International Journal of Agriculture and Plant Science
www.agriculturejournal.in
Online ISSN: 2664-7664
Received: 26-02-2026, Accepted: 29-03-2026, Published: 13-04-2026
Volume 8, Issue 2, 2026, Page No. 32-38

Bioethanol production from sugarcane waste and applications for sustainable ecosystem

Khushahal Thakur, Dr. Asma Fayaz
University Institute of Agricultural Sciences, Chandigarh University, Punjab, India
Corresponding Author: **Dr. Asma Fayaz**

Abstract

The growing demand for renewable energy has renewed interest in agricultural residues as viable feedstocks.Sugarcane waste including bagasse, press mud, and molasses represents an abundant lignocellulosic resource with considerable potential for bioethanol production. Converting these residues into fuel reduces the environmental burden associated with open field burning and improper disposal. Advances in pretreatment methods, enzyme technologies, and fermentation strategies have significantly improved the efficiency of breaking down fibrous components, allowing higher ethanol yields from materials traditionally considered difficult to process. Beyond serving as a cleaner transportation fuel, bioethanol derived from sugarcane waste contributes to lowering greenhouse gas emissions, supporting circular bioeconomy models, and promoting energy independence in rural farming regions. Its integration within existing sugar mills further strengthens resource efficiency by linking energy generation with agricultural production systems. As pressures related to climate change and fossil fuel depletion. Sugarcane waste based bioethanol emerges as a promising pathway for sustainable ecosystem management. This review examines current technological developments, challenges, and practical applications, emphasizing the role of sugarcane residues in shaping a more resilient and environment friendly energy approach.

Keywords: Sugarcane waste, bioethanol production, lignocellulosic residues, bagasse, press mud, molasses, pretreatment methods, fermentation strategies, renewable fuel, sustainable ecosystem

Introduction

The global shift to renewable energy is an urgent response to the twin problems of climate change and fossil fuel depletion (Yuan *et al*., 2008) [32].Among the various renewable options, bioethanol has surfaced as a prominent liquid fuel for transportation, with its production and usage being required by over forty countries across the globe (Binot *et al*., 2019) [3]. For a fast-growing nation like India, which relies on importing about 85% of its crude oil needs, striving for energy self-sufficiency through local biofuels is not only an environmental obligation but also a crucial socioeconomic necessity (Haq & Kalam, 2022) [9].Converting these abundant, low-cost wastes into bioethanol presents a transformative opportunity to address multiple national challenges simultaneously: reducing fossil fuel imports, managing agricultural waste, mitigating air pollution, and generating rural employment (Kapoor *et al*., 2020) [12]. The process aligns perfectly with the principles of a circular bioeconomy, where waste streams are valorized into energy and products, thereby closing the loop in the sugarcane agro-industrial system (Yadav *et al*., 2020) [31].

However, the path to commercial viability for 2G ethanol is fraught with technical and economic hurdles. The recalcitrant structure of lignocellulose necessitates energy-intensive pretreatment, efficient enzymatic hydrolysis, and robust fermentation of mixed sugars (Galbe & Zacchi, 2012) [6]. The Indian context introduces additional challenges, such as seasonal feedstock availability, diverse agro-climatic conditions affecting biomass composition, and the need for cost-effective, scalable technology suitable for medium-sized sugar mills (Dixit *et al*., 2022) [5].This in-depth review aims to critically evaluate the entire value chain associated with bioethanol production utilizing waste from Indian sugarcane. It will explore the composition of different residues, assess advanced pretreatment and conversion techniques with an emphasis on innovations from India, conduct a detailed evaluation of both environmental and economic viability, and present a model for integrated biorefineries. By integrating recent findings from Indian research institutions alongside global best practices, this paper aspires to serve as a key resource for policymakers, industry participants, and researchers dedicated to unlocking the potential of bioethanol derived from sugarcane waste as a fundamental element of India's sustainable energy future.

Types and Generation Statistics of Sugarcane Residues

The sugarcane industry generates substantial quantities of lignocellulosic residues, which are broadly classified into field residues and processing residues (Kuhad and Singh, 2022) [14]. Sugarcane trash, also known as straw, comprises the leaves and tops remaining after harvesting, representing approximately 15–25% of the total biomass of the complete sugarcane crop (Bhaskar *et al*., 2021) [2]. Research indicates that residue biomass yields exceed 3.5 tonnes per hectare annually, with average cellulose, hemicellulose, lignin, and ash content of 36.0%, 31.5%, 4.7%, and 0.7% respectively (Bhaskar *et al*., 2021) [2]. Bagasse, the fibrous residue obtained from crushing cane in the mills, is produced at approximately 30 tons per 100 tons of sugarcane crushed, with moisture content around 49% and a heating value of 2200 Kcal/kg on a wet basis (Kapoor *et al*., 2020) [12]. Press mud (filter cake) is generated during juice clarification at rates of 3.5–4.5% of total cane crushed, containing organic carbon (20–25%), nitrogen (0.9–1.25%), and phosphorus (2.5–3.0%) (Jain, 2020) [10]. Globally, sugarcane production yields approximately 280 million metric tons of bagasse and straw annually (Binot *et al*., 2019) [3]. Regional distribution varies considerably, with India alone generating approximately 41 million tonnes of sugarcane tops and leaves (Bhaskar *et al*., 2021; Sarkar *et al*., 2021) [2, 25]. The composition of these residues exhibits variability depending on agro-climatic conditions, sugarcane varieties, and harvesting practices (Pandey *et al*., 2022; Sharma *et al*., 2021) [19, 26]. Notably, not all residues are available for valorization, as significant portions are already utilized for mill energy or face collection constraints (Sarkar *et al*., 2021; Singh *et al*., 2020; Singh and Pal, 2021) [25, 28, 29]. For instance, bagasse characteristics typically show total solids of 58.9%, volatile matter of 97.6%, and C/N ratio of 29.6, while press mud contains 47.9% total solids with lower C/N ratio of 9.7 (Jain, 2020) [10].

1. Chemical and Structural Properties

The chemical composition of sugarcane residues determines their potential for bioconversion and valorization pathways. Bagasse and straw are lignocellulosic materials composed primarily of cellulose, hemicelluloses, and lignin, with lower amounts of extractives and ash (Kuhad and Singh, 2022) [14]. Detailed compositional analysis reveals that sugarcane bagasse contains approximately 45–50% cellulose, 25–32% hemicellulose, and

17–25% lignin, though significant variability exists across different agro-climatic zones (Pandey *et al*., 2022; Sharma *et al*., 2021) [19, 26]. However, recent research on post-harvest residue suggests that some previously published values may overestimate lignin content; one study found crop residue contained only 4.7% lignin, 36.0% cellulose, and 31.5% hemicellulose (Bhaskar *et al*., 2021) [2], indicating that residue composition differs markedly from bagasse. Press mud exhibits distinct chemical characteristics, with organic matter content around 28.2%, total organic carbon of 16.3%, and total nitrogen of 1.7% (Jain, 2020) [10]. The structural complexity of sugarcane lignins has been elucidated through advanced analytical techniques including pyrolysis-GC/MS and nuclear magnetic resonance spectroscopy (Yuan *et al*., 2008) [32]. Notably, the lignins from bagasse and straw differ fundamentally in their monomeric composition. Bagasse lignin is syringyl-rich with a p-hydroxyphenyl: guaiacyl: syringyl (H:G:S) molar ratio of 2:38:60, whereas straw lignin is guaiacyl-rich with H:G:S of 4:68:28 (Yuan *et al*., 2008) [32]. This compositional difference reflects variations in interunit linkages: bagasse lignin contains primarily β-O-4' alkyl-aryl ether substructures (representing 83% of NMR-measurable linkages), while straw lignin has lower β-ether levels (75%) but higher relative levels of phenylcoumarans (β-5', 15%) and dibenzodioxocins (3%) (Yuan *et al*., 2008) [32]. Both lignins are extensively acylated at the γ-hydroxyl of the side-chain (42% and 36% acylation in bagasse and straw, respectively), predominantly with p-coumarates on syringyl units and acetates on guaiacyl units (Yuan *et al*., 2008) [32]. The flavone tricin has also been identified in sugarcane lignins, consistent with other grasses (Yuan *et al*., 2008) [32]. Additionally, bagasse fly ash, generated from combustion in cogeneration boilers, contains silica as the major component along with metal oxides and unburned carbon (up to 25%) (Sarkar *et al*., 2021) [25].

2. Structural Recalcitrance and Its Implications

The architectural complexity of sugarcane cell walls creates inherent recalcitrance that limits enzymatic hydrolysis and bioconversion efficiency. Lignocellulosic biomass exhibits natural resistance due to the high complexity in component organization and interaction within the cell wall (Galbe and Zacchi, 2012) [6]. Lignin serves as a physical barrier to cellulose, inhibits enzyme activity, and reduces enzyme accessibility (Kuhad *et al*., 2016) [13]. The recalcitrance varies significantly among different tissue fractions of sugarcane culm. Research comparing epidermis, internode, and node fractions revealed that the epidermis comprises the largest mass fraction (65%) of sucrose-free sugarcane culm, followed by internode (19%) and node (15.5%) fractions (Yuan *et al*., 2008) [32]. The epidermis demonstrated substantially higher resistance to acid pretreatment, with lower xylose solubilization and higher mass recovery of water-insoluble solids compared to internode and node fractions (Yuan *et al*., 2008) [32]. Enzymatic hydrolysis yields reflected this hierarchical recalcitrance: epidermis achieved only 18.6% hydrolysis, while node and internode reached 56.5% and 75.9%, respectively (Yuan *et al*., 2008) [32]. The epidermis also exhibited lower internal and external surface area, less structural damage after enzymatic hydrolysis under scanning electron microscopy, and required higher start temperature for thermal degradation (330°C) compared to internode (288°C) and node (265°C) (Yuan *et al*., 2008) [32]. These tissue-specific differences in recalcitrance underscore the importance of understanding biomass heterogeneity for process optimization (Singh *et al*., 2020) [28]. The structural features of lignin significantly influence pretreatment outcomes and enzyme adsorption (Galbe and Zacchi, 2012; Sharma *et al*., 2021) [6, 26]. Guaiacyl-rich lignins, as found in straw, tend to form more condensed structures with higher levels of phenylcoumarans and dibenzodioxocins (Yuan *et al*., 2008) [32], potentially increasing recalcitrance compared to syringyl-rich lignins. Pretreatment technologies are essential to overcome biomass recalcitrance, typically employing acids, alkaline compounds, ionic solutions, organic solvents, or pressurized steam to modify lignocellulosic structure (Galbe and Zacchi, 2012) [6]. The efficiency of these processes depends critically on both lignin content and structure, necessitating detailed knowledge of lignin characteristics for developing appropriate delignification methods (Yuan *et al*., 2008) [32].

3. Current Disposal Practices and Environmental Footprint

Traditional disposal practices for sugarcane residues have significant environmental implications. Open-field burning of sugarcane trash remains common in many countries despite its environmental consequences (Bhaskar *et al*., 2021; Jain *et al*., 2019; Shyamlal *et al*., 2022) [2, 11, 27]. In Louisiana, producers typically remove post-harvest residue by open-air burning because it is a cost-effective method to manage residue that would otherwise reduce yields of subsequent ratoon crops (Yuan *et al*., 2008) [32]. This practice contributes substantially to air pollution through particulate matter emissions and greenhouse gas release (Jain *et al*., 2019; Shyamlal *et al*., 2022) [11, 27]. The environmental burden extends beyond field residues to processing wastes. Sugarcane mills generate significant wastewater streams, and inadequately treated effluent disposal has resulted in extensive soil and water pollution (Jain, 2020) [10]. Vinasse, the liquid residue after ethanol distillation, presents particular challenges due to its high organic load and large volumes (Jain, 2020) [10]. Bagasse combustion for cogeneration, while recovering energy, produces fly ash requiring management (Sarkar *et al*., 2021)

[25]. However, there is increasing recognition of the need for circular economy approaches in sugarcane processing (Kapoor *et al*., 2020) [12]. Current practices are evolving toward more sustainable residue management. Some sugar mills utilize press mud mixed with distillery spent wash to produce enriched organic manure, which improves crop yields (Jain, 2020) [10]. Bio-composting facilities can produce substantial quantities of organic manure annually (Jain, 2020) [10]. Nevertheless, significant opportunities remain for improved valorization through cascading use of residues, including carboxylate production, bioplastic synthesis, biogas generation, and silicon recovery from bagasse ashes (Sarkar *et al*., 2021) [25]. Life cycle assessment studies have examined the environmental implications of different residue management strategies (Ghosh *et al*., 2021; Yadav *et al*., 2020) [8, 31], highlighting the potential for integrated approaches to reduce greenhouse gas emissions while extending product portfolios (Kapoor *et al*., 2020; Yadav *et al*., 2020) [12, 31]. The transition toward sustainable biorefinery concepts requires addressing both the technical challenges of recalcitrance and the environmental imperatives of minimizing pollution from traditional disposal methods (Singh *et al*., 2020; Singh and Pal, 2021) [28, 29].

Pretreatment Technologies for Lignocellulosic Biomass

Pretreatment is the most critical and cost-intensive step in the 2G ethanol process. Its objective is to disrupt the lignocellulosic matrix, reduce cellulose crystallinity, increase biomass porosity, and separate or modify lignin to make carbohydrates accessible to hydrolytic enzymes (Galbe & Zacchi, 2012) [6].

1. Physical and Mechanical Pretreatments

These methods aim to reduce particle size and increase surface area through mechanical force. Common techniques include milling (ball, vibratory, two-roll), grinding, and chipping. While effective in reducing the degree of polymerization and crystallinity, they are highly energy-intensive, often consuming more energy than the theoretical energy content of the biomass itself (Gautam *et al*., 2019) [7]. Their utility in standalone commercial applications is limited, but they serve as an essential preliminary step before chemical pretreatment. Recent Indian research has explored coupling mild mechanical pretreatment with biological methods to reduce overall energy consumption (Saini *et al*., 2020) [24].

2. Chemical and Physicochemical Approaches

This category represents the most widely researched and commercially pursued methods for Indian bagasse.

- **Dilute Acid Pretreatment (DAP):** Typically using sulfuric acid (1-4% w/w) at temperatures of 140-190°C, DAP effectively hydrolyzes hemicellulose to soluble sugars (mainly xylose) and partially depolymerizes lignin (Sharma *et al*., 2021) [26]. A major drawback is the formation of potent fermentation inhibitors like furfural (from pentose degradation) and 5-hydroxymethylfurfural (HMF, from hexose degradation). Sharma *et al*. (2021) [26] reported that optimizing conditions for Indian bagasse (1.5% H2SO4, 160°C, 20 min) achieved 85% hemicellulose removal but required rigorous detoxification of the hydrolysate before fermentation.
- **Alkaline Pretreatment:** Using bases like sodium hydroxide, calcium hydroxide (lime), or ammonia, this method is particularly effective for lignin removal via saponification of ester bonds and disruption of lignin-carbohydrate complexes. It causes less sugar degradation than acid methods but can lead to the formation of phenolate inhibitors (Arora *et al*., 2022) [1]. Lime pretreatment is attractive for India due to the low cost and ease of recovery. Arora *et al*. (2022) [1] demonstrated that lime pretreatment (0.1 g Ca(OH)2/g biomass, 90°C, 6 h) of bagasse removed 65% lignin and enhanced subsequent enzymatic digestibility by over 200%.

- **Steam Explosion (Autohydrolysis):** This physicochemical method subjects biomass to high-pressure saturated steam (160-260°C) for several minutes, followed by rapid decompression. The sudden pressure drop "explodes" the biomass structure. The inherent acetic acid from hemicellulose acts as a catalyst. It is considered less environmentally damaging due to minimal chemical use. Research at IIT Guwahati has optimized steam explosion for northeastern Indian cane varieties, achieving high glucan recovery at 180°C for 15 minutes (Mohan *et al*., 2021) [18].

- **Organosolv Pretreatment:** This method uses organic solvents (e.g., ethanol, methanol, acetic acid) often with an acid catalyst at elevated temperatures to solubilize lignin and hemicellulose, leaving a relatively pure cellulose pulp. While it produces high-quality, sulfur-free lignin as a valuable by-product, the high cost of solvents and the need for efficient recovery systems have hindered its commercial adoption in India (Kapoor *et al*., 2020) [12].

3. Biological Pretreatment Strategies

This environmentally benign approach employs lignin-degrading microorganisms, primarily white-rot fungi (Phanerochaete chrysosporium, Ceriporiopsis subvermispora), to selectively degrade lignin. The process is slow (weeks) and requires careful control of moisture, temperature, and sterility to prevent carbohydrate loss (Kuhad *et al*., 2016) [13]. Its greatest potential in the Indian context may lie in decentralized, low-capital systems or as a mild pre-step before a more vigorous chemical treatment. Studies at the University of Delhi have shown that a 21-day treatment with P. chrysosporium reduced lignin in sugarcane trash by 28% and improved saccharification yield by 35% (Kuhad & Singh, 2022) [14].

Hydrolysis and Fermentation Pathways

Following pretreatment, the liberated cellulose and remaining hemicellulose must be hydrolyzed into monomeric sugars (glucose, xylose, arabinose), which are then fermented to ethanol.

1. Enzymatic Hydrolysis: Mechanisms and Optimization

Enzymatic hydrolysis employs a synergistic cocktail of enzymes, primarily cellulases (endoglucanases, exoglucanases or cellobiohydrolases, and β-glucosidases) and hemicellulases (xylanases, β-xylosidases) (Modenbach & Nokes, 2012) [17]. The efficiency of this step is paramount for process economics. Key factors include:

- **Enzyme Loading:** Reducing the cost of enzymes (often ₹10-15 per liter of ethanol) is a major R&D goal. Strategies include on-site enzyme production and engineering more efficient enzymes (Saini *et al.*, 2020) [24].

- **Solid Loading:** Operating at high solids content (≥15% w/w) is necessary to achieve high ethanol titers (≥4% v/v) for economical distillation. However, this leads to mixing difficulties, mass transfer limitations, and increased inhibitor concentration (Borrega & Sixta, 2015) [4]. · Hydrolysis Time: Typically requires 48-72 hours. Intensification via process engineering (e.g., fed-batch substrate addition, ultrasound-assisted mixing) is being explored to reduce this time (Patel *et al.*, 2021) [20].

Indian research has focused on discovering novel, robust enzymes from native biodiversity.

Saini *et al.* (2020) [24] characterized a thermostable cellulase from a Bacillus strain isolated from Himalayan hot springs, which retained 80% activity at 65°C, potentially reducing cooling costs.

2. **Fermentation Strategies: From SHF to CBP**

- **Separate Hydrolysis and Fermentation (SHF):** Hydrolysis and fermentation occur in separate vessels at their respective optimal conditions (e.g., 50°C for enzymes, 30-32°C for yeast). This allows for process control but is time-consuming and exposes sugars to potential contamination (Srivastava *et al.*, 2021) [30].

- **Simultaneous Saccharification and Fermentation (SSF):** Enzymes and fermenting microbes are added together. Glucose released by enzymes is immediately consumed by yeast, reducing end-product inhibition of cellulases. This is the most widely adopted strategy for 2G ethanol. Mohan *et al.* (2021) [18] optimized SSF for alkaline-pretreated bagasse, achieving an ethanol yield of 72% of theoretical in 72 hours.

- **Consolidated Bioprocessing (CBP):** The ultimate integrated approach where a single microbial community (or engineered strain) produces hydrolytic enzymes and ferments sugars simultaneously. This promises the lowest cost but requires the development of super-microbes, an active area of synthetic biology research (Kuhad & Singh, 2022) [14].

3. **Microbial Strains: The Workhorses of Fermentation**

- **Native Saccharomyces cerevisiae:** The industrial workhorse for glucose fermentation lacks the ability to metabolize xylose. Indian distillers commonly use robust strains like S. cerevisiae MTCC 174. Research focuses on improving their thermo-tolerance and inhibitor resistance through adaptive evolution (Kumar *et al.*, 2019) [15].

- **Pentose-Fermenting Yeasts:** Strains like Scheffersomyces stipitis and Candida shehatae can naturally ferment xylose but are often sensitive to inhibitors and low ethanol tolerance (Kuhad *et al.*, 2016) [13].

- **Metabolically Engineered Strains:** The frontier of strain development involves genetic engineering. Indian scientists have introduced xylose isomerase and xylulokinase genes from Pichia stipitis into S. cerevisiae, enabling co-consumption of glucose and xylose, albeit at sub-optimal rates (Kumar *et al.*, 2019) [15]. The challenge of co-factor imbalance (NADH/NADPH) during xylose metabolism remains a key research hurdle.

4. **Detoxification and Inhibitor Management**

The liquid fraction from acid pretreatment (hydrolysate) contains microbial inhibitors that must be removed or neutralized. Methods include:

- **Physical:** Evaporation, membrane filtration, adsorption on activated charcoal.
- **Chemical:** Overliming (pH adjustment with Ca (OH)2), treatment with reducing agents (e.g., sodium dithionite).
- **Biological:** Using specific enzymes (laccase, peroxidase) or inhibitor-tolerant microbes that can biodegrade furans and phenols.

A study on Indian press mud hydrolysate found that a combined overliming and activated charcoal treatment reduced furfural concentration by 95% and increased ethanol yield by 40% (Reddy & Singh, 2022) [23].

Bioethanol Production from Specific Sugarcane Residues

1. **Bagasse: The Primary 2G Feedstock**

Bagasse is the most promising feedstock due to its centralized availability in large quantities.

The process flow is well-established: Milling → Pretreatment → Enzymatic Hydrolysis → Fermentation → Distillation. The real challenge is integration and scale. India's first commercial-scale 2G ethanol plants, such as the one built by Praj Industries in Karnataka, use bagasse as the primary feedstock. Dixit *et al.* (2022) [5] performed a techno-economic analysis of a 100 KLPD (kilo-liters per day) bagasse-based plant in Maharashtra, reporting a

Minimum Ethanol Selling Price (MESP) of ₹52/liter, which is close to viability given government-administered prices.A critical advancement is the move toward the lignocellulosic biorefinery concept. Here, the process is designed to extract multiple value streams: C6 sugars to ethanol, C5 sugars to furfural or xylitol, and lignin to bio-based chemicals (phenols, dispersants) or solid fuel for the boiler. This multi-product approach dramatically improves economics. Kapoor *et al.* (2020) [12] modeled an integrated biorefinery where lignin was converted to phenolic resins, improving the project IRR by 4 percentage points.

2. **Press Mud: A Complementary Feedstock**

Press mud's high moisture and varied composition make it less suitable as a standalone 2G feedstock but excellent for co-digestion or mixed-feedstock systems. Its high protein content can act as a nutrient source during fermentation. A novel approach is its use for biohydrogen production via dark fermentation, followed by the use of the acid-rich effluent for biomethane production in a two-stage process. Alternatively, after simple acid hydrolysis, the released sugars can be fermented. Reddy & Singh (2022) [23] highlighted a key issue: fermentation of press mud hydrolysate with standard yeasts led to high concentrations of fused alcohols (3-methyl-1-butanol, 2-methyl-1-butanol), which are impurities problematic for catalytic upgrading of ethanol to higher-value chemicals.

3. Sugarcane Trash: Addressing the Logistics Challenge

Utilizing trash for ethanol is environmentally compelling but logistically complex. The primary barrier is its dispersed availability in fields. An efficient supply chain involving baling, collection, transportation, and storage must be established. Singh & Pal (2021) [29] analyzed that for a 100 KLPD plant, the economic collection radius for baled trash is about 50 km. Beyond this, transport costs become prohibitive. Storage is another major issue; unprotected bales can suffer dry matter losses of 15-25% over 6 months due to microbial degradation. Developing decentralized pre-processing hubs near sugarcane clusters, where trash undergoes initial size reduction and possibly mild pretreatment (like pelleting), could be a solution to reduce transportation costs and stabilize the biomass.

4. Integrated 1G-2G and Hybrid Systems

The most pragmatic model for India is the annexed 1G-2G biorefinery. An existing sugar mill integrates a 2G plant that uses bagasse and trash, while the 1G plant continues using molasses and cane juice (as per policy guidelines). This synergy offers shared infrastructure (utilities, distillation, effluent treatment), operational expertise, and financial resilience. Yadav *et al.* (2020) [31] conducted a life-cycle assessment of such an integrated system in Uttar Pradesh, finding it reduced GHG emissions by 85% compared to gasoline and improved the net energy ratio (energy out/energy in) to 2.1. Furthermore, hybrid systems that produce both ethanol and biogas from all waste streams (spent wash, leftover sludge) are emerging as models for zero-waste, energy-positive sugar complexes.

Technological Advances and Process Optimization

1. Bioreactor Design and Scale-up

Moving from laboratory to industrial scale requires sophisticated bioreactor engineering. For high-solids enzymatic hydrolysis (>15% solids), conventional stirred-tank reactors (STRs) face severe power draw and mixing challenges. Alternatives include helical ribbon impellers and pneumatically mixed reactors (Poppe *et al*., 2021) [21]. For fermentation, bubble column reactors offer excellent mass transfer for aerobic propagation of yeast, while packed-bed reactors with immobilized cells are being explored for continuous fermentation processes, potentially increasing productivity (Patel *et al*., 2021) [20].

2. Enzyme Engineering and Microbial Biotechnology

The high cost of commercial cellulase enzymes remains a bottleneck. Indian research focuses on two fronts:

1. **Producing cheaper enzymes:** Using solid-state fermentation with agro-residues as substrate to grow fungal producers like Trichoderma reesei.
2. **Engineering better enzymes:** Using protein engineering to improve the specific activity, thermostability, and inhibitor tolerance of core cellulases like cellobiohydrolase I (CBHI). Research at the International Centre for Genetic Engineering and Biotechnology (ICGEB), New Delhi, is employing directed evolution to create more robust enzyme variants (Saini *et al*., 2020) [24].

Similarly, systems biology and CRISPR-Cas9 gene-editing tools are being used to engineer superior yeast strains. Goals include expanding substrate range (to include arabinose), diverting metabolic flux exclusively to ethanol, and enhancing cellular tolerance mechanisms (Kumar *et al*., 2019) [15].

3. Process Integration and Energy Optimization

A stand-alone 2G ethanol plant can be energy-negative. The key is integration. The concept of process intensification through Pinch Analysis is vital. This technique designs a network of heat exchangers to recover waste heat from hot streams (e.g., distillation vapor condensate) to preheat colder streams (e.g., fermentation mash), dramatically reducing steam demand from the boiler (Kapoor *et al*., 2020) [12].Furthermore, all non-fermentable solids, primarily lignin, are combusted in a high-efficiency boiler to generate steam and power. A well-designed plant can generate surplus electricity, which can be exported to the grid, providing an additional revenue stream. Advanced systems explore gasifying lignin to produce syngas for further catalytic conversion to fuels or chemicals

Environmental Benefits and Ecosystem Applications

1. Greenhouse Gas Emission Reductions

A principal driver for biofuels is climate change mitigation. Life Cycle Assessment (LCA) is the standard tool to quantify this. Ghosh *et al*. (2021) [8] conducted a cradle-to-gate LCA for bagasse-based ethanol in India. The study found that 2G ethanol from surplus bagasse reduced GHG emissions by 70-90% compared to gasoline, factoring in cultivation, transport, processing, and emissions offset from by-product electricity. When the avoided emissions from preventing open trash burning are included, the net benefit is even more substantial. The 2022 amendment to India's biofuel policy recognizes this by allowing ethanol production from trash, which carries additional GHG reduction credits.

2. Circular Bioeconomy and Waste Valorization

The sugarcane biorefinery is a textbook model for a circular economy. It transforms linear waste streams into a web of valuable products:

- **Energy:** Ethanol, surplus electricity, biogas.
- **Materials:** Lignin for chemicals, biochar from gasification for soil amendment, silica from bagasse ash.
- **Nutrients:** Digested effluent from wastewater treatment as liquid fertilizer.

This model aligns with national missions like "Waste to Wealth" and enhances the sustainability and profitability of the entire sugar sector (Yadav *et al*., 2020) [31].

3. Soil, Water, and Air Quality Impacts

- **Soil:** Eliminating trash burning preserves soil organic carbon and microbial health. Applying composted press mud and anaerobic digestate (from spent wash treatment) returns nutrients to the soil, reducing synthetic fertilizer dependency (Jain, 2020) [10].

- **Water:** Traditional disposal of spent wash (vinasse) from molasses distilleries is a major water pollution issue. In a biorefinery, this stream is first used for biogas generation, and the treated effluent is recycled in the process or used for irrigation, moving toward zero liquid discharge (ZLD).

- **Air:** The most immediate local benefit is the drastic reduction in particulate matter and toxic gases from the elimination of open-field burning (Shyamlal *et al*., 2022) [27].

4. Socio-economic Benefits

The technology generates rural employment across the value chain: in biomass collection and logistics, plant operations, and downstream industries. It provides an additional, stable revenue stream for sugar mills and farmers (if a mechanism for purchasing trash is established), improving the financial stability of the agrarian sector.

Economic Feasibility and Industrial Perspectives

1. Policy Support and Market Mechanisms

Economic viability in India is currently underpinned by strong policy support. The government announces administered prices for ethanol sourced from different feedstocks. For the 2023-24 season, the price for 2G ethanol from biomass like bagasse and trash is set significantly higher (e.g., ₹66.07/liter) than for 1G ethanol from cane juice (₹65.61) or B-heavy molasses (₹60.73), providing a clear financial incentive (Public Sector Undertaking data). Additionally, the government offers interest subvention schemes and capital grants (Viability Gap Funding) for setting up 2G bioethanol plants under the Pradhan Mantri JI-VAN Yojana (Purohit & Chaturvedi, 2021) [22].

2. Techno-Economic Analysis and Key Cost Drivers

- **Feedstock (≈30% of operating cost):** Sensitivity analysis showed that a 20% increase in bagasse cost raised MESP by 12%.
- **Enzymes (≈20%):** The single largest consumable cost.
- **Capital Cost (Depreciation & Finance):** High upfront cost for pretreatment and hydrolysis equipment.

The study concluded that with current government pricing and assuming a capacity utilization of 80%, an IRR of 14-16% is achievable, making it an investable proposition.

3. Industrial Case Studies and Learning Curves

The journey from demonstration to commercial scale has been a learning process. The initial 2G plants faced operational challenges related to feedstock handling, enzyme performance at scale, and continuous process stability. However, these pioneer plants, supported by companies like Praj, IOCL, and HPCL, have provided invaluable operational data. The industry is now moving toward standardized, modular plant designs that can be replicated across different mill locations, which will help bring down capital costs through economies of scale and learning.

Conclusion

Bioethanol production from sugarcane waste represents a profound convergence of India's energy security, environmental sustainability, and rural development objectives. This review has elucidated that the technological pathway, from pretreatment of recalcitrant bagasse to fermentation of mixed sugars, is maturing rapidly, bolstered by significant Indian research and development. The environmental imperative is clear: converting waste biomass into fuel can simultaneously address the crippling problem of agricultural residue burning and reduce the carbon footprint of the transportation sector.The economic case, while challenging, is being actively constructed through visionary policy support, financial incentives, and the evolving integrated biorefinery model that extracts value from every component of the biomass. The initial hurdles faced by pioneering commercial plants are providing the necessary learning to drive down costs and improve efficiency.The future of this industry in India is inextricably linked to the successful creation of a circular bioeconomy around the sugarcane sector. By viewing "waste" as a "resource," sugar mills can transform into bioenergy hubs, producing fuel, power, and chemicals. This transition requires sustained collaboration between government, research institutions, industry, and farming communities. With continued innovation, strategic investment, and robust policy frameworks, sugarcane waste-based bioethanol can undoubtedly become a cornerstone of India's journey toward energy self-reliance and a sustainable, low-carbon future, contributing meaningfully to its net-zero emissions commitment by 2070.

References

1. Arora R, *et al*. Sequential acid and alkaline pretreatment of sugarcane bagasse for enhanced sugar recovery. Bioresource Technology Reports,2022:18:101058.
2. Bhaskar T, *et al*. Sustainable utilization of sugarcane trash for energy and value-added products in India: A review. Journal of Cleaner Production,2021:285:124856.
3. Binot R, *et al*. Market growth for biofuels. Global Biofuel Outlook,2019:12(4):112-125.
4. Borrega M, Sixta H. High-solid enzymatic hydrolysis of wood and other lignocellulosic materials. Cellulose,2015:22(4):2219-2232.
5. Dixit S, *et al*. Techno-economic analysis of second-generation ethanol production in India: Learning from demonstration plants. Biofuels, Bioproducts and Biorefining,2022:16(2):456-468.
6. Galbe M, Zacchi G. Pretreatment: The key to efficient utilization of lignocellulosic materials. Biomass and Bioenergy,2012:46:70–78.
7. Gautam P, *et al*. Evaluation of pilot-scale mechanical pretreatment for enhanced biogas production from sugarcane press mud. Waste and Biomass Valorization,2019:10(5):1265-1274.
8. Ghosh P, *et al*. Life cycle assessment of ethanol derived from bagasse: An Indian case study. Renewable Energy,2021:178:587-598.
9. Haq I, Kalam MA. Biofuel development in India: Prospects and challenges. Energy Reports,2022:8:558-567.
10. Jain S. Management of distillery spent wash through biomethanation and composting: An Indian perspective. Environmental Technology & Innovation,2020:19:100937.
11. Jain S, *et al*. Air pollutant emissions from open burning of sugarcane waste in India. Environmental Pollution,2019:245:1044-1052.

12. Kapoor M, *et al*. Towards energy-positive and water-efficient sugar mills via integrated biorefineries. Energy Conversion and Management,2020:222:113214.
13. Kuhad RC, *et al*. Bioethanol production from pentose sugars: Current status and future prospects. Renewable and Sustainable Energy Reviews,2016:55:249-272.
14. Kuhad RC, Singh A. Lignocellulosic Ethanol Production from Agro-Industrial Residues. Springer Nature, 2022.
15. Kumar S, *et al*. Isolation and characterization of a thermotolerant *Pichia kudriavzevii* strain for ethanol production from lignocellulosic hydrolysate. Bioresource Technology,2019:291:121867.
16. Mahajan S, *et al*. Ethanol blending policy in India: A review of opportunities and challenges. Transportation Research Part D: Transport and Environment,2021:92:102728.
17. Modenbach AA, Nokes SE. Enzymatic hydrolysis of biomass at high-solids loadings – A review. Biomass and Bioenergy,2012:56:526–544.
18. Mohan M, *et al*. Process optimization for simultaneous saccharification and fermentation of alkaline pretreated sugarcane bagasse for bioethanol production. Fuel,2021:292:120259.
19. Pandey AK, *et al*. Variability in composition of sugarcane bagasse across three different agro-climatic zones of India: Implications for biorefining. Biomass and Bioenergy,2022:156:106324.
20. Patel A, *et al*. Performance evaluation of a novel airlift bioreactor for ethanol fermentation from sugarcane syrup. Biochemical Engineering Journal,2021:176:108197.
21. Poppe JK, *et al*. High-solid enzymatic hydrolysis of sugarcane bagasse and ethanol production in column reactors under different aeration rates. 3 Biotech,2021:11(10):432.
22. Purohit P, Chaturvedi V. The future of biofuels in India: An assessment of the policy landscape. Climate Policy,2021:21(3):287-305.
23. Reddy KS, Singh N. Fermentation profile and fusel oil production in ethanol synthesis from sugarcane press mud. Journal of Bioscience and Bioengineering,2022:133(4):345-351.
24. Saini JK, *et al*. Production and characterization of a novel thermo-alkali stable cellulase from a Himalayan thermophile. International Journal of Biological Macromolecules,2020:162:1107-1116.
25. Sarkar S, *et al*. Agricultural residue valorization for bioenergy in India: A review. Environmental Science and Pollution Research,2021:28:68432-68455.
26. Sharma N, *et al*. Comparative evaluation of alkaline pretreatment methods for enzymatic saccharification of sugarcane bagasse. Sugar Tech,2021:23(5):1112-1121.
27. Shyamlal, *et al*. Impact of crop residue burning on air quality over Northern India. Atmospheric Environment,2022:274:118987.
28. Singh J, *et al*. Challenges and strategies for year-round operation of a lignocellulosic biorefinery in India. Biofuels,2020:11(3):273-281.
29. Singh N, Pal S. Logistics and supply chain management of sugarcane biomass for bioenergy production in India: A review. BioEnergy Research,2021:14(3):723-742.
30. Srivastava N, *et al*. Repeated-batch fermentation using flocculent *Saccharomyces cerevisiae* for efficient ethanol production from molasses. Energy & Fuels,2021:35(7):6055-6063.
31. Yadav P, *et al*. Techno-economic and environmental assessment of integrated 1G-2G bioethanol production in Indian sugar mills. Journal of Cleaner Production, 2020, 254, 120086.
32. Yuan JS, *et al*. Plants to power: Bioenergy to fuel the future. Trends in Plant Science,2008:13(8):421–429.
33. Energy, 178, 587-598.