ~30% [22].

iii. Improved efficiency in sugar and bioethanol yield

2.4. Fruit peels:

Fruit processing industries generate large amounts of peel waste, such as banana, orange, pineapple all rich in starch, pectin, and soluble sugars. Their utilization encourages blue economy where waste is converted to wealth.

Key innovation:

a. Co-culture SSF with Saccharomyces cerevisiae (yeast) and Aspergillus niger (producing pectinases and amylases) [23].
b. Up to 79% (w/v) ethanol concentration achieved under optimized solid-to-liquid ratios and enzyme loadings [23].

Key Advantages:

i. No pretreatment beyond size reduction and sterilization
ii. Potential for decentralized ethanol production near processing plants
iii. Reduction in environmental pollution

2.5. Marine macroalgae (Sargassum spp):

This marine macroalgae specie have no lignin, however, it comprises of complex polysaccharides (mannitol, alginate, laminarin) that need tailored hydrolysis.

- Recent innovation: Hydrothermal (liquid hot water) pretreatment at 170–190 °C solubilizes algal carbohydrates while avoiding sugar degradation [24].
- Fermentation approach: Engineered yeasts expressing alginate lyases and mannitol dehydrogenases enable fermentation of these sugars.
- Advantage: No need for costly delignification; offshore cultivation reduces land use competition.

These innovations in feedstock processing is vital because they enhance bioethanol sustainability (through the use of non-food or lignocellulosic waste biomass. They also ensure minimal dependence on fossil fuel due to increase conversion efficiency and improved yield. Overall, it promotes economic growth [11, 20]. The efficiency ratings the innovations in feedstock will be relative (e.g., High, Medium, Low) based on reported data and techno-economic feasibility as presented in Table 1.

Table 1: Comparative Efficiency of Recent Feedstock Processing Innovations

Feedstock (Innovation)	Key Processing Steps	Ethanol Yield / Sugar Recovery	Pretreatment Severity*	Enzyme/Process Efficiency	Cost-Effectiveness	References
Acid Whey (Enzymatic hydrolysis + lactose-positive yeast fermentation)	Lactose hydrolysis + SSF with K. marxianus	~4.4–8 % ethanol (w/v) from whey; high conversion efficiency due to absence of lignin	Very Low	High (minimal enzyme inhibition)	High to low pretreatment cost, uses waste stream	[18]
Eucalyptus Bark/Pulp – (Organosolv/ Alkaline + Surfactant-aided hydrolysis)	Organosolv/ alkali delignification + Surfactant-assisted enzyme hydrolysis + SSF	Glucan recovery ↑ 20%; ethanol yields near theoretical maxima in pilot scale	Medium	High (reduced non-productive binding)	Medium, requires chemical recovery but high lignin coproduct value	[19]
Sugarcane Bagasse (AFEX/Alkaline + High-solids SSCF)	Ammonia fiber explosion or alkali pretreatment	>100 g/L ethanol at 25–30% solids; ~30% yield gain with	Medium-High	High (engineered strains co-utilize xylose)	Medium-High with high solids reduce	[20, 25]

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	+ Fed-batch SSCF	pentose-fermenting yeast			distillation energy	
Macroalgae (Sargassum spp.) (Hydrothermal pretreatment + engineered yeast)	Liquid hot water + Enzymatic hydrolysis + Engineered yeast fermentation	High sugar recovery; ethanol yield depends on mannitol/alginate fermentation efficiency (~70–85% theoretical)	Medium	Medium-High (feedstock-specific enzymes needed)	Medium with no delignification, but marine biomass handling cost	[24, 26]
Fruit Peels (Co-culture SSF with fungi + yeast)	A. niger enzyme production in situ with S. cerevisiae fermentation	Up to 79% (w/v) ethanol under optimized conditions	Low	Medium-High (direct saccharification + fermentation)	High abundant waste, minimal pretreatment	[23]

III. RECENT PRETREATMENT ADVANCES

Pretreatment is crucial to disrupt the lignin, cellulose and hemicellulose architecture to improve enzyme accessibility. It remains one of the most capital and operationalcost intensive steps in 2G bioethanol production and frequently controls overall process feasibility. Integrated, combined, or mild “green” pretreatments can reduce chemical consumption and inhibitor formation while improving bioethanol yields. Conventional methods pf pretreatment such as Physical (extrusion, milling, steam explosion decreases particle size and crystallinity), Chemical (dilute acid, alkali, organosolv and ionic liquids confers effective lignin removaland hemicellulose solubilization but differ in cost, corrosion risk, and recyclability). Physicochemical processes (such as AFEX, steam explosion and liquid hot water (LHW), are effective in hemicellulose solubilization with modest inhibitor formation while biological: fungal delignification (white-rot fungi), enzymatic approaches low energy but slow [26]. On the other hand, hybrid or combined: coupling mild chemical with mechanical or biological steps improves efficacy and minimizes by-products.

3.1. Recent Advances in Pretreatment

3.1.1. Surfactant-assisted hydrolysis + Enzymatic Pretreatment (SAH-EP):

The SAH-EP is a promising recent pretreatment process that utilizes surfactants to enhance enzyme-accessibility to biomass structure. The amphiphilic nature of surfactants allows them to easily interact with both the hydrophobic and hydrophilic regions of the biomass thus, reducing the surface tension within the biomass matrix and increasing enzyme accessibility [19].

Key benefits

i. Enhances the efficiency of enzymatic hydrolysis
ii. Minimizes enzyme loading and cost
iii. Potentially able to improve reducing sugar and bioethanol yields

3.1.2. Two-step Fractionation + Organosolv Pretreatment

This method involves the sequential treatment of feedstocks with different organic solvents (ethanol, acetone, hexane) to fractionate (solubilizes the lignin and hemicellulose fractions) its components. Organosolv make the cellulose fraction more accessible to enzymes hence, improving their hydrolyzing capability leading to greater biomass conversion and sugar yield [27].

Key benefits

i. Efficient fractionation of feedstocks components
ii. Improved hydrolysis and yield
iii. Potential for high value products production such as high purity lignin

3.1.3. Combined Low-severity Chemical + Enzymatic Pretreatment

This is a hybrid approach that integrates mild chemical (dilute solutions) treatment with enzymatic hydrolysis. This approach goal is to reduce the severity of inorganic chemicals such as sulfuric, nitric and hydrochloric acids pretreatment while maximizing enzymatic hydrolysis efficiency.The combination approach leads to higher hydrolysis and reduced enzyme loading [28].

Key benefits;

i. Reduced usage and severity of chemicals
ii. Enhanced enzymatic hydrolysis efficiency
iii. Reduced cost and environmentally friendly.

These pretreatment innovations offer promising routes for improving biomass conversion efficiency toward bioethanol production. The combination of pretreatment approaches using optimization conditions offer improved sugar and bioethanol yields. Other advantages of advanced pretreatment innovations over conventional approaches are presented in Table 2.

Table 2: Advantages of Advanced Pretreatment Processes vs Traditional Processes

Comparison criterion	Traditional pretreatment	Advanced pretreatment	Reference
Delignification & fractionation	Dilute acid, steam explosion, and basic alkali treatments often incompletely separate lignin and can leave heterogeneous lignin that is hard to valorize.	Organosolv and two-step fractionation produce higher-purity lignin fractions and better delignification, enabling lignin valorization to chemicals/materials.	[27, 28]
Formation of fermentation inhibitors	Severe acid or high-temperature treatments generate HMF, furfural and phenolics that inhibit downstream fermentation (require detoxification).	Mild combined or sequential pretreatments (low-severity chemical + hydrothermal or surfactant-assisted) reduce inhibitor formation and lower detox costs.	[21, 28]
Enzyme requirement & saccharification efficiency	High enzyme loadings required due to non-productive binding of enzymes to lignin and poor substrate accessibility.	Surfactant-assisted hydrolysis, tailored enzyme cocktails and enzyme immobilization reduce non-productive binding and lower enzyme loadings while increasing sugar release.	[19, 29]
Energy & water footprint	Steam explosion and repeated washing can be energy- and water-intensive at scale.	Hydrothermal (LHW), AFEX modifications, and combined low-severity approaches can lower chemical inputs; when coupled with energy integration they can reduce net energy use.	[26]
Chemical recovery & environmental impact	Dilute acid corrodes equipment and generates corrosive waste streams; treatment chemicals often not recovered.	Organosolv and some ionic-liquid processes are designed for solvent recovery and recycle, reducing hazardous effluents and long-term environmental burden.	[24, 27]
Coproduct valorization potential	Traditional pretreatments yield lignin of limited quality (condensed/heterogeneous), restricting high-value uses.	Advanced fractionation yields higher-quality lignin and hemicellulose streams suitable for chemical upgrading, improving overall biorefinery economics.	[7, 11, 12]
Feedstock	Some methods (e.g., steam	AFEX, tailored ionic liquids,	[12, 13]

flexibility	explosion) work variably across softwoods, hardwoods, and agricultural residues.	and combined chemico-biological routes are more adaptable to diverse feedstocks (woody, herbaceous, algal), enabling broader feedstock portfolios.	
Scalability & techno-economic footprint	Well-established but can require large CAPEX for corrosion-resistant materials and extensive downstream detoxification.	Integrated pretreatment–saccharification–fermentation designs, and pretreatments that improve coproduct value, improve ROI and reduce payback time in recent TEA studies.	[29, 30]

IV. FERMENTATION TECHNOLOGIES AND INNOVATIONS

This procedure converts sugars (hexoses and pentoses) into bioethanol with the use of several microorganisms like bacteria, fungi and yeast. Saccharomyces cerevisiae (yeast) is the furthermost utilized microorganism during fermentation however; it cannot metabolize xylose. To overcome this challenge, genetic engineering is these days preferred for the advancement of recombinant strains that can convert both pentose and hexose sugars to ethanol [31]. The bioethanol fermentation step can be carried out in different ways such as:

4.1. Separate Hydrolysis and Fermentation (SHF):

SHF is a well-known conventional fermentation process that separate the hydrolysis (saccharification) step from the fermentation step. In this process, hydrolytic enzymes (cellulases/xylanases) hydrolyze the biomass (1G/2G/3G) to monosaccharides, mostly glucose and xylose. Residual biomass is removed by filtration, while the sugar-rich hydrolysate is subjected to fermentation by fermentative microorganisms.

4.2. Simultaneous Saccharification and Fermentation (SSF)

Simultaneous saccharification and fermentation (SSF) is an advanced process adopted currently in biorefining industries. Itcombines both simultaneous enzymatic hydrolysis and fermentation, in one reactor system, that is, concurrent enzymes metabolization of feedstocks to sugars and microbial strains conversion to ethanol[32]. SSF is acompetent process for higher bioethanol yield, inhibition elimination, higher productivity, reduced processing time, minimal operation costs, and reduced contamination risk [33]. The main motives for the higher efficiency of SSF are the immediate consumption of glucose released during enzymatic hydrolysis and conversion to ethanol by the fermenting strain, thus preventing the feedback inhibition caused by sugar accumulation as in SHF [33].

4.3. Simultaneous Saccharification and Co-Fermentation (SSCF)

The invention of SSCF arises due to the inability of the SSF process to metabolize pentose sugars (principally xylose) by hexose-utilizing strains or acid-pretreated method. Though, xylose (foremost pentose) comprisesup to 25–35% of the lignocellulosic structure. To make bioethanol production more economical and advantageous, pentose sugar, (xylose) must also be utilized. So, xylose is fermented along with glucose in a method calledSSCF via naturally or genetically engineered pentose sugar-utilizing strains [31, 34]. Nevertheless, in this process, microorganisms metabolize glucose first before xylose, leading to high glucose concentration. To further r enhance SSCF process, keeping glucose concentration below 2.3 g/L leads to the complete utilization of xylose and glucose through the same transporters [34].Additionally, two-step SSCF, which encompassesthe hydrolysis and fermentation of xylan and xylose before glucose, progresses xylose utilization meaningfully, as the glucose releasing rate is lowered in the first step of the process, and have no effect on the microbial consumption of xylose. Two-step SSCF similarlydecreases the redox imbalance as a result of nutrient and oxygen presence that promotes xylose utilization, and evades ethanol inhibition [23, 34]. Meanwhile, pentoses and hexose-utilizing strains must be compatible and ethanol tolerance.

International Journal of Advances in Engineering and Management (IJAEM)
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4.4. Simultaneous Saccharification, Filtration, and Fermentation (SSFF)

Despite eradicating the concerns of feedback inhibition during enzymatic hydrolysis and using different optimal conditions in SSF and SSCF, the issue of reprocessing fermenting strain could be resolved by implementing a more advanced procedure: simultaneous saccharification, filtration, and fermentation (SSFF). In this process, the already treated feedstock is enzymatically hydrolyzed, and a sugar-rich hydrolysate is filtered by means of a cross-flow membrane before fermenting to ethanol [23,34]. The fermentation medium is thoroughly mixedin the fermentation system, and the residual biomass is kept in the hydrolysis vessel while sugar-rich filtrate uninterruptedly fed into the fermentation vessel. A successful flocculating strain of S. cerevisiae can be reused for five cultivations times in SSFF with approximately ethanol yield of 85% in SSFF [32].

4.5. Direct Microbial Conversion/Consolidated Bioprocessing (DMC/CBP)

The DMC/CBP is an innovative procedure that integrates multiple steps of biomass conversion into a single process where a single microorganism produces enzymes that metabolizes biomass to sugars, and convert the sugars to bioethanol. The merits of this process is centered on elimination of separate enzyme production and hydrolysis steps thereby, minimizing cost and complexity. Though, no known naturally occurring microorganism can perfectly fulfill all the requirements involved in DMC/CBP, that is, degrade LCB completely and convert all the sugars released to bioethanol. Therefore, the need to be modified them via metabolic engineering. Hence, genetically engineered microorganisms (GMOs) with exceptional hydrolytic and ethanologenic activities have been applied to convert feedstocks directly. This methodmarks in high ethanol yield, at minimalcost and time with higher productivity [35]. Sharma et al. [23] reported that GMO C. phytofermentans (ATCC 700394) hydrolyzed 76% and 88.6% of glucan and xylan, respectively, by adopting ammonia fiber explosion (AFEX) to pretreat corn stover within 10 days which yielded approximately 2.8 g/Lbioethanol with 71.8% conversion observed by SSCF (3.9 g/L) separately. Besides, the menace of contamination was also eradicated in this method due to cellulose non-adherent contaminants that are competitively removed by desirable cellulose-adherent microbes using sugars released from biomass [35, 36].

CBP merges enzyme production, hydrolysis, and fermentation in one organism or co-culture. Recent reviews emphasize potential cost savings and process intensification but also highlight scale sensitivity and engineering challenges (enzyme secretion, sugar transport, ethanol tolerance). Native cellulolytic thermophiles and engineered ethnologies are under development. Table 3 outlines the benefits and limitations of each of the processes.

Table 3: Benefits and Limitations of Fermentation Technologies and Innovations in Bioethanol Production

Fermentation Technology / Innovation	Benefits	Limitations	References
Separate Hydrolysis and Fermentation (SHF)	• Allows optimization of hydrolysis and fermentation separately • Well-established, widely studied method	• Feedback inhibition by sugar accumulation • Higher contamination risk • Longer process time compared to integrated systems	[23, 31]
Simultaneous Saccharification and Fermentation (SSF)	• Eliminates sugar accumulation and feedback inhibition • Higher ethanol yield & productivity • Reduced process time and operational costs • Lower contamination risk	• Does not efficiently utilize pentoses (xylose) • Compromise in operating conditions (enzyme vs fermentation optima)	[23, 32, 34]
Simultaneous Saccharification and Co-	• Co-ferments glucose and xylose using	• Glucose repression of xylose utilization	[31, 34]

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Fermentation (SSCF)	engineered strains • Up to 30% increase in yield compared to SSF • Potential for improved lignocellulosic biomass utilization	• Requires advanced strain engineering • Process optimization needed to balance sugar uptake	
Simultaneous Saccharification, Filtration, and Fermentation (SSFF)	• Continuous removal of inhibitors via filtration • Reuse of flocculating yeast strains up to 5 cycles • Achieves ~85% ethanol yield • Lower contamination risk	• Additional equipment (membranes) increases capital cost • Membrane fouling potential • Still requires upstream pretreatment	[32, 34]
Direct Microbial Conversion / Consolidated Bioprocessing (DMC/CBP)	• Combines enzyme production, hydrolysis, and fermentation in one step • Eliminates separate enzyme production, reducing cost • Reduced contamination risk due to integrated processing • Potential for high yield and productivity	• No naturally occurring strain can perform all steps efficiently • Requires extensive metabolic engineering • Scale-up and process control challenges • Lower ethanol titers compared to optimized multi-step systems in current applications	[23, 35]

Recent developments in feedstock processing, pretreatment technologies, and fermentation strategies have significantly advanced the feasibility of sustainable bioethanol production beyond first-generation crops.With continued innovation and strategic deployment, advanced bioethanol can play a critical role in reducing fossil fuel dependence, decarbonizing transport, and building a more sustainable bioeconomy.

V. CONCLUSION

The continuous advancement of feedstock utilization strategies, pretreatment innovations, and fermentation technologies has the potential to transform bioethanol into a truly sustainable alternative to fossil fuels. The integration of low-cost, non-food biomass sources including; agricultural residues, industrial by-products, and marine resources, not only reduces reliance on edible crops but also supports circular bioeconomy models through waste valorization. Recent pretreatment innovations, particularly hybrid and low-severity methods, have addressed key limitations of traditional processes by improving delignification, reducing inhibitor formation, and enabling higher sugar recoveries at lower enzyme loadings. Furthermore, the shift from conventional fermentation methods to integrated or consolidated processes enhances process efficiency, reduces operational complexity, and improves pentose sugar utilization, which is crucial for lignocellulosic biomass conversion. However, challenges remain, particularly in scaling up third-generation algae systems, optimizing genetically engineered strains for industrial robustness, and ensuring techno-economic feasibility. Future research should prioritize the development of multifunctional microbial platforms, energy-efficient process integration, and robust biorefinery designs capable of producing both bioethanol and high-value coproducts. With continued innovation and system optimization, bioethanol production can achieve greater energy yields, reduced greenhouse gas emissions, and a more sustainable role in the global energy mix.

DECLARATION

- The authors declare no conflict of interest in respect to financial or personal relationships with other people or organizations that could inappropriately influence this work.
- The authors can also confirm that this manuscript has been read by all and approved for onward submission to this journal and if accepted would not be published elsewhere.
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