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Review

Corn Stover: Revisiting of the Opportunities and Barriers of Its Composition, Bioenergy Applications, and Sustainability

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Abstract: Corn Stover (CS), rich in lignocellulosic materials, poses challenges in biodegradability, necessitating pretreatment methods to enhance biofuel yields. Biogasification through anaerobic digestion and bioethanol production via fermentation are promising pathways, though both face technical barriers, particularly in pretreatment efficiency and enzyme limitations. Economic factors, including high feedstock collection and transportation costs, hinder large-scale adoption. The environmental implications of CS removal, such as soil nutrient depletion and erosion risks, highlight the need for balanced residue management practices. Technological advancements, such as improved pretreatment techniques, biomass densification, and co-digestion strategies, have shown potential to enhance process efficiency and reduce costs. However, integrating circular economy principles by valorizing co-products like lignin and digestate further strengthens the sustainability of CS utilization. This review examines the composition of CS, its applications in bioenergy, and the environmental and economic considerations associated with its use. Future research directions emphasize genetic and process innovations to boost biogas and bioethanol yields, scalable industrial applications, and policy frameworks that support large-scale deployment. Ultimately, CS holds significant promise in contributing to global renewable energy goals, provided that technological, economic, and environmental challenges are effectively addressed.

Keywords: biogasification; bioethanol; bioenergy applications; corn stover; lignocellulosic biomass

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1. Introduction

In current societies, the existence of continuous, sustainable, and economic energy is necessary for economic development and growth (Søndergaard et al., 2015). Modern civilization is so dependent on energy that it is impossible to imagine life without it. A disruption or stoppage of its supply would halt the economic machine (Kougias et al., 2014; Labatut et al., 2011). Currently, issues such as hazardous waste materials, the exhaustibility of fossil resources, and increasing energy consumption are subjects of intense research globally (Anal, 2019; Kakihana et al., 2012). These issues make it paramount that it is no longer feasible to rely on existing energy sources (Teng et al., 2014). Moreover, research into new, sustainable sources developed over the past few decades highlights the importance of these concerns and the associated sciences (Lindkvist, 2020).

Global energy policies that promote the inefficient use of fossil fuels have proven environmentally irresponsible because they cause significant environmental damage at local, regional, and global levels. Studies have shown that integrating renewable energy sources into the overall energy mix can mitigate or prevent these negative impacts (Jameel et al., 2024; Tsapekos et al., 2017). While biogas has a long history of recognition, its widespread use has increased primarily over the last century, especially in the last three decades. Biogas, derived from biomass, is particularly useful in rural areas, as it is both inexpensive and locally produced (Fotidis et al., 2014; Y. Li et al., 2013).

The escalating global grain production, which reached 1,030 million tons in 2016, has amplified interest in corn stover (CS) as a renewable energy feedstock (Czajkowski et al., 2019). Despite its promising applications, several challenges hinder the widespread utilization of CS. Residue removal impacts soil health, potentially leading to erosion and reduced soil organic carbon (SOC) sequestration (Mann et al., 2002; Swan et al., 1996). In addition, innovations such as improved techniques for rind and pith components, aim to optimize stover's utility while mitigating environmental concerns (H. Y. Li et al., 2014). Economic considerations, including collection and transportation costs, remain significant barriers to its broader adoption. Given the growing emphasis on renewable energy and sustainable agricultural practices, CS's potential as a bioenergy feedstock warrants a comprehensive assessment. Recent work also indicates that the future competitiveness of lignocellulosic bioenergy will depend not only on improvements in conversion efficiency but also on the integration of digital optimization and broader system-level assessment. Machine-learning approaches are increasingly being used to identify nonlinear interactions across pretreatment, hydrolysis, fermentation, and anaerobic digestion, thereby reducing empirical trial-and-error in process design, while residue-based feedstocks such as corn stover are gaining additional relevance because they can expand bioenergy supply without requiring additional land area. Accordingly, a comprehensive assessment of corn stover bioenergy should consider both artificial intelligence (AI)/ machine learning (ML)-assisted process optimization and the wider socio-economic context, including energy security, carbon-intensity governance, and rural value creation (Farheen et al., 2026; International Energy Agency [IEA], 2023, 2024; Khan et al., 2023; Phromphithak et al., 2021; REN21, 2024; C. Wang et al., 2023). Thus, situating CS within the broader transition toward sustainable energy systems, this study seeks to clarify the key challenges and opportunities shaping its future development.

2. Corn Stover

Corn stover (CS) refers to husks (8%), cobs (15%), leaves (28%), and stalks (48%) left on the farm after harvest. Despite its abundance, only about 6% of corn stovemer is typically collected for use, with the majority left to decompose and enrich soil organic matter (Menardo et al., 2015; Sokhansanj et al., 2002). CS, a typical lignocellulosic biomass, generally consists of 70% cellulose, hemicellulose, and 15–20% lignin, forming a complex and recalcitrant structure (Cui et al., 2012; Guan et al., 2025; Sluiter et al., 2010; Zhong et al., 2021). The heterogeneous composition of corn stover affects its degradability and suitability for various applications (Sokhansanj et al., 2010). About half of the corn plant is corn stover (CS), meaning the mass ratio of corn stover to corn grain is 1:1 (Perlack et al., 2005). CS is the most abundant agricultural residue in the United States (Aghaei et al., 2022).

3. Composition

3.1. Chemical Composition

Lignocellulose is considered an attractive raw material to produce volatile fatty acids (VFAs) through co-digestion with waste-activated sludge (WAS), due to its availability in large quantities and low cost (Guo et al., 2015; A. Zhou et al., 2013). Cellulose is an unsubstituted homopolysaccharide consisting of β-1,4-linked D-glucopyranosyl units. Many cellulose chains aggregate to form crystalline, highly organized microfibrils via extensive inter- and intra-molecular hydrogen bonds, which hinder cellulose degradation. Only amorphous cellulose sections—regions where the ordered structure is lost—are readily accessible to hydrolytic enzymes (Perrot et al., 2022).

Glucuronoarabinoxylan (GAX), the primary matrix polysaccharide in grasses, features a highly O-acetylated linear β-1,4-linked D-xylopyranose backbone, further decorated with pentose, hexose, and (methyl)uronic or hydroxycinnamic acid side chains (Houfani et al., 2020; A. Zhou et al., 2016). This structural heterogeneity impedes enzymatic degradation, necessitating multiple enzymes with specific substrate recognition and cleavage capabilities to efficiently convert GAX.

Lignin, an aromatic heteropolymer composed mainly of guaiacyl, syringyl, and/or p-hydroxyphenyl monolignol subunits, presents the most challenging component for enzymatic depolymerization due to its highly hydrophobic and heterogeneous nature (Gao et al., 2020). Together, these structural and compositional complexities contribute to the recalcitrance of CS lignocellulose to enzymatic degradation, requiring the coordinated action of multiple hydrolytic enzymes.

Recent studies suggest that the presence of cellulose and hemicellulose in pretreated lignocellulosic residues enhances WAS acidification, potentially influencing the composition and metabolic activity of fermentation bacteria (Guo et al., 2015). Moreover, CS hydrolysates contain large amounts of monomeric sugars (e.g., glucose, xylose, and arabinose), making them ideal carbohydrate feedstocks for VFAs production. Furthermore, understanding the contribution of whole CS to VFA recovery from WAS digestion provides a foundation for cost-efficient biomass stabilization and bioenergy recovery in wastewater treatment plants (WWTPs; A. Zhou et al., 2016).

3.2. Nutrient Distribution Characteristics

Studies on CS consistently show strong partitioning of nutrients between grain and vegetative fractions, with grain retaining most nitrogen (N) and phosphorus (P), while stalks, leaves, and husks concentrate substantially higher potassium (K) levels, often nearly threefold greater than grain on a dry matter basis (H. Y. Li et al., 2014; Sawyer & Mallarino, 2014). However, standing-plant measurements frequently overestimate K export because K^+ is highly soluble and subject to intense leaching from vegetative tissues following physiological maturity, particularly after rainfall events between the black layer and grain harvest (Karlen et al., 2015; Sawyer, n.d.; Sawyer & Mallarino, 2012). In contrast, phosphorus concentrations remain comparatively stable over this period (Oltmans & Mallarino, 2011).

Field surveys in Iowa indicate that stover collected at combine harvest typically contains approximately 3 lb P_2O_5 and 19 lb K_2O per dry ton, although observed ranges are wide due to site conditions and weather variability, with potassium occasionally exceeding 40 lb K_2O per ton (Darr et al., 2014; Oltmans & Mallarino, 2011). Nutrient concentrations measured from baled stover often show even greater dispersion, reflecting biological heterogeneity and soil contamination during collection, which can artificially inflate apparent mineral content, particularly for K and trace elements (Darr et al., 2014; Karlen et al., 2015).

4. Bioenergy Applications

Bioenergy encompasses energy production methods that utilize biomass, renewable, plant-derived organic matter. This includes dedicated energy crops, agricultural residues, forestry waste, aquatic vegetation, and municipal waste. Certain characteristics make some biomass more suitable for energy production, such as energy density, moisture content, chemical composition, particle size, production rate, and sustainable availability (Zych, 2008). Among crop residues, CS shows strong potential as a biomass feedstock (Graham et al., 2007).

4.1. Biogasification (Anaerobic Digestion): Process, Efficiency, and Yield

Anaerobic digestion (AD) is a complex biological and physicochemical process that converts organic matter into biogas and digestate in the absence of oxygen (Kangle et al., 2012). Key stages include hydrolysis, acidogenesis, acetogenesis, and methanogenesis. AD can be conducted under two conditions: liquid anaerobic digestion (L-AD, TS < 15%) and solid-state anaerobic digestion (SS-AD, TS > 15%; Ge et al., 2014). SS-AD offers several advantages, such as compost by-products, reduced energy inputs, fewer moving parts, and minimal floating/stratification issues (Brown & Li, 2013). CS has high total solids and contains recalcitrant carbohydrates (J. Zhu et al., 2015). Hence, co-digestion is often required to enhance its degradation. Co-digestion not only improves digestion efficiency and microbial diversity but also sustains microbial growth (El-Mashad & Zhang, 2010). A diverse microbial community is essential for effective anaerobic digestion, and understanding microbial interactions is key to optimizing reactor performance (Liu et al., 2010, 2016; J. Zhou et al., 2013). Additional microbial community exploration can help establish more precise relationships between structure and function.

Co-digestion reduces environmental impact and reliance on fossil fuels (Radwan et al., 1993). But a corn stalk is hard to biodegrade (Myint et al., 2007; Schober & Trösch, 2000; Vedrenne et al., 2008). To enhance lignocellulose hydrolysis, several pretreatment methods have been applied, including size reduction, steam explosion, fungal degradation, ammonification, and alkaline treatments (Bauer et al., 2009; Fernandes et al., 2009). Co-digestion offers promising benefits such as diluting toxic compounds, balancing nutrients, stimulating microbial synergy, and increasing biogas yield (Ağdağ & Sponza, 2007; Parawira et al., 2004, 2008). While research is extensive for co-digestion involving straw and other biosolids, fewer studies focus specifically on corn stalks and other biowaste solids (G. Chen et al., 2010; Parawira et al., 2008; H. Wang et al., 2009).

G. Chen et al. (2010) reported that mono-digestion of corn stalk achieved a maximum methane yield of 217.60 ± 13.87 mL/g TS at an initial TS of 4.8%, with acidification occurring at 6.0% TS and a pH of 5.10 on day 4. Co-digestion improved methane yields by 4.42–58.61% through enhanced VFAs production and better pH regulation. The highest biogas yield (410.30 ± 11.01 mL/g TS) and methane yield (259.35 ± 13.85 mL/g TS) were observed with 40% vermicompost (VC) addition. X-ray diffraction analysis revealed that VC co-digestion reduced corn stalk crystallinity by 29.4%, suggesting improved biodegradability.

Recent studies show that data-driven models (such as the use of AI/ML not as a substitute for process understanding, but as a practical layer for prediction, control, and optimization under highly nonlinear operating conditions) can identify critical operational variables, optimize lignocellulosic biomass-to-manure ratios, and construct soft sensors for instability indicators, suggesting that corn stover digestion can be improved more effectively through multi-parameter, data-assisted control than through isolated one-factor adjustments (Ganeshan et al., 2024; Khan et al., 2023; Sonwai et al., 2023; Zou et al., 2024).

4.2. Bioethanol Production: Pretreatment Strategies and Fermentation Challenges

The introduction of bioethanol into the transport sector was a vital step in reducing fossil fuel dependence. Countries such as the USA, Brazil, and India already blend bioethanol with gasoline

(Morales et al., 2015; Soam et al., 2016; Wojtusik et al., 2016). For sustainable production, lignocellulosic waste, rather than food crops, should serve as the primary feedstock (Agostinho et al., 2015). CS is one of the most abundant lignocellulosic residues, given the global scale of corn production (1.06×10^9 t/year), surpassing wheat and rice (Y. Zhao et al., 2018). However, CS's complex lignocellulosic matrix resists biological conversion (Loow et al., 2016). Pretreatment is thus essential to break down crystalline cellulose and free cellulose and hemicellulose from lignin for enzymatic hydrolysis and fermentation. While downstream steps are well established, pretreatment remains a key research focus (Capolupo & Faraco, 2016; R. Kumar et al., 2016).
Pretreatment methods include:

- **Physical:** Milling, extrusion, microwave.
- **Physicochemical:** Steam explosion, LHW, AFEX, supercritical CO_2.
- **Chemical:** Acid/alkaline treatments, organic solvents, ionic liquids.
- **Biological:** Use of fungi and other microbes (Aditiya et al., 2016).

Enzymatic hydrolysis dominates carbohydrate conversion, though acid and hydrothermal techniques are also used. These technologies vary widely in efficiency, operating conditions, and ethanol yields. Commercial-scale implementations remain limited, with no single method yet preferred (Aditiya et al., 2016; H. Chen & Fu, 2016). Bioethanol is a widely used conventional biofuel and gasoline additive (Balat et al., 2008). It is categorized into four generations, with second-generation ethanol, produced from crop residues like CS, offering a more sustainable path than first-generation sources that compete with food and require high water input. Second-generation ethanol avoids the food-vs-fuel dilemma and utilizes agricultural waste. However, the required pretreatment step adds technical and economic complexity. Innovations are increasingly targeting this challenge (Lászlok et al., 2020; Y. Zhao et al., 2018), helping move second-generation biofuels closer to commercial viability. The EU, for example, aims to source 3.5% of its transport biofuel consumption from advanced biofuels by 2030 (Aghaei et al., 2022). Effective pretreatment must disrupt the crystalline structure of cellulose and separate it from lignin to enable enzymatic hydrolysis. This step is one of the costliest and technically demanding stages of bioethanol production (Shadbahr et al., 2015), accounting for up to 16–19% of a biorefinery's capital costs (Da Costa Sousa et al., 2009). Moreover, enzyme costs can make up 70% of hydrolysis expenses (Baral & Shah, 2017), emphasizing the importance of efficient pretreatment. Pretreatment methods—physical, chemical, biological, or hybrid—must be evaluated based on yield, waste generation, cost, chemical recyclability, and feedstock characteristics (Karimi et al., 2013).

4.2.1. Physical Pretreatment

This aims to reduce particle size and increase the surface area to volume ratio, typically through milling, pyrolysis, or irradiation. Although physical pretreatment alone is usually insufficient, it can be used before, during, or after other treatments. For example, post-chemical pretreatment size reduction offers advantages like lower energy consumption. However, not all processes benefit from this step (Karimi et al., 2013).

4.2.2. Chemical Pretreatment

Chemical pretreatment modifies the structure of biomass using acids, alkalis, solvents, or ionic liquids. Alkaline pretreatment—among the oldest methods—uses agents like NaOH, $Ca\ (OH)_2$, or Na_2CO_3 to break lignin–carbohydrate bonds. Its effectiveness depends on concentration, temperature, and duration (Karimi et al., 2013; Molaverdi et al., 2019). Mirmohamadsadeghi et al. (2016) achieved a 95% glucose yield with Na_2CO_3 pretreatment. Zheng et al. (2009) developed a wet-state NaOH method that reduced pretreatment time by 86% and used 66.7% less NaOH than the solid-state alternative. Acid pretreatments like steam explosion, LHW, and dilute acid treatments target hemicellulose. Dilute acid pretreatment converts hemicellulose to xylose and then furfural, an inhibitor of fermentation (Mosier et al., 2005). Y. Zhu et al. (2005) showed that preheating to remove moisture before dilute acid treatment improved sugar yields. Um et al. (2003) found sulfuric acid superior to phosphoric acid for this application.

4.2.3. Physicochemical Methods

Steam explosion involves high-pressure, high-temperature treatment followed by rapid depressurization, releasing acetic and uronic acids that autocatalyze hemicellulose breakdown (K. Wang et al., 2015). Catalysts like sulfuric acid or SO_2 can be added, reducing pH to 3–4. Chang et al. (2012) reported substantial reductions in cellulose, hemicellulose, and lignin contents following this treatment. AFEX, a variation of steam explosion using liquid ammonia, is performed under mild temperatures and high pressures. Teymouri et al. (2005) optimized AFEX for CS, achieving nearly 100% glucose and 80% xylose yields.

4.2.4. Emerging Chemical Methods

MgO pretreatment, as shown by Aghaei et al. (2022), neutralizes acetic acid during liquid hot water (LHW) pretreatment, preventing the formation of inhibitors like furfural. Compared to LHW, MgO pretreatment improved hemicellulose recovery, enhanced lignin removal, and increased sugar yields by 6%. Organosolv pretreatment uses organic solvents (e.g., methanol, ethanol) with or without catalysts to fractionate lignocellulose into cellulose, hemicellulose, and lignin. It minimizes carbohydrate degradation and enables easy solvent recovery (X. Zhao et al., 2009). Qing et al. (2017) combined alkaline and organosolv treatments to achieve a 98.6% sugar yield.

4.2.5. Ionic Liquids and DESs

Ionic liquids are highly effective in dissolving biomass, enabling efficient separation of glucan-rich fractions (L. Sun et al., 2013; Uppugundla et al., 2014). However, nutrient supplementation may be required due to losses during pretreatment. Geng and Henderson (2012) achieved a 96% glucose yield by combining mild alkali pretreatment with ionic liquids. Deep eutectic solvents (DESs), a biocompatible class of ionic liquids, consist of hydrogen bond donors and quaternary ammonium salts. Unlike traditional ionic liquids, DESs can be derived from non-ionic components (A. K. Kumar & Sharma, 2017). G.-C. Xu et al.(2016) achieved 99% glucose yield using optimized DESs. Microwave-assisted DES pretreatment, currently under development, reduces processing time significantly (Z. Chen & Wan, 2018).

4.2.6. Biological pretreatment

Biological pretreatment is a safe and environmentally friendly method that utilizes lignocellulose-degrading microorganisms to enhance the digestibility of CS. Various biological strategies, such as fungal treatment, microbial consortia, and enzymatic pretreatment, have been employed as upstream processes in biofuel production from CS (Tabatabaei et al., 2020). Soft- and brown-rot fungi primarily degrade cellulose, while white-rot fungi are more effective at lignin degradation (Singh et al., 2018). These organisms secrete extracellular enzymes, such as lignin peroxidases and laccases, which facilitate the breakdown of lignin and improve the accessibility of cellulose and hemicellulose.

Although biological pretreatment is not energy-intensive (Da Costa Sousa et al., 2009), it is generally time-consuming and requires large-scale infrastructure and equipment (Tabatabaei et al., 2020). Several studies have successfully applied different biological pretreatment strategies to CS (Saha et al., 2016; F.-h. Sun et al., 2011; Wan & Li, 2010). For example, Song et al. (2013) demonstrated biological pretreatment using Irpex lacteus in the presence of manganese ions. Their enhanced method, which involved manganese supplementation, achieved a glucose yield that was 61.39% higher than that of the conventional biological approach.

Combining multiple pretreatment methods can lead to improved yields, though this approach requires a detailed economic evaluation. For instance, combining steam explosion with alkali treatment is more effective than single-method treatments, as each technique targets different structural bonds within lignocellulose (Karimi et al., 2013).

Comparative analyses of pretreatment methods—including steam explosion, AFEX, dilute sulfuric acid, and biological pretreatment—reveal significant differences in cost and efficiency. Biological pretreatment typically requires twice the amount of feedstock compared to diluting sulfuric acid and demands over ten times the capital investment. Operating costs are also roughly double, underscoring the need for further development before this method becomes industrially viable (Baral & Shah, 2017). However, in terms of external energy requirements, biological pretreatment consumes only one-fifth the energy required for ammonia fiber explosion, making it attractive from an energy conservation standpoint.

From an environmental perspective, the use of greener solvents such as deep eutectic solvents (DESs), ionic liquids, and supercritical fluids is gaining attention. Among these, DESs are especially promising due to their environmental friendliness and cost-effectiveness (Roy et al., 2020). Nevertheless, all these emerging methods require additional research to reach industrial scalability.

In a notable life cycle assessment (LCA) study, Smullen et al. (2019) evaluated four pretreatment strategies—NaOH, ammonia, sulfuric acid, and methanol—across multiple environmental categories. Methanol was found to have the lowest global warming potential but the highest eutrophication impact. Overall, ammonia and methanol emerged as the most favorable options in terms of impacts on air, soil, and water. Conversely, sulfuric acid and NaOH had higher impacts on global warming, eutrophication, and photochemical oxidation potential.

4.3. Digital and AI- Assisted Process Optimization in CS Bioconversion

Unlike conventional mechanistic or statistical models, AI-based approaches, especially artificial neural networks (ANNs), show superior capability in modeling complex, multi-dimensional process behavior using real-time and historical datasets (Pereira et al., 2020; Shenbagamuthuraman & Kasianantham, 2023). For instance, ANN-based frameworks have been shown to outperform traditional response surface methodology (RSM) by more accurately capturing non-linear relationships between pretreatment severity, enzymatic hydrolysis efficiency, and inhibitor formation, leading to enhanced sugar recovery and fermentation performance (Shenbagamuthuraman & Kasianantham, 2023).

Consequently, the AI platforms dynamically adjust operational conditions in response to fluctuations in feedstock quality, thereby stabilizing fermentation performance and reducing energy consumption (Pereira et al., 2020). Evidence from enzymatic saccharification and fermentation modeling shows that ANN-based optimization can significantly enhance yield while reducing experimental iterations, highlighting its potential to accelerate process development and scale-up (Gitifar et al., 2013; Sewsynker-Sukai et al., 2017). However, this potential is contingent on the availability of high-quality datasets, as model performance remains sensitive to data variability and limitations inherent in industrial bioenergy systems (Grahovac et al., 2016).

Similarly, in bioethanol production, the most useful role of AI/ML is to connect pretreatment decisions with downstream hydrolysis and fermentation performance rather than to optimize each unit operation in isolation. Studies show that machine-learning models can successfully relate biomass characteristics, solvent or catalyst identity, pretreatment severity, solids recovery, and sugar-release outcomes, which means that the most meaningful optimum for corn stover is not simply maximum cellulose accessibility, but the best overall balance among deconstruction efficiency, inhibitor minimization, fermentability, and process economics (Haldar et al., 2023; Phromphithak et al., 2021; C. Wang et al., 2023).

4.4. Comparison with Other Biomass Feedstocks: Advantages and Limitations

Several authors (Adler et al., 2015; Nelson, 2002; Perlack et al., 2005) have suggested that harvesting CS can be a “win-win” management practice, often stating that CS is an underutilized resource that could be used as a feedstock while simultaneously reducing residue management costs, which currently range from \$49–74 ha^{-1} (Karlen et al., 2015). However, the decision to harvest CS stover for bioenergy or any other use is not that simple, as CS (plant residue) also supports many ecosystem services (Johnson et al., 2009; Wilhelm et al., 2007, 2010).

5. Environmental and Economic Considerations

5.1. Sustainability and Carbon Footprint: Life Cycle Assessment (LCA)

Uncertainties surrounding the life cycle assessment (LCA) of corn stover (CS) utilization for lignocellulosic ethanol remain substantial and are closely tied to methodological choices, which significantly influence reported sustainability outcomes. A major source of variability lies in the definition of system boundaries, as many studies either restrict analysis to the ethanol production stage or apply expanded boundaries that incorporate displacement effects such as fossil fuel substitution and coproduct credits, yet still fail to capture broader system-level constraints, including competition for biomass and land resources (Hedegaard et al., 2008). This limitation is particularly relevant for CS, where residue removal may interfere with essential ecological functions such as soil carbon retention and nutrient cycling. Empirical evidence, however, suggests that these impacts are context-dependent; for instance, a long-term field study in central Pennsylvania found that partial removal (50%) of corn stover had minimal effects on soil organic carbon and nutrient levels, with only a reduction in surface phosphorus observed, while maintaining adequate soil cover to mitigate erosion risks (Adler et al., 2015; Wilhelm et al., 2010).

In addition to system boundary issues, inconsistencies in the choice of functional units, ranging from energy output to land area or transport service, further complicate cross-study comparisons and can significantly alter interpretations of environmental performance (Hedegaard et al., 2008; von Blottnitz & Curran, 2007). Carbon accounting also introduces considerable uncertainty, particularly in relation to soil carbon dynamics and indirect land-use change (ILUC), both of which depend heavily on assumptions regarding crop yields, land availability, and market-mediated responses. These uncertainties are compounded by limited understanding of the ethanol conversion stage, as most LCA studies emphasize feedstock production or compare bioethanol systems with fossil fuels using generalized assumptions about conversion technologies (Davis et al., 2009; González-García et al., 2010). Consequently, critical environmental burdens associated with conversion processes—such as energy-intensive pretreatment, hydrolysis, and distillation—are often underrepresented, largely due to process uncertainties and the lack of commercial-scale lignocellulosic ethanol facilities (Borrion et al., 2012).

Methodological differences in LCA approaches further contribute to divergent findings. Attributional LCAs, typically characterized by narrower system boundaries, tend to report favorable greenhouse gas (GHG) reductions and positive energy balances. In contrast, consequential LCA approaches, which account for alternative biomass uses and broader market interactions, often yield less optimistic conclusions, indicating that diverting biomass to ethanol production may displace more efficient energy pathways and reduce overall environmental benefits (Hedegaard et al., 2008). Furthermore, variations in coproduct allocation methods and the frequent exclusion of wider environmental impact categories—such as acidification, eutrophication, and toxicity—lead to inconsistent assessments, with some studies reporting unfavorable impacts despite climate-related benefits (von Blottnitz & Curran, 2007).

5.2. Soil Health and Agricultural Impacts: Soil Response and Management Strategies

The main agronomic concern of CS removal is its long-term impact on soil fertility and productivity. CS contains essential nutrients (e.g., C, N, P, K, Ca, Mg), and its return to the soil is critical for nutrient recycling and sustaining yields. Removing 40% of CS can reduce soil N by 20%, P by 14%, and K by 110% (Fixen, 2007). In tropical Mexico, CS removal led to declines in soil organic carbon (SOC), total N, and extractable P (Salinas-Garcia et al., 2001). Historically, conventional tillage and residue removal have depleted up to 70% of SOC in agricultural soils (Wilhelm et al., 2007). Nutrient loss varies with removal rate and site conditions, while some studies show minimal impact (Karlen et al., 1984), others report significant SOC and N losses (Blanco-Canqui & Lal, 2007; Karlen et al., 1994). Threshold removal rates of 30–50% are often proposed based on erosion control (Graham et al., 2007), yet higher stover retention is likely needed to sustain soil fertility (Wilhelm et al., 2007). Effects on soil structure are inconsistent: Karlen et al. (1994) found no change in aggregate stability, but Blanco-Canqui et al. (2006) observed rapid declines. Partial harvests can mitigate pest pressures and reduce N fertilizer needs (Coulter & Nafziger, 2008). Guidelines recommend harvesting only in high-yield areas with sufficient residue left to prevent erosion and maintain SOC (Adler et al., 2015; Wilhelm et al., 2007).

CS removal's effects on nitrogen are less studied than on SOC. Full removal under no-till may reduce soil N by 10–20% (Blanco-Canqui & Lal, 2009), though minimum tillage can improve N retention when at least 33% of residue remains (Salinas-Garcia et al., 2001). Results vary depending on fertilizer use (Karlen et al., 1994). Moreso, some studies show no yield decline (Adler et al., 2015), while others observe small positive or negative effects (Karlen, 2014). However, high residue levels can lower soil temperatures, harbor pests, and reduce germination (Sindelar et al., 2013), but also conserve moisture during droughts (Baumhardt et al., 2013). Excessive removal depletes SOC and nutrients (Blanco-Canqui et al., 2006; Wilhelm et al., 2004), though some findings suggest more nuanced impacts (Clapp et al., 2000).

CS plays a historical and modern role in agriculture and bioenergy (H. Xu et al., 2019). Sustainable removal depends on site-specific factors, including soil type, slope, climate, tillage, and crop rotation (Aghaei et al., 2022). Harvest efficiency is under 40% using conventional dry methods, while wet harvests reduce field passes (Sokhansanj et al., 2002). One-pass systems are being developed to improve efficiency and retain sufficient residue (Luo et al., 2009; Shinners et al., 2007). CS harvest can enhance seedbed conditions and reduce disease pressure, but may also reduce soil C and N, and increase erosion risks (Mann et al., 2002). A synthesis of 409 data points showed SOC stocks declined by 8% in soils with stover removal, regardless of tillage, but depending on removal rate, soil depth, and rotation (Anderson-Teixeira et al., 2009; Johnson et al., 2006). Though CS is a viable biofuel feedstock, long-term sustainability hinges on maintaining SOC and soil function. Residues regulate temperature and moisture, protect against erosion, and support biological processes (Blanco-Canqui & Lal, 2009). In high-residue or sensitive systems, stover can hinder crop establishment or increase agrochemical needs. Effective management is critical to balance energy use with soil health (Wilhelm et al., 2004).

5.3. Economic Viability: Cost of Collection, Processing, and Commercialization

Feedstock cost accounts for approximately 35–50% of the total cost of producing ethanol or power. The exact proportion depends on biomass species, yield, location, climate, local economic factors, and the type of systems used for harvesting, packaging, processing, storing, and transporting the biomass (Sokhansanj & Fenton, 2006). Harvesting and collection involve gathering and removing biomass from the field, depending on its condition at harvest. These operations vary based on biomass type (e.g., grass, wood, or crop residue), moisture content, and intended end use. For crop residues, harvest operations must be coordinated with grain harvest, whereas dedicated crops (grass and wood) can be harvested in separate, biomass-only operations. Collection refers to picking up biomass, packaging it, and transporting it to a nearby storage site. The most common collection method is baling, typically into either round or square bales. Round bales are popular on many U.S. farms (Cundiff, 1996). However, their use in large-scale biomass applications is limited because round bales tend to deform under static loads and are difficult to transport efficiently, especially if not perfectly round (Sokhansanj & Fenton, 2006).

Estimating nutrient removal through CS harvest is complicated by the translocation and leaching of soluble nutrients, such as potassium (K), from the upper plant parts between physiological maturity and harvest. Combined with operational variability, this leads to inconsistent nutrient composition data (Avila-Segura et al., 2011; Birrell et al., 2014; Karlen et al., 2014), making it difficult to make precise, field-specific decisions regarding CS harvest and marketing (Karlen et al., 2015). Bio-based energy has the potential to enhance energy independence, drive rural economic growth, and provide environmental benefits. However, supplying the large volumes of low-density biomass needed for industrial-scale biorefineries presents logistical challenges for transport, handling, and storage.

Despite interest in uniform feedstock and better supply logistics, densified biomass has not been widely adopted by biorefineries (Nahar et al., 2021). Earlier studies (Sokhansanj & Fenton, 2006; Sultana et al., 2010) assumed that the costs of densification would primarily offset transportation savings. However, they often overlooked interactions between densification and downstream conversion processes.

5.4. Macro-Level Socio-Economic Impacts: Energy Security and Carbon Markets

Beyond plant-level performance, corn stover bioenergy also has macro-level significance as a residue-based energy option that can diversify domestic supply without requiring additional land area. In this sense, its importance is not limited to greenhouse-gas mitigation: authoritative energy assessments increasingly frame sustainable biofuels as relevant to energy security and rural job creation, while broader renewables literature emphasizes that locally embedded renewable-energy systems can strengthen economic development and livelihoods when value chains are retained within producing regions (IEA, 2023, 2024; REN21, 2024)

The socio-economic contribution of corn stover is also shaped by carbon-trading and low-carbon credit markets through which low-carbon attributes are measured and monetized. Under the U.S. Renewable Fuel Standard, RINs operate as tradable compliance credits and post-2022 volume-setting explicitly considers rural economic development and agricultural supply effects, while the Low Carbon Fuel Standard uses declining carbon-intensity benchmarks to generate tradable credits for fuels that outperform the benchmark; in parallel, public low-carbon agriculture programs are beginning to pair biomass recycling with MRV systems, local agro-processing, job creation, and even exploration of voluntary carbon-market access (California Air Resources Board, n.d.; IEA, 2024; Y. Li et al., 2024; Uuited States Environmental Protection Agency, 2025; World Bank, 2024)

6. Challenges

Pretreatment remains one of the most significant technical barriers to efficiently converting lignocellulosic biomass like CS into biofuels. This critical step, necessary to overcome biomass recalcitrance, is economically and environmentally challenging due to its high energy requirements, long reaction times, and chemical usage (Yang & Wyman, 2008). Pretreatment alone accounts for 20%–30% of total biofuel production costs, yet little research has addressed energy consumption across different pretreatment methods. Although pelleting has been shown to improve hydrolysis yields (Guragain et al., 2013; Nahar & Pryor, 2014, 2017; Rijal et al., 2012). Its effects on energy savings and greenhouse gas (GHG) reductions remain underexplored (Nahar et al., 2021). High production costs continue to limit the commercial viability of lignocellulosic ethanol at scale (Shadbahr et al., 2015). Infrastructure and logistics also pose major challenges across the biomass supply chain, particularly regarding storage, transport, and processing. Transportation costs are highly dependent on biomass bulk density, which influences the overall economics of biofuel production (Sokhansanj & Fenton, 2006).

7. Barriers and Strategies

Corn stover utilization significantly reduces lifecycle carbon emissions and enables diverse products such as ethanol, biogas, lignin-derived materials, in a circular bioeconomy (Zabed et al., 2023; Zhang et al., 2025). Table 1 outlines major barriers with some evidence/impacts, and remedies/mitigation strategies.

Table 1. Barriers and Strategies of Corn Stover Utilization.

Barrier	Evidence & Impact	Remedy
Biomass recalcitrance to enzymatic conversion	Lignin-carbohydrate complexes inhibit hydrolysis efficiency (Himmel et al., 2007).	Deploy integrated pretreatment pathways such as alkali-assisted steam explosion or ionic liquid fractionation to disrupt lignin structure and improve cellulose accessibility. Combine with genetically engineered low-lignin feedstocks to enhance digestibility and reduce severity requirements. (J. Wang et al., 2026)
High pretreatment/enzyme costs.	Pretreatment is the most energy- and cost-intensive stage, significantly influencing economic and environmental performance (Baral & Shah, 2017).	Implement process-integrated pretreatment systems (e.g., NaOH/ethanol organosolv with solvent recovery, or steam explosion coupled with heat integration). Adopt on-site enzyme production, enzyme recycling, or immobilized enzyme systems to reduce operational cost (Pei et al., 2026)
Low bulk density and high logistics cost	Low density increases transportation and handling costs, limiting supply chain efficiency (Sokhansanj & Turhollow, 2004).	Introduce densification technologies such as pelleting, briquetting, or baling combined with decentralized preprocessing depots to reduce transport distances and stabilize supply chains (Manandhar & Shah, 2018).
Moisture variability & storage	Fresh stover often exceeds 40% moisture in-season, causing aerobic spoilage (dry matter losses approximately 8–28% at 20–50% MC).	Optimize harvest timing within low-moisture windows, apply high-moisture densification (e.g., pelleting) or forced-air drying systems, and utilize covered or anaerobic storage systems (e.g., silage, sealed bags) to minimize spoilage losses (Smith et al., 2020).
Soil erosion & SOC loss	Long-term SOC depletion reduces fertility and increases erosion (Wilhelm et al., 2010).	Apply precision residue harvesting with site-specific removal thresholds, integrate soil monitoring tools, and return nutrients via digestate or biochar application to maintain soil health (Zhang et al., 2025).
Nutrient depletion/ Feedstock heterogeneity	CS removal extracts essential nutrients (N, P, K), and variability in composition affects conversion efficiency (Hess et al., 2009).	Develop standardized feedstock quality specifications, integrate advanced preprocessing (size reduction, fractionation), and implement nutrient recycling systems to offset fertilizer demand and stabilize feedstock quality (Battaglia, 2018).
Limited industrial scale-up and sustainability data	Few commercial cellulosic biorefineries exist due to supply-chain and economic hurdles (Pei et al., 2026). As such, most LCAs rely on modeled or pilot systems (Cherubini & Ulgiati, 2010).	Promote integrated biorefinery models with co-located preprocessing, conversion, and valorization units (e.g., lignin-to-chemicals, biogas integration). Support through policy incentives (e.g., Renewable Identification Numbers, carbon credits) and public–private partnerships. Advance process-specific LCAs at demonstration scale incorporating co-product valorization and real operational data.

8. Future Perspectives and Research Directions

The future of CS utilization in bioenergy production hinges on innovative strategies that enhance yields, integrate circular economy principles, scale industrial applications, and foster interdisciplinary collaboration. Improving biogas and bioethanol yields requires both genetic and process innovations. Genetically engineered corn varieties with lower lignin content and higher cellulose concentrations can significantly enhance digestibility, thereby increasing biogas and ethanol yields (M. Li et al., 2016). Concurrently, advancements in pretreatment techniques—such as steam explosion, alkaline treatments, and enzymatic hydrolysis—can improve efficiency of lignocellulosic breakdown, making more fermentable sugars available for conversion (Alvira et al., 2010). The integration of these innovations can substantially boost overall energy yields while maintaining economic feasibility.

Circular economy approaches further enhance the sustainability of CS stover utilization by promoting waste valorization and co-product development (Beckham et al., 2016). These strategies not only reduce environmental impacts but also improve the economic viability of biorefineries. Scalability and industrial application are critical for commercial success. Decentralized biorefinery models can reduce transportation costs and logistical challenges in corn-producing regions (Sokhansanj et al., 2008), while biomass densification techniques, such as pelletization and briquetting, enhance storage and transport efficiency (Kaliyan & Morey, 2006).

Policy incentives, including subsidies and carbon credits, will be vital in encouraging industrial adoption and driving investments in large-scale bioenergy projects. Moreso, a particularly promising direction is the use of interpretable AI/ML frameworks that link feedstock properties, pretreatment severity, sugar release, anaerobic-digestion stability, lifecycle carbon intensity, and low-carbon credit eligibility, so that process optimization is aligned with commercial viability and broader socio-economic performance rather than yield alone (R. Gupta et al., 2024; IEA, 2024; Khan et al., 2023; C. Wang et al., 2023). Collectively, these future directions promise to elevate CS's role as a sustainable bioenergy feedstock while advancing broader circular economy and climate objectives.

9. Conclusion

Corn stover (CS) generated at approximately 1.66×10^9 t yr^{-1} globally, nearly half of total maize biomass, represents an abundant, low-cost, non-food lignocellulosic resource with minimal land-use change implications. The high structural carbohydrate content provides a substantial reservoir of fermentable sugars, supporting efficient second-generation bioethanol and biogas production without exacerbating food–fuel competition. Moreover, CS-derived fuels exhibit low carbon intensity (21 g CO_2e MJ^{-1}) and significant greenhouse gas mitigation potential relative to fossil fuels, positioning CS as a strategic feedstock for compliance with renewable fuel standards and broader climate objectives. Its versatility across value chains, including fermentative biofuels, anaerobic digestion, and lignin valorization into advanced materials, further aligns CS with circular bioeconomy principles. The existence of large, underutilized residue pools, such as the 27–111 Mt yr^{-1} potentially available in the U.S. Corn Belt, underscores its scalability and the feasibility of decentralized biorefineries that can reduce rural energy poverty and transport emissions.

However, the realization of these resource advantages is inherently constrained by agronomic, environmental, and logistical considerations that must be carefully managed to ensure long-term sustainability. Residue harvest increases annual nutrient removal compared to grain-only systems, necessitating site-specific retention thresholds to safeguard soil organic carbon (SOC) and erosion control. Evidence suggests maintaining between 6 and 9.25 Mg ha^{-1} of residue, depending on agroecological conditions, reinforcing the need for adaptive, yield-based harvesting guidelines. Simultaneously, logistical and preprocessing constraints, particularly the deformation and transport inefficiencies associated with round bales, highlight the importance of densification strategies. Emerging evidence indicates that pelleting and granulation not only enhance bulk density and handling efficiency but may also improve pretreatment performance and reduce downstream costs. Ensuring feedstock cleanliness, uniform moisture, and controlled particle size remains essential for stable biorefinery operations.

In this context, advancing from constraint management to system optimization requires an integrated approach that maximizes value across the entire biomass conversion. Beyond fuels, co-product valorization strengthens system-level sustainability. Lignin upgrading to bioplastics, adhesives, and carbon fibers, alongside nutrient recycling through anaerobic digestate application, closes material loops and enhances economic resilience. However, optimizing environmental performance at commercial scale demands further research into process design and technological improvements in ethanol plants. Ultimately, progress will depend on interdisciplinary collaboration across agronomy, engineering, and policy to harmonize residue management, conversion efficiency, and supply chain integration, thereby enabling the sustainable and scalable deployment of CS within the evolving economy.

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Abbreviations

The following abbreviations are used in this manuscript:

CS	Corn Stover
VFAs	Volatile Fatty Acids
WAS	Waste-Activated Sludge
WWTPs	Wastewater Treatment Plants
AD	Anaerobic Digestion
L-AD	Liquid Anaerobic Digestion
SS-AD	Solid-State Anaerobic Digestion
TS	Total Solids
VC	Vermicompost
AFEX	Ammonia Fiber Explosion
LHW	Liquid Hot Water
DESs	Deep Eutectic Solvents
LCA	Life Cycle Assessment
SOC	Soil Organic Carbon
GHG	Greenhouse Gas
EU	European Union
RINs	Renewable Identification Numbers
K_2O	Potassium Oxide (potash fertilizer equivalent)
P_2O_5	Phosphorus Pentoxide (phosphate fertilizer equivalent)
CO_2e	Carbon Dioxide Equivalent
USA	United States of America
MgO	Magnesium Oxide
NaOH	Sodium Hydroxide
Na_2CO_3	Sodium Carbonate
SO_2	Sulfur Dioxide
IEA	International Energy Agency

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