

Article

The Economic Feasibility of Producing Industrial Syrup from the Enzymatic Hydrolysis of Corn Stover Using Acidic Deep Eutectic Solvent

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Abstract

The Aspen Plus process simulation with techno-economic assessment was used to evaluate the industrial-scale feasibility of enzymatic hydrolysis of corn stover. Choline chloride (ChCl)-based deep eutectic solvents containing lactic acid (LA), formic acid (FA), and acetic acid (AA) as hydrogen bond donors were used to pretreat the corn stover. Optimal pretreatment conditions (140 °C and a solid-to-liquid ratio of 1:30) achieved high levels of lignin (77.3%, 72.9% and 73.5%) and xylan (90.2%, 93.5% and 90.5%) removal for ChCl/LA (1:5), ChCl/FA (1:5) and ChCl/AA (1:5), respectively, while retaining significant levels of glucan (81.3%, 76.2% and 82%). Subsequent enzymatic hydrolysis at 10% substrate loading yielded glucose at 93.7%, 91.2% and 82.7%, respectively. The DES pretreatment and solvent recovery units accounted for 41.9% of capital costs at a solid-to-liquid ratio of 1:30. Increasing the solid-to-liquid ratio to 1:10 reduced total capital investment by 41.6%. Operational costs were heavily influenced by DES solvent consumption (81.2–92.7% of raw material costs). Of the DESs, the ChCl/FA (1:5) pretreatment process offered the best economic performance, achieving a minimum selling price (MSP) of USD 988.2 per ton. Sensitivity analysis identified glucose yield as the most critical cost driver ($\pm 20\%$ variation caused a $\pm 25\%$ change in the MSP, followed by DES recycling efficiency. Fluctuations in DES prices had a limited impact ($\pm 20\%$ variation caused a change in MSP of only 2.4–3.8%) due to the solvent recycling mechanism. This study demonstrates the potential of DES pretreatment for industrial application through process optimization, solvent recycling and valorization of by-products.

Keywords: deep eutectic solvent; enzymatic hydrolysis; process simulation; techno-economic analysis; industrial syrup



Academic Editor: Francisco José Hernández Fernández

Received: 15 December 2025

Revised: 6 February 2026

Accepted: 1 March 2026

Published: 4 March 2026

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1. Introduction

The depletion of fossil resources and the increase in global greenhouse gas emissions have made the development of sustainable resources particularly crucial in addressing the energy crisis and environmental pollution [1,2]. Lignocellulosic biomass, the most abundant renewable carbon source in nature, has emerged as a strategic resource in addressing the dual challenges of the energy and environmental crises due to its wide availability, low cost and carbon-neutral properties [3]. This natural polymeric composite material, consisting of cellulose, hemicellulose, and lignin, possesses unique structural properties

and has garnered significant attention due to its potential conversion into various high-value products. Modern biorefinery technologies can efficiently transform lignocellulosic biomass into biofuels, high-value chemicals, and advanced functional materials, providing critical support for establishing a green, low-carbon circular economy [4–6].

The sugar-platform conversion technology, which is based on pretreatment, enzymatic saccharification and fermentation, is a key area of research in the field of biomass energy. It enables the efficient conversion of lignocellulosic feedstocks into renewable liquid fuels such as fuel ethanol. However, the tightly cross-linked, complex structure of lignocellulosic biomass poses a significant challenge to enzymes. This severely limits cellulase accessibility to polysaccharide substrates, thereby hindering efficient saccharification. Therefore, developing advanced pretreatment technologies is crucial for overcoming this bottleneck. Pretreatment can significantly enhance subsequent enzymatic efficiency by disrupting the encapsulation of lignin and hemicellulose [7–9].

The traditional pretreatment processes, such as acid/alkali pretreatments and steam explosion, have several disadvantages, including harsh reaction conditions, low efficiency, and severe environmental pollution [10–12]. The deep eutectic solvents (DESs) have emerged as a novel class of green solvent that has attracted widespread attention [13–15]. DES is formed through the self-assembly of hydrogen bond acceptor (HBA) and hydrogen bond donor (HBD) via intermolecular hydrogen bonds. They offer many advantages, including environmental friendliness, recyclability, and the use of cost-effective raw materials, as well as simple preparation processes. Consequently, DESs have become a cutting-edge area of research for replacing ionic liquids and conventional organic solvents in lignocellulosic biomass pretreatment [16,17]. Studies have shown that DESs can effectively cleave ether linkages in lignin-carbohydrate complexes (LCCs), selectively extracting lignin while minimally affecting the structural integrity of cellulose [18,19]. This precise fractionation capability increases the efficiency of enzymatic hydrolysis by two to five times following DES pretreatment, providing a new way to create an efficient sugar-platform. The DES pretreatment technology not only overcomes the limitations of traditional methods but also opens a new, green, and efficient pathway for lignocellulosic biorefining.

Choline chloride (ChCl) is the most commonly used HBA due to its biocompatibility, low cost and biodegradability [20,21]. The physicochemical properties of DES can be precisely tailored by adjusting the type of HBD (e.g., carboxylic acids, polyols and amides) and its molar ratio with ChCl to achieve selective deconstruction of biomass components [22]. Studies have shown that acidic HBDs (e.g., lactic acid and formic acid) can greatly improve the depolymerization of LCCs via proton catalysis, demonstrating superior efficiency in lignin removal compared to neutral or alkaline systems [23,24]. However, despite the excellent performance of ChCl-based DES in the pretreatment stage, its efficiency is influenced by multiple factors, including the physicochemical properties of HBDs, the conditions of the pretreatment process, and the composition of the feedstock. Therefore, it is crucial to investigate the effects of DES molar ratios (HBA: HBD), pretreatment temperature and solid-to-liquid ratio on pretreatment efficiency, as well as analyze lignin and hemicellulose removal rates and cellulose retention under different conditions, in order to identify optimal pretreatment parameters. Such research is important for guiding the efficient conversion of lignocellulosic biomass resources.

The pretreated biomass is then subjected to enzymatic hydrolysis using cellulase to break down the cellulose into fermentable monosaccharides. This process is essential for converting lignocellulosic biomass into sugars. In industrial production, evaporation processes are required on the resulting hydrolysate to obtain a high-concentration, fermentable sugar solution that serves as an excellent carbon source for subsequent microbial fermentation. As a standardized and scalable bio-based platform chemical, industrial

sugar syrup is primarily used to produce bio-based chemicals [25,26]. It can be fermented directly into energy products such as fuel ethanol and butanol, or processed further into high-value chemicals such as lactic acid and citric acid, as well as bio-based plastics and rubber [27–29]. Taking a modular approach to treating industrial sugar syrup as a primary product and evaluating its market price is crucial for assessing the economic feasibility of bioethanol production. Process simulation software is a vital technical evaluation tool for scaling up from laboratory to industrial production through systematic modeling and simulation [30,31]. This model-based process optimization method can effectively identify key cost drivers and provide a scientific basis for reducing production costs.

Techno-economic analysis (TEA) is a vital tool for assessing the technical feasibility and economic viability of innovations. Its applications span a wide range of fields, including environmental science, energy, infrastructure, manufacturing, and information technology [32–34]. In biorefinery assessments, TEA typically calculates the minimum selling price (MSP) of target products to determine economic sustainability. This is often complemented by sensitivity analyses to address uncertainties and operational challenges. Humbird et al. evaluated the economic performance of producing fermentable sugars from corn stover via dilute acid pretreatment and ammonia-conditioned enzymatic hydrolysis, reporting a blended sugar MSP of 0.12 USD/lb [35]. Baral and Sha conducted a TEA comparison of four pretreatment methods (steam explosion, dilute sulfuric acid pretreatment, ammonia fiber explosion, and biological pretreatment) for corn stover-derived fermentable sugars, with corresponding production costs of 0.43, 0.42, 0.65, and 1.41 USD/kg, respectively [36]. In a separate study, Baral et al. optimized the conditions for alkaline pretreatment and enzymatic hydrolysis of sugarcane bagasse, achieving a sugar production cost of 1.32 USD/kg under refined bioprocessing parameters [37]. Notably, research addressing the economic feasibility and cost analysis of DES pretreatments remains limited. In the field of biomass valorization, Kumar et al. conducted a multi-scenario TEA for a natural deep eutectic solvent (NADES)-based biorefinery with a processing capacity of 1 ton/day. Their findings revealed that multi-product valorization strategies outperformed conventional single-output biorefineries in terms of cost-effectiveness. The co-production of high-value products such as lignin and xylan was identified as being economically indispensable, thus validating the profitability of integrated biorefinery configurations [38]. Peng et al. evaluated the economics of ethanol production using DESs of ChCl/lactic acid (1:2) versus ChCl/urea (1:2) pretreatments. The acid-based DES reduced the MSP of ethanol to 2128 USD/ton, which is significantly lower than the MSP for the urea-based DES (3049 USD/ton), thus demonstrating its superior economic competitiveness [39].

In this study, a series of ChCl-based DESs were synthesized for the pretreatment of corn stover in combination with lactic acid (LA), formic acid (FA), and acetic acid (AA) as HBDs. This allowed the effects of key pretreatment parameters to be evaluated systematically, including the HBD/HBA molar ratio, pretreatment temperature, and solid-to-liquid ratio. We investigated the composition, morphology (as determined by scanning electron microscopy), structure (as determined by FT-IR and XRD), and accessibility of the synthesized cellulose-rich solid substrate. We also investigated the substrate's enzymatic hydrolysis under different solid loading and enzyme dosage conditions. Subsequently, an industrial-scale syrup production process was simulated using Aspen Plus (V11). Thermal energy analysis (TEA) was then performed to estimate capital expenditure and identify the strengths and limitations of the production pathway. Finally, sensitivity and risk analyses were conducted to assess the influence of variations in pretreatment parameters on overall process costs and to identify key areas for future process optimization. In summary, we identified the optimal reaction conditions for acidic DES pretreatment. Based on the experimental results, we conducted an economic feasibility analysis of the DES

pretreatment process for the simulation of industrial syrup production, providing valuable references for its practical application in industrial-scale production.

2. Materials and Methods

2.1. Materials

Corn stover was purchased from Lianyungang City, Jiangsu Province, China. The corn stover powder was soaked, washed and filtered with the purpose of removing the water-soluble substances in it, and then dried at 60 °C and sieved to 40 mesh size for sealed storage at room temperature. Choline chloride (ChCl), lactic acid (LA), formic acid (FA), acetic acid (AA), and sodium acetate were purchased from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China). Sulfuric acid (95–98 wt%) was purchased from Yantai Sanhe Chemical Reagent Co., Ltd. (Yantai, China). Cellulase was purchased from Novozymes (Tianjin, China) Biotechnology Co., Ltd. at 700 EGU/g.

2.2. Preparation of DESs

The ChCl was used as the HBA, and either LA, FA, or AA was used as the HBD. They were combined at specified molar ratios and stirred at a constant temperature of 80 °C until a homogeneous, colorless, transparent liquid was formed. The prepared DES was cooled to room temperature in a dryer filled with silica gel.

2.3. Pretreatment of Corn Stover

The pretreatment was carried out in a 200 mL polytetrafluoroethylene (PTFE) reactor, which was sealed with a stainless steel tank that could be removed using a wrench. Three grams of dry corn stover was placed in the PTFE reactor and mixed thoroughly with the desired solvent. After sealing, the PTFE reactor and stainless steel tank were placed in a JXF-8-200 homogeneous reactor (Yantai Songling Chemical Equipment Co., Ltd., Yantai, China). The system was heated at an average rate of 5 °C/min until the desired temperature was reached. After 3 h of incubation, the system was rapidly cooled using tap water. The cellulose-rich residues were collected by filtration, first washed with the corresponding DES (200 mL) and then with water until a neutral pH was achieved. The washed samples were then dried in an oven at 105 °C for 6 h to evaluate the yield. The solid yield was calculated using the following equation:

$$\text{Solid yield(\%)} = \frac{\text{Mass of pretreated dry solid(g)}}{\text{Mass of untreated dry solid(g)}} \times 100\% \quad (1)$$

2.4. Composition Analysis

The compositions of the raw material and the pretreated substrate was determined using a two-step acid hydrolysis method, as recognized by the US Department of Energy's National Renewable Energy Laboratory (NREL) [40]. Approximately 0.3 g of the dry sample (m_0) was transferred to a pressure-resistant tube, to which 3 mL of 72% sulfuric acid was added. The mixture was then incubated in a water bath at 30 °C for one hour. After this time, 84 mL of deionized water was added to the mixture. The tube was then autoclaved at 121 °C for 1 h, after which the resulting mixture was filtered through a pre-weighed, glass-fritted crucible (m_1). The retained solids were oven-dried to a constant weight (m_2), then combusted in a muffle furnace at 550 °C for 4 h. After cooling to ambient temperature, the ash residue was weighed (m_3). The absorbance (A) of the filtrate was measured at 320 nm using ultraviolet spectrophotometry. Monosaccharide content was quantified via high-performance liquid chromatography (HPLC; Shimadzu, Kyoto, Japan), using an Aminex HPX-87H analytical column (300 × 7.8 mm²; Bio-Rad Laboratories, Hercules, CA, USA) and a differential refractive index detector. The column temperature was maintained

at 45 °C. Samples were automatically injected (20 µL injection volume) with 5 mmol/L H₂SO₄ serving as the mobile phase at a flow rate of 0.6 mL/min.

The computation formula is as follows [41]:

$$\text{Klason lignin}(\%) = \frac{m_2 - m_3}{m_0} \times 100\% \quad (2)$$

$$\text{Ash}(\%) = \frac{m_3 - m_1}{m_0} \times 100\% \quad (3)$$

$$\text{Acid soluble lignin}(\%) = \frac{A \times V}{\epsilon \times m_0} \times 100\% \quad (4)$$

2.5. Enzymatic Hydrolysis

Enzymatic hydrolysis was performed on both untreated and pretreated corn stover samples under controlled conditions of 50 °C, pH 4.8 and agitation at 150 rpm for 96 h. For each reaction, 2 g of pretreated biomass (dry weight) was combined with 40 mL of sodium acetate buffer solution in a 100 mL Erlenmeyer flask. The hydrolysis experiments evaluated two cellulase loadings (15 and 7.5 filter FPU per gram of cellulose) across three substrate concentrations (2.5%, 5% and 10% *w/v*). Aliquots for sugar analysis were collected at the following intervals: 1, 3, 6, 9, 12, 24, 36, 48, 72, and 96 h. Prior to high-performance liquid chromatography (HPLC) analysis, each sample was centrifuged at 3000 rpm for 5 min and filtered through a 0.22 µm membrane. The glucose yield is the most direct and widely applicable indicator of the overall efficiency of the process. The glucose content of the filtrate was quantified by HPLC and the corresponding yield was calculated using the following equation:

$$\text{Glucose yield}(\%) = \frac{\text{Mass of glucose in hydrolysate(g)}}{\text{Mass of glucan} \times 1.1(\text{g})} \times 100 \quad (5)$$

2.6. Characterization of the Cellulose-Rich Residues

2.6.1. Fourier Transform Infrared (FT-IR)

The mixture of the sample and potassium bromide, with a mass ratio of 100:1, was pressed into a tablet to be tested by Nicolet 510P FT-IR spectrophotometer (Shanghai Simaiou Analytical Instrument Co., Ltd., Shanghai, China). The wavenumber range was 4000 cm^{−1} to 400 cm^{−1} with a resolution of 4 cm^{−1} [42].

2.6.2. X-Ray Diffraction (XRD)

The sample was scanned from 10° to 40° at a rate of 5°/min using a Rigaku Mini-Flex600 (Rigaku Corporation, Kyoto, Japan) with a Cu-Kα source to analyze the crystallinity in the biomass before and after DES pretreatment. The intensity of the spectrum peaks was used to calculate the crystallinity index, as shown in Equation (6) [43].

$$\text{CrI}(\%) = \frac{I_{002} - I_{\text{am}}}{I_{002}} \times 100\% \quad (6)$$

CrI—crystallinity index, *I*₀₀₂—peak intensity of crystalline region (2θ ≈ 22.6°) and *I*_{am}—peak intensity of amorphous region (2θ ≈ 16.2°).

2.6.3. Scanning Electron Microscopy (SEM)

The freeze-dried samples (untreated and pretreated corn stover) were coated with gold-palladium in a sputter coater. The morphological structure was observed by SEM (JSM-6700 F, JEOL Ltd., Kyoto, Japan) at an accelerating voltage of 10 kV.

2.6.4. Cellulose Accessibility Analyzes

Congo red staining was performed to assess the cellulose accessibility under wet condition. The detection was carried out by referring to the description of Wiman [44]. Langmuir-type adsorption was obtained with 1% substrate in 0.1 M sodium acetate buffer solution (pH 4.8) and incubation temperature of 50 °C. A 50 mL centrifuge tube was charged with 30 mL of a 1% (*w/v*) suspension of freeze-dried sample in sodium acetate buffer. Subsequently, Congo red dye was added to achieve a final concentration of 2 g/L. After incubating the mixture in a dye solution at 50 °C with agitation at 180 rpm for 24 h, it was centrifuged at $740\times g$ for 10 min. The absorbance of the resulting supernatant was then recorded at 498 nm. The concentration of Congo red in the solution was determined by referencing a pre-established standard curve. Substrate accessibility was quantified based on the amount of dye adsorbed during the assay.

2.7. Process Simulation

The industrial-scale production of syrup via DES-pretreated biomass was modeled using Aspen Plus simulation software. The representation of biomass constituents, including cellulose, lignin, and other components, along with their physicochemical properties, was adopted from the methodology established by the National Renewable Energy Laboratory [35]. Activity coefficients in the liquid phase were determined using the non-random two-liquid (NRTL) thermodynamic model [39], which is well suited for accurately simulating polar mixtures such as the industrial syrup–water system addressed in this study. For DES properties not found in the Aspen Plus database, user-defined parameters were introduced. These were based on published critical data [45] and thermophysical properties [46], as summarized in Table S1.

2.8. Economic Analysis

The economic feasibility of industrial syrup preparation under different DES pretreatments was compared through economic analysis of operating costs, fixed capital investment, and financial metrics. This included calculating the minimum selling price (MSP) at the break-even scenario (zero net present value, NPV) to evaluate and guide the construction and operation of the industrial syrup plant. Policy factors such as subsidies, authorizations, or carbon credits were not considered [35].

Equipment costs were referenced to the value of 816 in the 2024 Chemical Engineering Plant Cost Index (CEPCI), expressed in U.S. dollars in 2024 [47]. The base year for equipment purchases and associated parameters followed the methodology outlined in the NREL report. $Cost_{2024}$ specifically denotes equipment expenses in 2024. The scale ratio between the designed plant capacity and the size of the reference equipment is represented by S^n_r , where n is a scaling exponent typically ranging from 0.2 to 1, which is determined by the production capacity characteristics of the relevant equipment. Total capital investment (TCI) was computed using Equation (8) as the sum of working capital and other project financing components.

Transportation and installation costs, in addition to equipment procurement expenses, were incorporated into the economic model through Equation (9), with the corresponding scaling and installation factors for standard equipment detailed in Table S2. Inside battery limits (ISBL) equipment costs, including pretreatment, industrial syrup production, and distillation units, constitute a key part of total direct costs (TDC). Ancillary expenses, including warehouse, site development and piping costs, were allocated through the ISBL framework. Indirect costs (IDC), incorporating the project contingency, site costs, engineering contingency, etc., were calculated as a percentage of TDC according to Equation (12). Fixed

capital investment (FCI) is the sum of TDC and IDC. Working capital, which is essential for sustained operational continuity [48], was estimated at 5% of FCI using Equation (14).

A comprehensive operational expenditure analysis was performed using the Aspen Process Economic Analyzer (V11). Total operating cost (TOC) comprises fixed operating costs (FOC) and variable operating costs (VOC). FOC allocation incorporated labor salary costs and labor burden (90% of total salaries), consistent with the technical assessment by NREL [35]. The VOC included energy consumption, raw material inputs, chemical reagents, and water requirements, and the corresponding procurement sources and market prices are documented in Table S3.

$$\text{Cost}_{2024} = \text{Cost}_{\text{base year}} \times (S)_r^n \times \frac{\text{CEPCI}(2024)}{\text{CEPCI}(\text{base year})} \quad (7)$$

$$\text{TCI} = \text{TIC} + 17.5\% \times \text{ISBL} + \text{IDC} + \text{Land} + \text{Working capital} \quad (8)$$

$$\text{TIC} = \sum (\text{Cost}_{2024} \times \text{IF})_i \quad (9)$$

$$\text{ISBL} = \sum (\text{Cost}_{2024} \times \text{IF}) \quad (10)$$

$$\text{TDC} = \text{TIC} \times 17.5\% \times \text{ISBL} \quad (11)$$

$$\text{IDC} = 60\% \times \text{TDC} \quad (12)$$

$$\text{FCI} = \text{TDC} + \text{IDC} \quad (13)$$

$$\text{Working capital} = \text{FCI} \times 5\% \quad (14)$$

$$\text{TOC} = \text{FOC} + \text{VOC} \quad (15)$$

$$\text{FOC} = \left(\sum \text{salaries} \right) \times 190\% + \text{ISBL} \times 3\% + \text{FCI} \times 0.7\% \quad (16)$$

$$\text{NPV} = \text{Ci} + \sum_{n=1}^N \frac{\text{CF}_n}{(1+r)^n} \quad (17)$$

$$\text{NPV} = \text{Ci} + \sum_{n=1}^N \frac{\text{CF}_n}{(1+\text{IRR})^n} = 0 \quad (18)$$

Net present value (NPV) is a key metric for assessing investment profitability, as it quantifies the present value of future net cash flows over the duration of the project. A higher NPV indicates greater investment attractiveness, reflecting the direct relationship between NPV magnitude and economic returns. These financial indicators are mathematically defined in Equations (17) and (18), where NPV represents the discounted sum of cash flows (CF), taking into account the initial investment (Ci), the project's lifespan (N years), and the discount ratio [49].

The minimum selling price (MSP) was derived through discounted cash flow analysis to identify the syrup price threshold that yields a zero NPV. In this analysis, an industrial syrup production facility was modeled with a discount rate of 10% and a 25-year operational lifespan (equivalent to 8410 h of operation per year). The calculation of income tax was performed subsequent to the accounting for depreciation, which was computed on a straight-line basis over the 25-year plant life with a salvage value of 5% of the initial fixed asset cost. This process serves to reduce taxable income and is reflected in the after-tax cash flows utilized for the calculation of NPV and MSP. Construction of the plant was assumed to span three years, with capital expenditure distributed at 8%, 60%, and 32% of total capital investment (TCI) across the respective years. This is consistent with NREL's benchmark assumptions [35]. Key investment parameters are summarized in Table 1.

Table 1. Basic assumptions of economics.

Item	Description
Plant capacity	30 tons per hour of dry wood
Plant life	25 years
CEPCI (2024)	816
Annual operating time	8410 h
Percentage of plant construction spending in years 1, 2, and 3	8% in year 1; 60% in year 2; 32% in year 3
Construction period	3 years
Start-up time	3 months
Revenues during start-up	50%
Variable costs incurred during start-up	50%
Fixed costs incurred during start-up	100%
Salvage value	5%
Equity	100%
Income tax rate	25%
IRR	10%
Working capital	5% of fixed capital investment

Although the economics of a designed system can be determined through economic analysis, its assumed parameters may introduce uncertainties that significantly impact economic viability if altered [32]. To ensure analytical accuracy and evaluate the effect of key parameters on the MSP of industrial molasses biorefineries, this study employed sensitivity analyses. MSP variations were calculated when the prices of raw materials, biomass costs, utility rates, investment parameters, by-product values and reaction conditions fluctuated within $\pm 20\%$, thereby identifying pivotal cost drivers [38,50].

3. Results and Discussion

3.1. Effect of Pretreatment Conditions on the Chemical Composition of Corn Stover

3.1.1. The HBD/HBA Molar Ratio

The effect of the HBD/HBA molar ratio of DES on the pretreatment efficiency was investigated at 120 °C for 3 h, with a solid-to-liquid ratio of 1:10. The composition of the corn stover, both before and after the pretreatment process, is shown in Table 2. The untreated corn stover was found to consist of 37.2% glucan, 23.8% xylan, 26.4% lignin, and 1.9% acid-soluble lignin. When the HBD/HBA ratio was increased from 1:2 to 1:5, the glucan content increased gradually from 57.5% (ChCl/LA), 53.2% (ChCl/FA), and 53.7% (ChCl/AA) to 66.3%, 65.5%, and 64.2%, respectively. This enhancement in glucan content was attributed to the progressive removal of lignin and xylan by the DESs.

Table 2. The composition of corn stover with DES pretreatments at different HBD/HBA molar ratios.

DES Type	HBA/HBD	Glucan (%)	Xylan (%)	Klason Lignin (%)	Acid Soluble Lignin (%)	Ash (%)	Solid Yield (%)
untreated	-	37.2 $\pm$ 0.2	23.8 $\pm$ 0.4	19.3 $\pm$ 0.6	1.2 $\pm$ 0.1	3.2 $\pm$ 0.5	-
ChCl/LA	1:2	49.8 $\pm$ 0.5	10.9 $\pm$ 0.8	20.7 $\pm$ 1.2	0.5 $\pm$ 0.2	6.0 $\pm$ 0.8	64.7
	1:3	55.1 $\pm$ 0.5	7.1 $\pm$ 0.2	19.9 $\pm$ 1.1	0.6 $\pm$ 0.3	5.4 $\pm$ 0.3	58.1
	1:4	55.6 $\pm$ 0.4	7.0 $\pm$ 0.6	19.4 $\pm$ 0.8	0.6 $\pm$ 0.1	6.6 $\pm$ 1.3	53.3
	1:5	57.5 $\pm$ 0.2	6.1 $\pm$ 0.3	18.9 $\pm$ 0.5	0.5 $\pm$ 0.2	6.4 $\pm$ 1.2	48.6
ChCl/FA	1:2	53.2 $\pm$ 0.8	6.5 $\pm$ 0.7	22.6 $\pm$ 1.5	0.7 $\pm$ 0.3	6.3 $\pm$ 0.7	59.3
	1:3	55.9 $\pm$ 1.3	5.6 $\pm$ 0.2	24.5 $\pm$ 1.2	0.6 $\pm$ 0.2	6.9 $\pm$ 0.5	54.7
	1:4	56.6 $\pm$ 0.5	3.8 $\pm$ 0.7	23.8 $\pm$ 1.3	0.8 $\pm$ 0.3	6.9 $\pm$ 1.5	51.2
	1:5	58.7 $\pm$ 0.2	2.8 $\pm$ 0.1	23.3 $\pm$ 0.9	0.5 $\pm$ 0.1	5.8 $\pm$ 0.5	45.6
ChCl/AA	1:2	46.5 $\pm$ 0.1	12.5 $\pm$ 0.9	19.2 $\pm$ 0.4	0.8 $\pm$ 0.4	4.7 $\pm$ 0.6	70.4
	1:3	48.8 $\pm$ 1.4	10.8 $\pm$ 0.2	20.1 $\pm$ 1.6	0.7 $\pm$ 0.3	5.7 $\pm$ 1.1	66.8
	1:4	51.2 $\pm$ 0.9	9.9 $\pm$ 0.6	19.2 $\pm$ 0.8	0.6 $\pm$ 0.2	5.8 $\pm$ 1.0	61.1
	1:5	53.7 $\pm$ 0.5	9.7 $\pm$ 0.2	20.2 $\pm$ 1.2	0.6 $\pm$ 0.1	5.5 $\pm$ 0.6	56.6

The pretreatments were carried out at 120 °C for 3 h with a solid-to-liquid ratio of 1:10.

As shown in Figure 1a,b, reducing the HBA/HBD molar ratio (i.e., increasing the HBD content) increased the acidity of the solvent, enhancing the removal of lignin and xylan. The optimal removal efficiencies for both components were achieved at an HBA/HBD ratio of 1:5. Specifically, ChCl/LA (1:5) pretreatment yielded xylan and lignin removal rates of 87.5% (Figure 1a) and 54.1% (Figure 1b), respectively. Similarly, ChCl/FA (1:5) pretreatment resulted in 94.6% xylan removal (Figure 1a) and 42.1% lignin removal (Figure 1b), and ChCl/AA (1:5) pretreatment achieved maximum removal rates of 76.6% (Figure 1a) and 42.2% (Figure 1b) for xylan and lignin, respectively. Concurrently, the pretreated substrates retained high cellulose contents of 75.5% (ChCl/LA (1:5)), 71.9% (ChCl/FA (1:5)), and 82.2% (ChCl/AA (1:5)), as shown in Figure 1c.

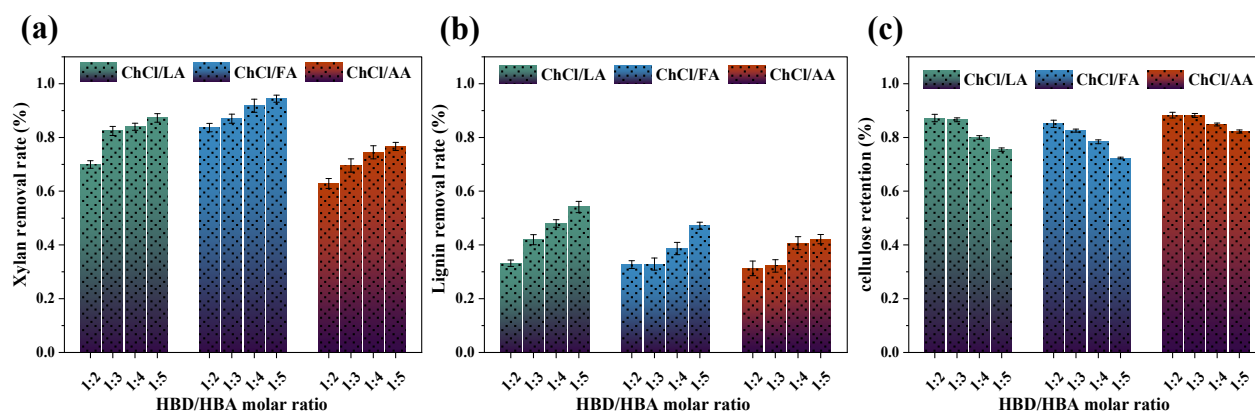


Figure 1. The xylan removal (a), lignin removal (b), and cellulose retention (c) of corn stover after DES pretreatments at 120 °C for 3 h with a solid-to-liquid ratio of 1:10 and different HBD/HBA molar ratios.

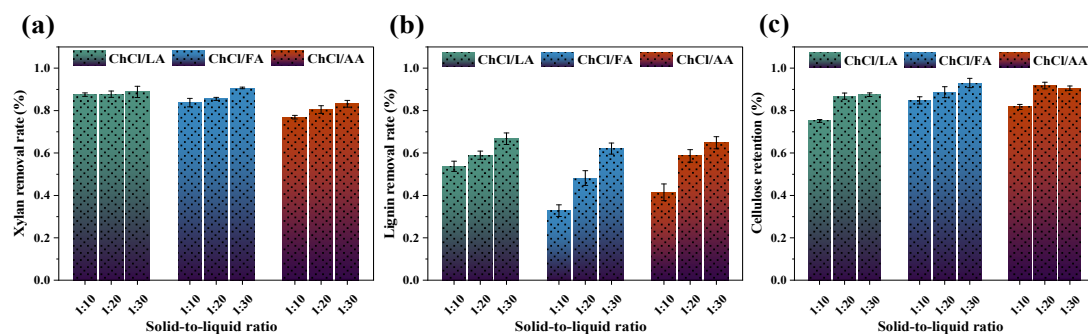
3.1.2. Solid-to-Liquid Ratio

The effect of the solid-to-liquid ratio on the efficiency of DES pretreatment was investigated at 120 °C for 3 h. As shown in Table 3, reducing the ratio from 1:10 to 1:30 significantly increased the glucan content of the solid residue. Specifically, pretreatment with ChCl/LA (1:5) increased the glucan content from 57.5% to 66.3%. Meanwhile, pretreatments with ChCl/FA (1:5) and ChCl/AA (1:5) showed increases from 53.2% to 65.5% and 53.7% to 64.2%, respectively. This enhancement is primarily due to the lower solid-to-liquid ratio promoting biomass swelling and facilitating more effective lignin and hemicellulose degradation and dissolution into the liquid phase. A significant enhancement in lignin and xylan removal efficiency was observed at a solid-to-liquid ratio of 1:30. Pretreatment with ChCl/LA (1:5) increased lignin removal from 54.1% to 66.7% (Figure 2a) and improved xylan removal slightly from 87.5% to 88.8% (Figure 2b). Similarly, pretreatment with ChCl/FA (1:5) significantly increased lignin removal from 32.9% to 62.5% (Figure 2a) and xylan removal from 83.9% to 90.7% (Figure 2b). Meanwhile, pretreatment with ChCl/AA (1:5) increased the lignin removal rate from 42.7% to 65.4% (Figure 2a) and the xylan removal rate from 76.9% to 83.2% (Figure 2b). Notably, cellulose retention was significantly higher at lower solid-to-liquid ratios than at higher ones (Figure 2c). At a solid-to-liquid ratio of 1:30, cellulose retention reached nearly 90% for all three DES pretreatments. This can be attributed to the lower solid-to-liquid ratio facilitating more thorough biomass swelling and enhancing pretreatment uniformity, thereby minimizing cellulose degradation.

Table 3. The composition of corn stover with DES pretreatments at different solid–liquid ratios.

DES Type	Solid-to-Liquid Ratio	Glucan (%)	Xylan (%)	Klason Lignin (%)	Acid Soluble Lignin (%)	Ash (%)	Solid Yield (%)
untreated	-	37.2 ± 0.2	23.8 ± 0.4	19.3 ± 0.6	1.2 ± 0.1	3.2 ± 0.5	-
ChCl/LA	1:10	57.5 ± 0.2	6.1 ± 0.3	18.9 ± 0.5	0.5 ± 0.2	6.4 ± 1.2	48.6
	1:20	62.1 ± 0.7	5.6 ± 0.6	15.5 ± 1.2	0.8 ± 0.4	6.7 ± 0.9	52.0
	1:30	66.3 ± 0.3	5.4 ± 1.2	13.2 ± 0.7	0.7 ± 0.6	5.2 ± 0.6	49.1
ChCl/FA	1:10	53.2 ± 0.8	6.5 ± 0.7	22.6 ± 1.5	0.7 ± 0.3	6.3 ± 0.7	59.3
	1:20	58.5 ± 1.4	6.1 ± 0.2	17.8 ± 0.3	1.2 ± 0.9	6.6 ± 1.4	56.4
	1:30	65.5 ± 1.2	4.2 ± 0.1	13.9 ± 0.8	0.6 ± 0.2	5.2 ± 0.3	52.8
ChCl/AA	1:10	53.7 ± 0.5	9.7 ± 0.2	20.2 ± 1.2	0.6 ± 0.1	5.5 ± 0.6	56.6
	1:20	59.7 ± 0.7	8.1 ± 0.6	14.1 ± 0.7	0.8 ± 0.4	6.8 ± 0.5	57.2
	1:30	64.2 ± 0.4	7.6 ± 0.6	12.8 ± 0.5	0.8 ± 0.3	2.7 ± 0.2	52.5

The pretreatments were carried out at 120 °C for 3 h with an HBD/HBA ratio of 1:5.

**Figure 2.** The xylan removal (a), lignin removal (b), and cellulose retention (c) of corn stover after DES pretreatment at 120 °C for 3 h with at HBD/HBA ratio of 1:5 and different solid-to-liquid ratios.

3.1.3. Incubation Temperature

Higher temperatures could increase the disruption of the hydrogen-bonding network between lignin and carbohydrates, improving the interaction between biomass and DES [51]. As shown in Table 4, the efficiency of pretreatment is significantly dependent on the incubation temperature. Following pretreatment with ChCl/LA (1:5), ChCl/FA (1:5), and ChCl/AA (1:5), the yield of the solid residue progressively decreased with increasing temperature. Concurrently, the glucan content in the solid residues increased, indicating that elevated temperatures facilitate DES-mediated cleavage of biomass chemical bonds, thereby promoting the removal of lignin and hemicellulose. Figure 3a,b show that the removal of lignin and hemicellulose exceeded 78% and 90%, respectively, at an incubation temperature of 180 °C. However, the glucan losses of over 30% occurred due to highly acidic conditions at such high temperature. Therefore, 140 °C was identified as the optimal incubation temperature for DES pretreatment of corn stover.

Table 4. The composition of corn stover with DES pretreatments at different incubation temperatures.

DES Type	Temperature (°C)	Glucan (%)	Xylan (%)	Klason Lignin (%)	Acid Soluble Lignin (%)	Ash (%)	Solid Yield (%)
untreated	-	37.2 ± 0.2	23.8 ± 0.4	19.3 ± 0.6	1.2 ± 0.1	3.2 ± 0.5	-
ChCl/LA	120	66.3 ± 0.3	5.4 ± 1.2	13.2 ± 0.7	0.7 ± 0.6	5.2 ± 0.6	49.1
	140	70.2 ± 1.1	5.4 ± 0.4	10.2 ± 0.5	0.5 ± 0.2	8.3 ± 1.2	43.1
	180	67.6 ± 0.7	2.2 ± 0.7	11.1 ± 1.8	0.3 ± 0.1	7.1 ± 1.1	39.2
ChCl/FA	120	65.5 ± 1.2	4.2 ± 0.1	13.9 ± 0.8	0.6 ± 0.2	5.2 ± 0.3	52.8
	140	68.3 ± 1.1	3.7 ± 0.4	12.9 ± 0.4	0.5 ± 0.3	8.9 ± 0.7	41.5
	180	69.1 ± 1.4	6.8 ± 2.5	12.3 ± 0.7	0.4 ± 0.2	3.1 ± 0.4	34.9
ChCl/AA	120	64.2 ± 0.4	7.6 ± 0.6	12.8 ± 0.5	0.8 ± 0.3	2.7 ± 0.2	52.5
	140	69.2 ± 1.2	5.1 ± 1.2	11.9 ± 1.4	0.5 ± 0.2	9.1 ± 2.1	44.1
	180	72.6 ± 1.6	1.5 ± 0.7	11.3 ± 1.7	0.4 ± 0.1	6.0 ± 0.5	38.5

The pretreatments were carried out with a solid-to-liquid ratio of 1:30 and a HBD/HBA ratio of 1:5 for 3 h.

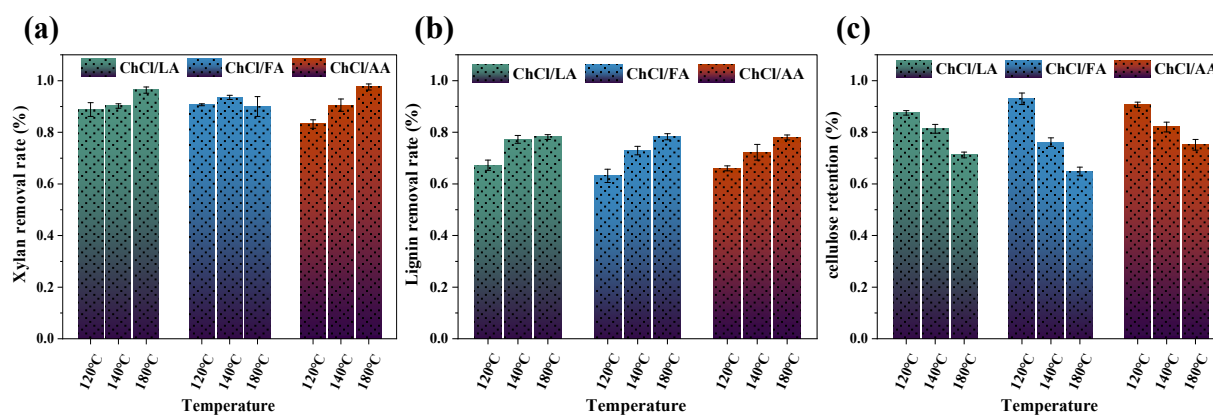


Figure 3. Xylan removal (a), lignin removal (b), and cellulose retention (c) of corn stover after DES pretreatment at different incubation temperatures for 3 h with a solid-to-liquid ratio of 1:30 and an HBD/HBA molar ratio of 1:5.

Overall, the optimum pretreatment conditions were obtained with an HBD/HBA molar ratio of 1:5, a solid-to-liquid ratio of 1:30, and an incubation temperature of 140 °C. Under these conditions, ChCl/LA (1:5) pretreatment achieved 77.3% lignin removal and 90.2% xylan removal while retaining 81.3% of the glucan. ChCl/FA (1:5) pretreatment showed 72.9% lignin removal and 93.5% xylan removal, retaining 76.2% of the glucan. ChCl/AA (1:5) pretreatment showed 72.3% lignin removal and 90.5% xylan removal while retaining 82% of the glucan. The enhanced performance of ChCl/LA, particularly in terms of lignin removal, can be ascribed to the bifunctional molecular structure of lactic acid. The hypothesis is that the combination of a carboxylic acid group and a hydroxyl group is more effective in disrupting lignin–carbohydrate complexes and hydrogen-bonding networks within the biomass matrix. This, in turn, leads to enhanced solvent penetration and component separation.

3.2. Enzymatic Hydrolysis

The enzymatic hydrolysis is a crucial step in producing fermentable sugars from cellulose [52]. Glucose yield is a key criterion for evaluating the efficiency of DES pretreatment. The efficiency of enzymatic hydrolysis is closely related to the chemical composition of the samples following DES pretreatment. An increased cellulose content provides a greater adsorption surface area for cellulase, thereby enhancing its hydrolysis efficiency [53]. Conversely, a lower hemicellulose content minimizes cellulose encapsulation and reduces the physical barrier to enzymatic hydrolysis [54]. Meanwhile, a reduced lignin content significantly decreases non-productive adsorption of cellulase [55].

The enzymatic hydrolysis of both pretreated and untreated samples was conducted for 96 h at a substrate concentration of 2.5% (*w/v*) under high (15 FPU/g-cellulose) and low (7.5 FPU/g-cellulose) cellulase loadings. As demonstrated in Figure 4a,b, the conversion of cellulose to glucose occurred rapidly in the initial stage, but then plateaued after 24 h, due to kinetic limitations arising from decreased substrate accessibility, enzyme deactivation, and product inhibition. With the lower cellulase loading of 7.5 FPU/g cellulose, the glucose yield from the untreated corn stover was very low at only 17.4% (Figure 4a). Even with the higher cellulase loading, the glucose yield remained relatively low at 26.6% (Figure 4b), indicating that the highly recalcitrant structure of the raw corn stover significantly inhibited enzymatic hydrolysis.

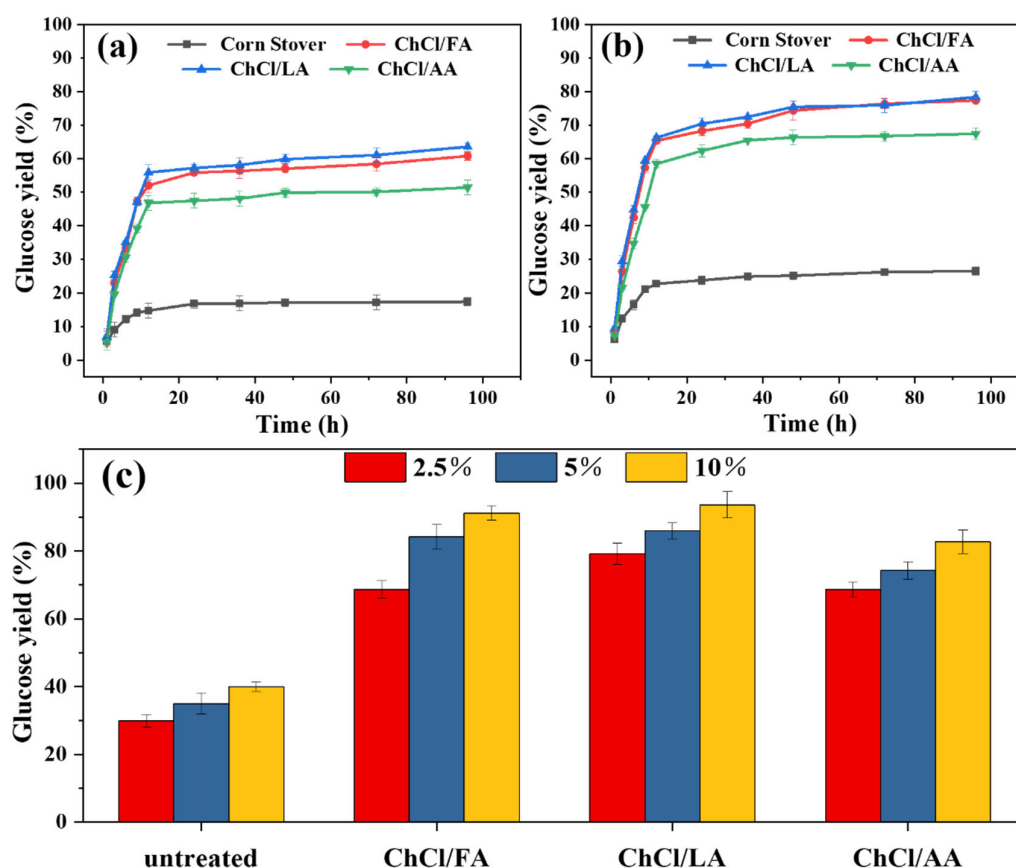


Figure 4. The glucose yields of pretreated substrates after enzymatic hydrolysis: (a) at a substrate concentration of 2.5% with a cellulase loading of 7.5 FPU/g-cellulose; (b) at a substrate concentration of 2.5% with a cellulase loading of 15 FPU/g-cellulose; (c) the effect of substrate concentration on the glucose yield with a cellulase dosage of 15 FPU/g-cellulose.

After DES pretreatments, the glucose yields of all samples significantly increased due to the removal of lignin and hemicellulose, and more cellulose being exposed. With a lower cellulase loading of 7.5 FPU/g-cellulose (Figure 4a), the glucose yields after 96 h of enzymatic hydrolysis increased to 63.6%, 60.43%, and 51.46% for corn stover pretreated with ChCl/LA (1:5), ChCl/FA (1:5), and ChCl/AA (1:5), respectively. Further increasing the cellulase loading to 15 FPU/g cellulose (Figure 4b) improved the glucose yields even more, reaching 78.4%, 77.4%, and 67.5% for corn stover pretreated with ChCl/LA (1:5), ChCl/FA (1:5), and ChCl/AA (1:5), respectively.

The enzymatic hydrolysis was also significantly influenced by substrate concentration. The effect of substrate concentration on hydrolysis performance was investigated. As shown in Figure 4c, raising the substrate concentration to 10% notably enhanced the efficiency of enzymatic hydrolysis across all DES-pretreated samples. Of these, ChCl/LA (1:5) pretreated corn stover exhibited the highest glucose yield, reaching 93.7% after 96 h of hydrolysis. By comparison, the glucose yield was slightly lower for ChCl/FA (1:5) pretreated corn stover (91.2%), while the lowest efficiency was demonstrated by ChCl/AA (1:5) pretreated samples (82.7%). When the substrate concentration is low, the enzymes become excessively dispersed in the solution. This reduces adsorption of the enzyme by the substrate, resulting in lower hydrolysis efficiency. Increasing the substrate concentration appropriately enhances the effective enzyme concentration and facilitates enzyme–substrate interaction, thereby significantly improving cellulolytic hydrolysis efficiency.

3.3. Characterization of Cellulose-Rich Substrate

Figure 5a indicates the FT-IR of solid substrate. The absorption band at 3420 cm^{-1} is attributed to the stretching vibration of the hydroxy groups. The band at 2918 cm^{-1} corresponds to the asymmetric C-H stretching vibration. Other characteristic bands of cellulose are observed at 1200 cm^{-1} (O-H in-plane deformation), 1111 cm^{-1} (C-O-C stretching vibration within the glucoside ring), 1057 cm^{-1} (C-O stretching vibration), and 1034 cm^{-1} (C-H in-plane deformation). Compared to the untreated raw material, the intensities of these bands increased after pretreatment. This increase is attributed to the enrichment of cellulose components in the pretreated solid residue. Such cellulose enrichment enhances the efficiency of subsequent enzymatic hydrolysis.

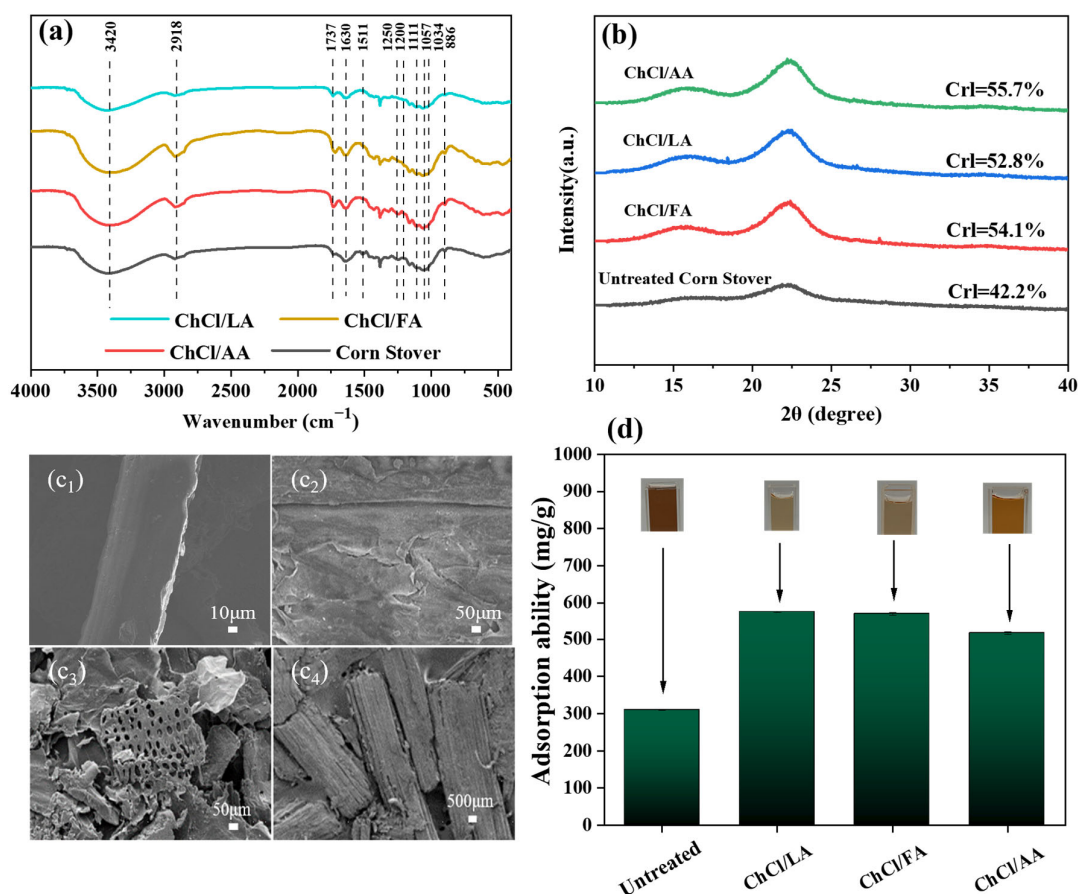


Figure 5. The FT-IR spectra (a), XRD spectra (b), SEM images ((c₁) untreated corn stover; (c₂) corn stover pretreated with ChCl/FA (1:5); (c₃) corn stover pretreated with ChCl/LA (1:5); (c₄) corn stover pretreated with ChCl/AA (1:5)), and Congo red adsorption abilities (d) of untreated and pretreated corn stover.

The absorption band at 1737 cm^{-1} , which is characteristic of ether linkages between lignin and hemicellulose acetyl groups, was completely eliminated following DES pretreatments. The disappearance is attributed to the DES hydrolyzing the hemicellulose acetyl groups. The characteristic absorption bands of lignin were observed at 1630, 1511, 1250, and 886 cm^{-1} , corresponding to aromatic ring skeletal stretching, C-O stretching, and the planar vibration of syringyl lignin, respectively. After DES pretreatments, the intensity of these bands decreased, indicating partial lignin removal. These results demonstrate that DES effectively removes significant amounts of lignin and hemicellulose, thereby enhancing the efficiency of subsequent enzymatic hydrolysis.

The XRD patterns of the untreated raw material and the DES-pretreated cellulose-rich solid substrate were recorded over a 2θ range of $10\text{--}40^\circ$, as shown in Figure 5b. All samples exhibited the typical cellulose I β (cellulose type 1) structure due to the characteristic peaks of 2θ angles at around 16.2° and 22.6° corresponding to the (110) and (200) crystallographic planes [56]. The crystallinity index (CrI) was calculated, revealing values of 42.2% for untreated corn stover. Following DES pretreatment, the CrI of samples increased, attributed to the removal of hemicellulose and amorphous cellulose. Although the CrI increased after pretreatment, the enzymatic hydrolysis efficiency of the DES-pretreated cellulose was further enhanced due to greater cellulose exposure resulting from the removal of hemicellulose and lignin [40].

The accessibility of cellulose refers to the number of binding sites in lignocellulosic biomass that are available for interaction with enzymes [57]. The accessible surface area and porosity of biomass materials are critical factors that influence the efficiency of enzymatic saccharification [24]. As shown in Figure 5(c₁–c₄), the surface morphology of corn stover before and after DES pretreatment was examined. The untreated feedstock had a smooth, intact surface, whereas the DES-pretreated samples had a rough texture with distinct cracks and pores. This morphological transformation clearly shows that DES pretreatments effectively removed the lignin and hemicellulose components that encapsulate the cellulose microfibrils. This creates groove-like features and porous structures on the fiber surfaces, significantly enhancing the accessibility to enzymatic attack.

To characterize these modifications quantitatively, the Congo red staining method was used to measure the dye adsorption capacity of substrates in a wet environment. This method more accurately reflects changes in the accessibility of pretreated substrates because it simulates the hydrated environment of enzymatic hydrolysis systems. As shown in Figure 5d, the untreated corn stover exhibited adsorption capacities of 309 mg/g. After pretreatment with ChCl/LA (1:5), ChCl/FA (1:5), and ChCl/AA (1:5), corn stover showed significantly enhanced adsorption capacities of 573 mg/g, 568 mg/g, and 516 mg/g, respectively. These results confirm that DES pretreatments increase the surface area accessible to enzymes, enabling enhanced penetration and adsorption, thereby increasing the saccharification efficiency.

3.4. Process Modeling

The simulation process for industrial syrup production was established (Figure 6), consisting of four core process units: (1) the feedstock pretreatment unit, responsible for initial material processing; (2) the DES pretreatment unit, utilizing DES for efficient biomass deconstruction; (3) the enzymatic hydrolysis unit, employing biocatalytic methods for targeted saccharification; (4) the DES recycling unit, enabling solvent recovery and reuse. The main mass flow of components of DES pretreatment process were shown in Table S4.

The feedstock pretreatment section employs conventional mechanical processing methods. First, the raw corn stover material is reduced to particles smaller than 0.4 mm using a blade mill and hammer crusher. It is then screened through a vibrating sieve. This increases the accessible surface area for subsequent pretreatment, thereby improving mass and heat transfer efficiency, which makes this step indispensable [58]. Meanwhile, the DES solution is prepared and mixed with the crushed biomass feedstock.

The crushed corn stover is fed into the pre-treatment reactor at a rate of 30 tons per hour. Three acidic DESs with an optimal incubation temperature of 140°C were selected for simulation analysis at solid-to-liquid ratios of 1:10, 1:20, and 1:30. The synthesized DES is pumped into the pre-treatment reactor. After the reaction, waste heat is recovered via a double-stream heat exchanger (Heater 1) to pre-heat the feedstock (Stream 5). The pretreated slurry then enters Splitter-1, a filtration unit that separates solids from liquids

(Stream 6). The solid residue separated during this process (Stream 7) then proceeds to the enzymatic hydrolysis section for saccharification, while the filtrate (Stream 13) enters the recovery section for lignin extraction and DES/water recycling.

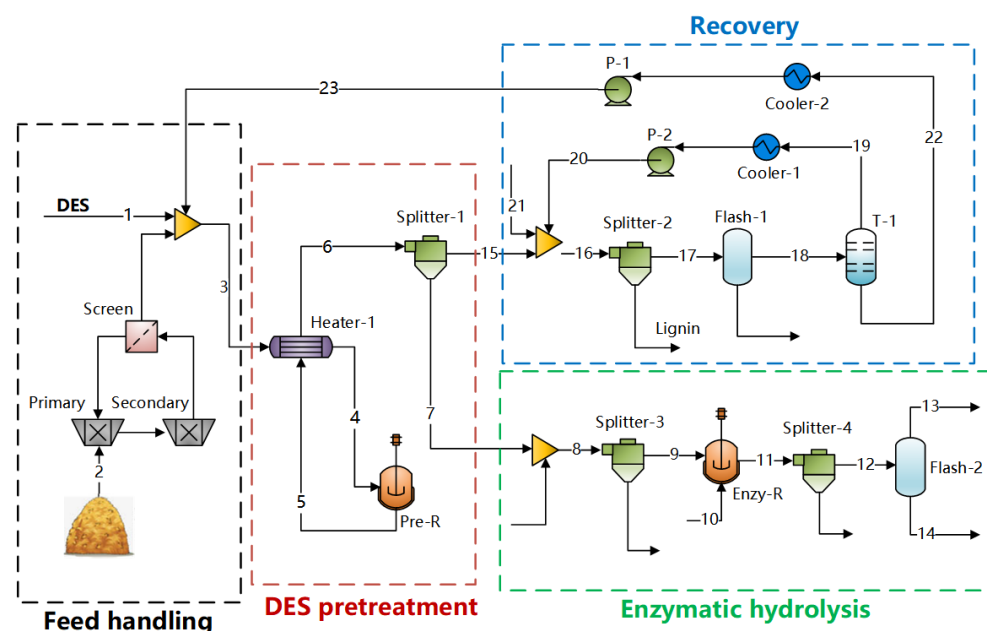


Figure 6. The simulation of the production workflow of industrial syrup from the enzymatic hydrolysis of DES-pretreated corn stover using Aspen Plus.

The enzymatic hydrolysis process involves washing, enzymatic saccharification and evaporation/concentration. The pretreated lignocellulosic material is first washed with water, then conveyed via a belt feeder into the saccharification reactor (Stream 9). The cellulase is added at a loading of 15 FPU/g-cellulose, with a substrate concentration of 10% (*w/v*). Continuous enzymatic hydrolysis is then carried out for 96 h under controlled conditions. After hydrolysis, the unreacted residues are removed by filtration. The resulting liquid is then fed into a rotary evaporator to concentrate it, yielding an industrial-grade sugar syrup with a concentration of around 50% (*w/v*) [26,59].

The pretreated filtrate enters the recovery section, where the lignin is obtained by precipitation after a large amount of water is added. The remaining liquid contains DES, water and sugars (Stream 15). As DES has a higher boiling point than the other components in the system, a multi-stage flash distillation process is used to separate 95% of the DES. After the lignin is filtered out, the liquid is sent to the first evaporator to vaporize the DES and water. The resulting mixed vapor is then introduced into a distillation column for fractionation, separating and recovering the water and DES.

3.4.1. Cost Estimation

Figure 7a shows the breakdown of the total capital investment (TCI) for DES pretreatment in the production of industrial syrup under different solid-to-liquid ratios. The DES pretreatment unit and the recovery unit account for the largest proportion of the total investment cost. Specifically, at a solid-to-liquid ratio of 1:30, these two units contribute 21.5% and 20.4% to the TCI, respectively. This is primarily due to the substantial increase in the usage of DES solvent at the lower solid-to-liquid ratio. This necessitates the use of larger processing equipment, which consequently leads to a significant rise in capital costs. Interestingly, when the solid-to-liquid ratio is increased to 1:10, the total investment cost decreases by USD 120.24 million compared to the 1:30 ratio, representing a substantial reduction of 41.6%. These results clearly demonstrate the significant impact of solid loading

on total investment costs, indicating that increasing solid loading can effectively reduce the capital expenditure required for industrial-scale production.

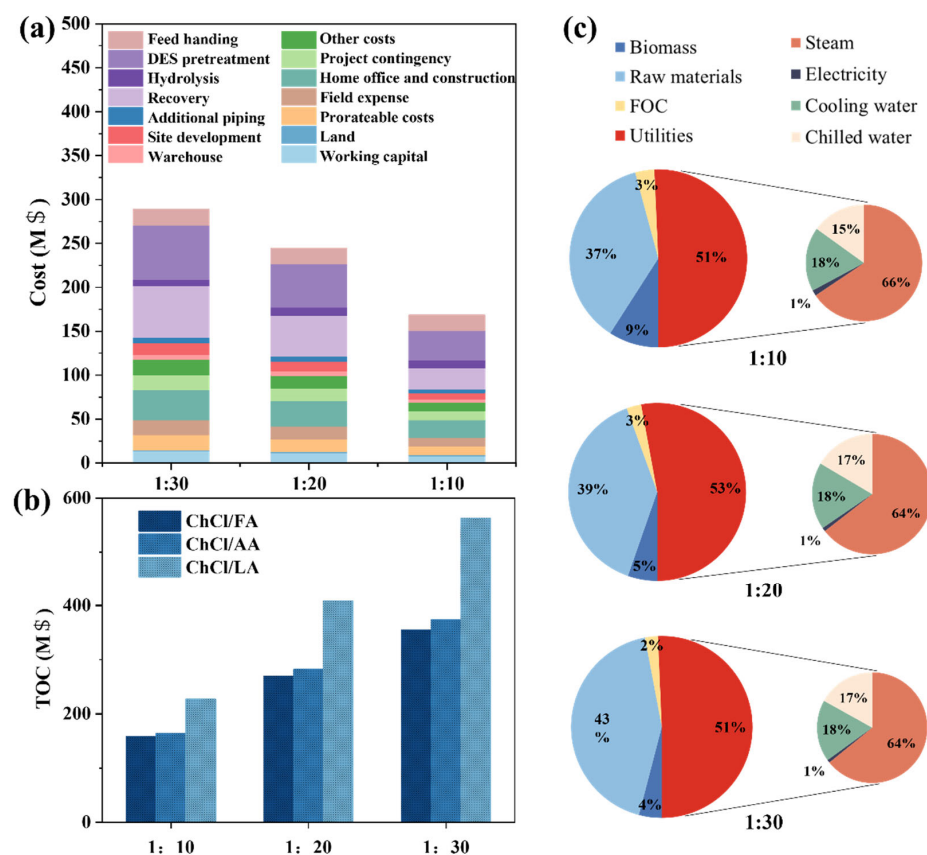


Figure 7. The total capital investment (a) and the total operating cost (b) at different solid–liquid ratios. The total operating cost breakdown of ChCl/FA (1:5) pretreatment (c).

Figure 7b shows the annual TOC of the three DES pretreatments at different solid-to-liquid ratios. It is clear that as the solid-to-liquid ratio decreases (i.e., more DES is used), the raw material procurement costs increase substantially, leading to significantly higher TOC values. Specifically, the TOC increases by more than 50% at a 1:30 ratio compared to a 1:10 ratio. Of the three DES pretreatments, the ChCl/LA (1:5) pretreatment has the highest TOC, primarily due to the substantially higher market price of LA compared to FA and AA. This elevated raw material cost directly contributes to the sharp rise in operating expenses. In contrast, ChCl/FA demonstrates the lowest TOC, making it the most economically favorable option under the tested conditions.

Taking the cost-optimal ChCl/FA (1:5) pretreatment as an example, Figure 7c shows an analysis of its annual TOC cost distribution, with the detailed FOC parameters listed in Table S5. The utilities and raw material costs are the main contributors to the TOC. Specifically, raw material expenses (corn stover, DES, water, and enzyme) consistently account for over 37% of TOC across all solid-to-liquid ratios. DES is the dominant factor in raw material costs, accounting for 81.2%, 89.6%, and 92.7% of total material expenses at solid-to-liquid ratios of 1:10, 1:20, and 1:30, respectively. This demonstrates that selecting lower-cost DES systems could substantially enhance the economic viability of industrial-scale operations.

Notably, utility costs make a more significant contribution to the TOC in all DES pretreatment processes, accounting for over 51% in each case. As shown in Figure 7c, the largest proportion of utility costs is accounted for by steam consumption, followed by cooling water and chilled water. This primarily stems from two factors: first, the DES recovery process requires distillation to remove large quantities of solvents and impurities,

and second, using pure DES for biomass pretreatment necessitates the complete removal of moisture from the system, which leads to a significant increase in steam usage. Therefore, developing efficient DES recovery processes and achieving solvent recycling would markedly enhance the economic viability of the production process. A comprehensive comparison of TOC cost analyses for the three DESs at different solid-to-liquid ratios revealed that increasing the solid loading offers dual economic benefits. On the one hand, it significantly reduces DES consumption, directly lowering raw material costs. On the other hand, it substantially decreases steam consumption during DES recovery. This synergistic effect optimizes TOC costs in high-solid-loading processes.

3.4.2. Economic Evaluation

Figure 8(a₁,b₁,c₁) show the cumulative cash flow trends for the three DES pretreatment methods with different solid-to-liquid ratios. The discount rate is 10%, and the selling price of industrial syrup is 700 USD/ton [60]. The revenue includes income from selling lignin by-products for use in power generation, and its specific pricing and sources are detailed in Table S3. With the same selling price for the product, the net present value (NPV) is significantly higher under high solid-to-liquid ratios than under low ones, indicating that the latter offer better investment returns and market competitiveness. However, the cumulative NPV results over the 25-year project lifecycle show that none of the three DES pretreatment methods are economically viable, as they all have negative NPV values at the end of the cycle. This is primarily due to the excessively high annual operating costs, which lead to sustained losses throughout the production cycle and continuous negative growth in NPV. Of the three DESs, the ChCl/FA (1:5) pretreatment at a solid-to-liquid ratio of 1:10 performs best. It has the smallest negative NPV and is closest to the break-even point, thus demonstrating relatively better economic potential.

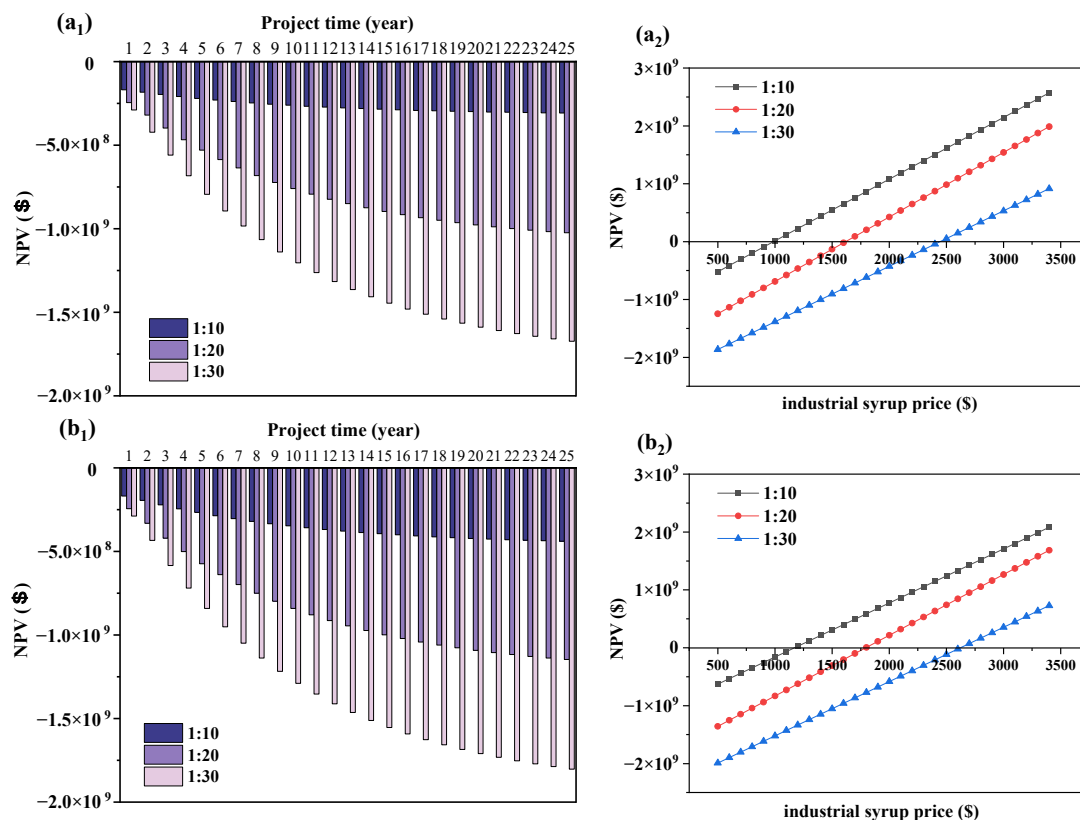


Figure 8. Cont.

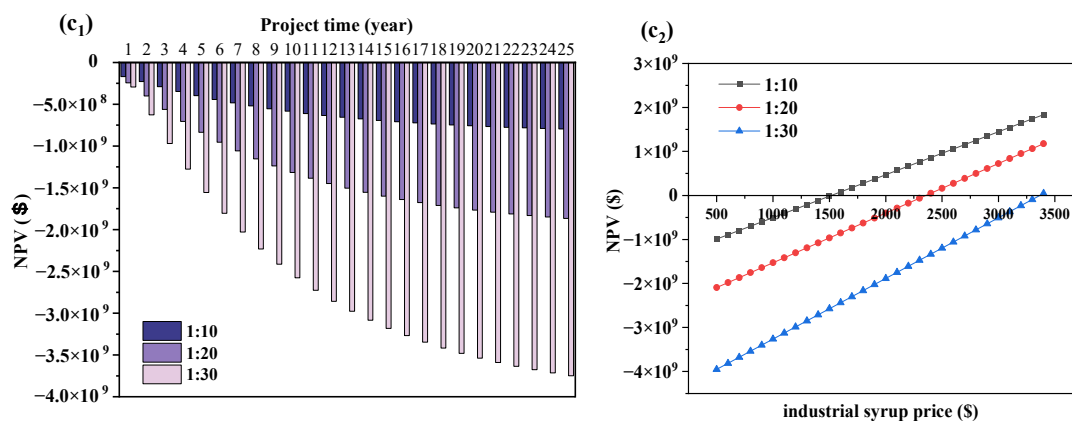


Figure 8. The cumulative cash flow diagram for a 25-year project using pretreatments of (a₁) ChCl/FA (1:5), (b₁) ChCl/AA (1:5), and (c₁) ChCl/LA (1:5). The effects of the selling price of industrial syrup on the net present value using pretreatments of (a₂) ChCl/FA (1:5), (b₂) ChCl/AA (1:5), and (c₂) ChCl/LA (1:5).

Figure 8(a₂,b₂,c₂) show how industrial syrup selling prices affect the NPV of three DES pretreatment methods, as well as the minimum selling price (MSP) needed to achieve an NPV of 0. The results show that raising the selling price changes the NPV from negative to positive. Among the three DES pretreatments, a solid-to-liquid ratio of 1:10 yielded the lowest MSP consistently, indicating optimal economic performance under these conditions. Specifically, at a ratio of 1:10, the MSPs were 988.2 USD/ton for ChCl/FA (1:5), 1169.9 USD/ton for ChCl/AA (1:5), and 1516.7 USD/ton for ChCl/LA (1:5). Notably, ChCl/FA (1:5) exhibited the most competitive MSP, coming closest to current market prices and suggesting superior economic feasibility. Although ChCl/LA (1:5) pretreatment produced a higher enzymatic glucose yield, the significantly higher cost of the raw materials meant that the MSP was substantially higher, which reduced its economic viability and limited its potential for industrial-scale implementation.

3.4.3. Sensitivity Analysis

A sensitivity analysis was conducted to evaluate the impact of cost fluctuations on the economic viability of ChCl/FA (1:5) pretreatment processes, involving examining the effects of variations in key parameters on the MSP. The sensitivity analysis model was constructed by adjusting each parameter by $\pm 20\%$ from its baseline value while keeping other variables constant. The tornado diagram analysis in Figure 9 shows that the efficiency of enzymatic hydrolysis has the greatest impact on MSP sensitivity, followed by the frequency of DES recycling. The prices of DES and steam occupy the third and fourth positions, respectively. Investment parameters (working capital percentage, tax rate, and project lifespan) and the prices of auxiliary chemical have a negligible impact on sensitivity.

The most critical factors affecting MSP is the glucose yield. When using the most cost-effective ChCl/FA (1:5) pretreatment, a 20% decrease in glucose yield leads to a 25% increase in MSP. Furthermore, DES recycling cycles also have a significant influence on the MSP. At solid-to-liquid ratios of 1:10, 1:20, and 1:30, variations in the number of recycling cycles of $\pm 20\%$ resulted in changes to the MSP of $\pm 6.8\%$, $\pm 8.0\%$, and $\pm 9.2\%$, respectively. This shows that improving the efficiency of enzymatic hydrolysis and the recyclability of DES are key ways to reducing production costs.

The MSP also demonstrates a high degree of sensitivity to variations in utility costs, particularly influenced by the price of steam. A $\pm 20\%$ change in steam cost led to MSP fluctuations exceeding $\pm 6\%$ across all solid-to-liquid ratios. Consequently, the development

of novel processes aimed at improving steam utilization efficiency and DES recovery constitutes a promising strategy for enhancing the overall economic viability of the process.

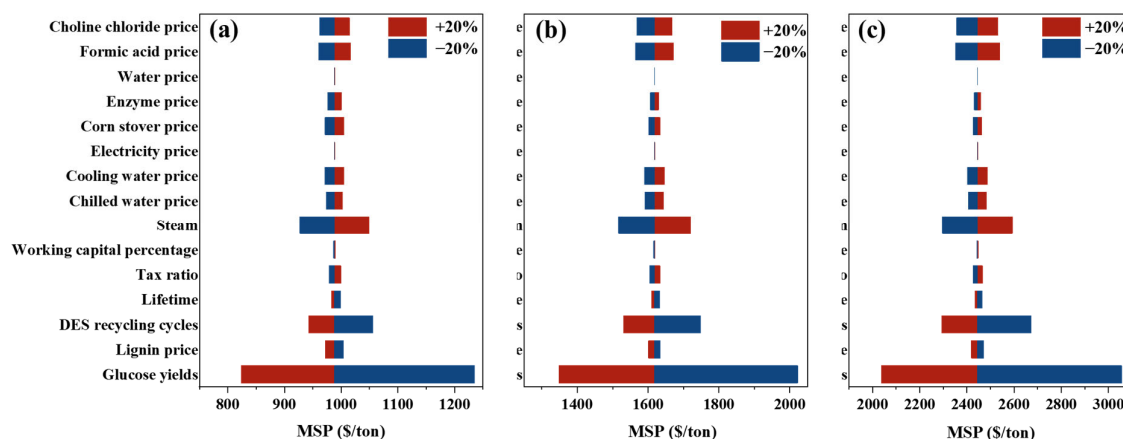


Figure 9. The MSP sensitivity analysis after ChCl/FA (1:5) pretreatment at solid-liquid ratios of 1:10 (a), 1:20 (b), and 1:30 (c).

Notably, although raw material costs for DES account for a significant proportion of annual operating expenses, fluctuations in their prices have a relatively limited impact on the MSP. For instance, a 20% increase in the price of ChCl resulted in MSP increases of just 2.4%, 3.1%, and 3.8% for solid-to-liquid ratios of 1:10, 1:20, and 1:30, respectively. Similarly, a 20% rise in the price of FA led to corresponding MSP increases of 2.5%, 3.3%, and 3.8% across the same ratios. This phenomenon is primarily due to the DES recycling mechanism, which substantially reduces the consumption of fresh raw materials and thus mitigates the impact of price fluctuations for individual components on the MSP.

In summary, multifaceted improvements, including process optimization, high-value utilization of by-products, and policy support, can effectively reduce costs and increase revenue. This can help to overcome the current economic bottlenecks in DES-pretreatment-based biorefining. Specific strategies for optimizing economic performance include: (1) Reducing DES costs and recycling energy consumption. Pure binary DES is a primary cost driver. Adopting water-containing ternary DES systems can significantly reduce the energy consumption and costs associated with DES separation and recycling. Furthermore, water partially displaces DES usage, leading to additional savings on raw material expenses. (2) High-value utilization of by-products. In this study, the lignin by-product was only sold as low-value fuel, yielding a minimal economic return. Developing pathways to convert it into high-value products could substantially increase overall revenue. (3) Optimizing processes and enhancing recycling. Effective approaches to boost economic efficiency include optimizing enzymatic hydrolysis processes to improve product yields, and enhancing the stability of DES recycling to increase the number of reuse cycles and reduce DES consumption. Furthermore, national policy support and government subsidies are crucial external catalysts that could facilitate an industrial breakthrough in DES pretreatment biorefining.

To date, research into the techno-economic analysis of deep eutectic solvents (DESs) remains limited. A recent review by Azzouz and Hayyan identified only 28 studies in this area, accounting for less than 0.3% of all DES-related publications [61]. This scarcity highlights a significant gap in our ability to assess the industrial scalability of DES-based processes. Our study focuses on industrial syrup production from DES-pretreated corn stover and contributes a detailed TEA to this emerging field. Specifically, the sugar production cost in the most economical scenario of this study (ChCl/FA (1:5) pretreatment) is notably lower than the monomeric sugar cost of USD 2.7–3.2/kg reported by Baral

and Shah for a process involving the use of an ionic liquid (1-ethyl-3-methylimidazolium acetate) [36]. This confirms the superior economic competitiveness of the acidic DES investigated in this study over ionic liquids. However, our production cost is still higher than the USD 0.59/kg achieved for mixed feedstock processing via hydrothermal pretreatment, as reported by Ashraf and Schmidt [58]. A key limitation of the model is its assumption of near-complete solvent recovery and treatment of lignin as a low-value fuel rather than exploring its high-value utilization, which has been identified as indispensable for the profitability of biorefineries. This research demonstrates that process optimization, specifically increasing solid loading and enhancing solvent recycling, can substantially reduce capital and operational expenditure, thereby improving the economic feasibility of DES-based biorefining. To achieve industrial scalability, future efforts must integrate innovations such as low-cost ternary DES systems, enhanced energy-efficient recovery, and supportive policy frameworks, bridging the gap between promising laboratory results and commercial feasibility.

4. Conclusions

The acidic ChCl-based DES pretreatments effectively fractionated the corn stover, selectively removing the lignin and hemicellulose while retaining more of the cellulose. Optimizing the process parameters (HBD/HBA molar ratio of 1:5, solid-to-liquid ratio of 1:30, and incubation temperature of 140 °C) resulted in over 70% lignin removal, over 90% xylan removal, and over 80% cellulose retention. Substrate characterization confirmed that DES-mediated structural deconstruction disrupted the biomass matrix. This significantly enhanced cellulose accessibility and enabled glucose yields of over 90% upon enzymatic hydrolysis. A techno-economic analysis demonstrated the superior economic viability of a ChCl/FA (1:5) pretreatment at a solid-to-liquid ratio of 1:10, achieving a minimum selling price of USD 988/ton, which is 30% lower than that of a ChCl/LA (1:5) pretreatment, due to reduced solvent costs. Process economics were most sensitive to enzymatic hydrolysis efficiency and DES recycling rates, with steam consumption and solvent prices being secondary cost drivers. Future efforts should prioritize the development of low-cost ternary DES systems, the valorization of lignin by-products, and the optimization of solvent recovery.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18052490/s1>, Table S1. The thermophysical parameters of ChCl; Table S2. The equipment size factor and installation factor; Table S3. The unit price of process material and utilities; Table S4. The mass flow of main components of ChCl/FA at 1:10 solid-liquid ratio (ton/h); Table S5. The total fixed operating cost evaluation results.

Author Contributions: Conceptualization, S.H. and H.Y.; Methodology, S.H. and H.Y.; Software, F.X.; Validation, F.X. and S.H.; Formal analysis, F.X.; Investigation, F.X. and S.H.; Resources, H.Y. and S.L.; Data curation, F.X.; Writing—original draft, F.X.; Writing—review & editing, F.X. and H.Y.; Visualization, F.X.; Supervision, H.Y. and S.L.; Project administration, H.Y. and S.L.; Funding acquisition, H.Y. and S.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the National Natural Science Foundation of China (32471818 and 32171735).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Materials. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lan, T.Q.; Wang, S.R.; Li, H.; Qin, Y.Y.; Yue, G.J. Effect of Lignin Isolated from P-Toluenesulfonic Acid Pretreatment Liquid of Sugarcane Bagasse on Enzymatic Hydrolysis of Cellulose and Cellulase Adsorption. *Ind. Crops Prod.* **2020**, *155*, 112768. [\[CrossRef\]](#)
2. Lou, R.; Zhang, X. Evaluation of Pretreatment Effect on Lignin Extraction from Wheat Straw by Deep Eutectic Solvent. *Bioresour. Technol.* **2022**, *344*, 126174. [\[CrossRef\]](#)
3. Sánchez-Badillo, J.A.; Gallo, M.; Rutiaga-Quñones, J.G.; Garza, J.; López-Albarrán, P. Insights on the Cellulose Pretreatment at Room Temperature by Choline-Chloride-Based Deep Eutectic Solvents: An Atomistic Study. *Cellulose* **2022**, *29*, 6517–6548. [\[CrossRef\]](#)
4. Liang, X.; Zhu, Y.; Qi, B.; Li, S.; Luo, J.; Wan, Y. Structure-Property-Performance Relationships of Lactic Acid-Based Deep Eutectic Solvents with Different Hydrogen Bond Acceptors for Corn Stover Pretreatment. *Bioresour. Technol.* **2021**, *336*, 125312. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Moncada, J.; Cardona, C.A.; Higuaita, J.C.; Vélez, J.J.; López-Suarez, F.E. Wood Residue (*Pinus patula* Bark) as an Alternative Feedstock for Producing Ethanol and Furfural in Colombia: Experimental, Techno-Economic and Environmental Assessments. *Chem. Eng. Sci.* **2016**, *140*, 309–318. [\[CrossRef\]](#)
6. Yu, H.; Xu, Y.; Hou, J.; Ni, Y.; Liu, S.; Liu, Y.; Yu, S.; Nie, S.; Wu, Q.; Wu, C. Efficient Fractionation of Corn Stover for Biorefinery Using a Sustainable Pathway. *ACS Sustain. Chem. Eng.* **2020**, *8*, 3454–3464. [\[CrossRef\]](#)
7. Himmel, M.E.; Ding, S.-Y.; Johnson, D.K.; Adney, W.S.; Nimlos, M.R.; Brady, J.W.; Foust, T.D. Biomass Recalcitrance: Engineering Plants and Enzymes for Biofuels Production. *Science* **2007**, *315*, 804–807. [\[CrossRef\]](#)
8. Wang, N.; Liu, K.; Hou, Z.; Zhao, Z.; Li, H.; Gao, X. Microwave-Assisted Deep Eutectic Solvents Pretreatment for Lignocellulose: Kinetics, Intensified Mechanism and Process Optimization. *Chem. Eng. Sci.* **2025**, *302*, 120881. [\[CrossRef\]](#)
9. Cisternino, G.; Baldassarre, F.; Ciccarella, G.; Mastroiilli, P.; Dell'Anna, M.M. Microwave Assisted Treatment of Carpentry Waste Wood Flour with Natural Deep Eutectic Solvents for Nanocellulose Production and Removal of Organic Pollutants. *Carbohydr. Polym. Technol. Appl.* **2024**, *8*, 100572. [\[CrossRef\]](#)
10. Kumar, A.; Rapoport, A.; Kunze, G.; Kumar, S.; Singh, D.; Singh, B. Multifarious Pretreatment Strategies for the Lignocellulosic Substrates for the Generation of Renewable and Sustainable Biofuels: A Review. *Renew. Energy* **2020**, *160*, 1228–1252. [\[CrossRef\]](#)
11. Fan, Y.; Ji, H.; Ji, X.; Tian, Z.; Chen, J. A Deep Eutectic Solvent with a Lignin Stabilization and Functionalization for Lignocellulosic Biomass Pretreatment. *Chem. Eng. J.* **2024**, *499*, 156482. [\[CrossRef\]](#)
12. Zhang, L.; Zhao, X.; Chen, L.; Zhang, X. Pretreatment with Fermentable and Recyclable Deep Eutectic Solvent (DES) for Improving Resource Utilization of Biomass. *Ind. Crops Prod.* **2022**, *190*, 115868. [\[CrossRef\]](#)
13. Guo, Y.; Zhang, J.; Wang, C.; Liu, M.; You, J.; Yin, L.; Shi, M. Green Pretreatment of Lignocellulosic Biomasses via Deep Eutectic Solvents. *Sustain. Chem. Pharm.* **2024**, *39*, 101569. [\[CrossRef\]](#)
14. Wafae, B.; Abdelmounaim, Y.; Ahmad, M.; Li, T. High-Yield Extraction of Nanocellulose Using Hydrated Formic Acid/Choline Chloride Deep Eutectic Solvent and High-Shear Homogenization (HDES/HSF). *J. Nanoparticle Res.* **2025**, *27*, 241. [\[CrossRef\]](#)
15. Zhang, R.; Chen, H.; Yu, Q.; Zhang, Y.; Liu, F.; Wang, F.; Chen, X.; Liu, Y. Extraction of Bioactive Compounds from Cinnamon Residues with Deep Eutectic Solvents and Its Molecular Mechanism. *Chem. Eng. Sci.* **2023**, *273*, 118630. [\[CrossRef\]](#)
16. Cheng, J.; Huang, C.; Liu, X.; Zhou, X.; Zhan, Y.; Chen, T.; Huang, C.; Meng, X.; Fang, G.; Ragauskas, A.J. Direct Extraction of Uniform Lignin Microspheres from Bamboo Using a Polyol-Based Deep Eutectic Solvent. *ACS Sustain. Chem. Eng.* **2023**, *11*, 10158–10163. [\[CrossRef\]](#)
17. Li, P.; Yang, C.; Jiang, Z.; Jin, Y.; Wu, W. Lignocellulose Pretreatment by Deep Eutectic Solvents and Related Technologies: A Review. *J. Bioresour. Bioprod.* **2023**, *8*, 33–44. [\[CrossRef\]](#)
18. Ee, L.Y.; Tan, Y.K.; Miao, J.; Chu, H.T.; Li, S.F.Y. High-Purity Lignin from Selective Biomass Fractionation with Ternary Deep Eutectic Solvents. *Green Chem.* **2023**, *25*, 3137–3151. [\[CrossRef\]](#)
19. Jiang, J.; Fu, J.; An, N.; Zhang, Y.; Chen, X.; Wang, L. Rapid and Effective Molten Oxalic Acid Dihydrate Pretreatment to Enhance Enzymatic Saccharification for Biohydrogen Production by Efficient Coextraction of Lignin and Hemicellulose in Wheat Straw. *Chem. Eng. J.* **2023**, *475*, 146422. [\[CrossRef\]](#)
20. Cheng, J.; Gao, Y.; Liu, J.; Zhang, Y.; Tian, M.; Zhang, M.; Zhang, Y.; Zhao, C.; Li, C. Facilitating Lignocellulose Fractionation of *Moringa Oleifera* Lam. Husk by Pretreatment with a Novel 1-Tetradecyl-3-Carboxymethylimidazolium Bromide-Based Deep Eutectic Solvent. *J. Clean. Prod.* **2024**, *483*, 144249. [\[CrossRef\]](#)
21. Xu, H.; Kong, Y.; Peng, J.; Song, X.; Liu, Y.; Su, Z.; Li, B.; Gao, C.; Tian, W. Comprehensive Analysis of Important Parameters of Choline Chloride-Based Deep Eutectic Solvent Pretreatment of Lignocellulosic Biomass. *Bioresour. Technol.* **2021**, *319*, 124209. [\[CrossRef\]](#)
22. Feng, Y.; Eberhardt, T.L.; Meng, F.; Xu, C.; Pan, H. Efficient Extraction of Lignin from Moso Bamboo by Microwave-Assisted Ternary Deep Eutectic Solvent Pretreatment for Enhanced Enzymatic Hydrolysis. *Bioresour. Technol.* **2024**, *400*, 130666. [\[CrossRef\]](#) [\[PubMed\]](#)

23. Huo, D.; Sun, Y.; Yang, Q.; Zhang, F.; Fang, G.; Zhu, H.; Liu, Y. Selective Degradation of Hemicellulose and Lignin for Improving Enzymolysis Efficiency via Pretreatment Using Deep Eutectic Solvents. *Bioresour. Technol.* **2023**, *376*, 128937. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Yu, H.; Xu, Y.; Hou, J.; Nie, S.; Liu, S.; Wu, Q.; Liu, Y.; Yu, S. Fractionation of Corn Stover for Efficient Enzymatic Hydrolysis and Producing Platform Chemical Using P-Toluenesulfonic Acid/Water Pretreatment. *Ind. Crops Prod.* **2020**, *145*, 111961. [\[CrossRef\]](#)
25. Jaffur, B.N.; Kumar, G.; Khadoo-Jeetah, P. Enhancing Deep Eutectic Solvent Systems for Efficient Fermentable Sugar Recovery from Lignocellulosic Fiber. *Int. J. Biol. Macromol.* **2024**, *269*, 131888. [\[CrossRef\]](#)
26. Kuo, P.-C.; Yu, J. Process Simulation and Techno-Economic Analysis for Production of Industrial Sugars from Lignocellulosic Biomass. *Ind. Crops Prod.* **2020**, *155*, 112783. [\[CrossRef\]](#)
27. Chen, J.; Zhang, B.; Luo, L.; Zhang, F.; Yi, Y.; Shan, Y.; Liu, B.; Zhou, Y.; Wang, X.; Lü, X. A Review on Recycling Techniques for Bioethanol Production from Lignocellulosic Biomass. *Renew. Sustain. Energy Rev.* **2021**, *149*, 111370. [\[CrossRef\]](#)
28. Gouws, M.R.; Bosman, C.E.; Dogbe, E.S.; Görgens, J.F. Comparative Techno-Economics of 2,3-Butanediol, Polyhydroxybutyrate and Citric Acid Production in a Biorefinery Using 1G and 1G2G Sugarcane-Based Feedstocks. *Chem. Eng. Sci.* **2024**, *286*, 119649. [\[CrossRef\]](#)
29. Parveen, F.; Saxena, A.; Hussain, A.; Giri, B.S.; Ashfaq, M. Facile Fractionation of Lignocellulosic Biomass: A Review on Promising Green Technology of Deep Eutectic Solvent for Bioethanol Production. *Biomass Convers. Biorefinery* **2025**, *15*, 13303–13322. [\[CrossRef\]](#)
30. Gezae Daful, A.; Görgens, J.F. Techno-Economic Analysis and Environmental Impact Assessment of Lignocellulosic Lactic Acid Production. *Chem. Eng. Sci.* **2017**, *162*, 53–65. [\[CrossRef\]](#)
31. Pei, X.; Fan, M.; Zhang, H.; Xie, J. Assessment for Industrial Production of Poplar Ethanol after Analysis of Influencing Factors and Predicted Yield. *Cellulose* **2024**, *31*, 10801–10829. [\[CrossRef\]](#)
32. Aui, A.; Wang, Y.; Mba-Wright, M. Evaluating the Economic Feasibility of Cellulosic Ethanol: A Meta-Analysis of Techno-Economic Analysis Studies. *Renew. Sustain. Energy Rev.* **2021**, *145*, 111098. [\[CrossRef\]](#)
33. Qian, Q.; Luo, Z.; Sun, H.; Wei, Q.; Shi, J.; Li, L. Life Cycle Assessment and Techno-Economic Analysis of Wood-Based Biorefineries for Cellulosic Ethanol Production. *Bioresour. Technol.* **2024**, *399*, 130595. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Van Heerden, C.; Bosman, C.E.; Farzad, S.; Görgens, J.F. Techno-Economics and Environmental Assessment of Sorbitol and Itaconic Acid Production from Sugarcane-Based Feedstock. *Chem. Eng. Sci.* **2024**, *299*, 120431. [\[CrossRef\]](#)
35. Humbird, D.; Davis, R.; Tao, L.; Kinchin, C.; Hsu, D.; Aden, A.; Schoen, P.; Lukas, J.; Olthof, B.; Worley, M.; et al. *Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover*; Technical Report NREL/TP-5100-47764; National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2011.
36. Baral, N.R.; Shah, A. Comparative Techno-Economic Analysis of Steam Explosion, Dilute Sulfuric Acid, Ammonia Fiber Explosion and Biological Pretreatments of Corn Stover. *Bioresour. Technol.* **2017**, *232*, 331–343. [\[CrossRef\]](#)
37. Baral, P.; Munagala, M.; Shastri, Y.; Kumar, V.; Agrawal, D. Cost Reduction Approaches for Fermentable Sugar Production from Sugarcane Bagasse and Its Impact on Techno-Economics and the Environment. *Cellulose* **2021**, *28*, 6305–6322. [\[CrossRef\]](#)
38. Kumar, A.K.; Sharma, S.; Dixit, G.; Shah, E.; Patel, A.; Boczkaj, G. Techno-economic Evaluation of a Natural Deep Eutectic Solvent-based Biorefinery: Exploring Different Design Scenarios. *Biofuels Bioprod. Biorefining* **2020**, *14*, 746–763. [\[CrossRef\]](#)
39. Peng, J.; Xu, H.; Wang, W.; Kong, Y.; Su, Z.; Li, B. Techno-Economic Analysis of Bioethanol Preparation Process via Deep Eutectic Solvent Pretreatment. *Ind. Crops Prod.* **2021**, *172*, 114036. [\[CrossRef\]](#)
40. Sluiter, A.; Hames, B.; Ruiz, R.; Scarlata, C.; Sluiter, J.; Templeton, D. *Determination of Sugars, Byproducts, and Degradation Products in Liquid Fraction Process Samples*; National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2006.
41. Xia, Q.; Zhang, L.; Zhan, P.; Tong, Z.; Qing, Y.; He, J.; Wu, Z.; Wang, H.; Shao, L.; Liu, N. Combination of Microwave with Acid Deep Eutectic Solvent Pretreatment for Reed (*Phragmites australis*) Fractionation. *Renew. Energy* **2024**, *225*, 120286. [\[CrossRef\]](#)
42. Mamilla, J.L.K.; Novak, U.; Grilc, M.; Likoza, B. Natural Deep Eutectic Solvents (DES) for Fractionation of Waste Lignocellulosic Biomass and Its Cascade Conversion to Value-Added Bio-Based Chemicals. *Biomass Bioenergy* **2019**, *120*, 417–425. [\[CrossRef\]](#)
43. Segal, L.; Creely, J.J.; Martin, A.E.; Conrad, C.M. An empirical method for estimating the degree of crystallinity of native cellulose using the X-ray diffractometer. *Text. Res. J.* **1959**, *29*, 786–794. [\[CrossRef\]](#)
44. Wiman, M.; Dienes, D.; Hansen, M.A.T.; Van Der Meulen, T.; Zacchi, G.; Lidén, G. Cellulose Accessibility Determines the Rate of Enzymatic Hydrolysis of Steam-Pretreated Spruce. *Bioresour. Technol.* **2012**, *126*, 208–215. [\[CrossRef\]](#) [\[PubMed\]](#)
45. Cui, P.; Liu, X.; Zhao, F.; Zhu, Z.; Wang, L.; Wang, Y. Molecular Mechanism, Thermo-economic, and Environmental Impact for Separation of Isopropanol and Water Using the Choline-Based DESs as Extractants. *Ind. Eng. Chem. Res.* **2020**, *59*, 16077–16087. [\[CrossRef\]](#)
46. Xu, H.; Kong, Y.; Peng, J.; Song, X.; Che, X.; Liu, S.; Tian, W. Multivariate Analysis of the Process of Deep Eutectic Solvent Pretreatment of Lignocellulosic Biomass. *Ind. Crops Prod.* **2020**, *150*, 112363. [\[CrossRef\]](#)
47. Xiao, Y.; Li, A.-R.; Li, B.; Li, M.; Yao, H.; Wang, Z. Energy Consumption and Economic Analysis of CO₂ Capture from Flue Gas by Membrane Separation Coupled with Hydrate Method. *Energy* **2024**, *312*, 133471. [\[CrossRef\]](#)
48. Li, R.; Zheng, Y.; Huang, C.; Lan, K. Economic Feasibility of the Biorefinery Processing Bamboo Residues with Biphasic Phenoxxyethanol-Acid Pretreatment Technology: Techno-Economic Analysis. *Chem. Eng. Sci.* **2025**, *302*, 120804. [\[CrossRef\]](#)

49. Gutiérrez Ortiz, F.J. Techno-Economic Assessment of Supercritical Processes for Biofuel Production. *J. Supercrit. Fluids* **2020**, *160*, 104788. [\[CrossRef\]](#)
50. Li, W.; Ghosh, A.; Bbosa, D.; Brown, R.; Wright, M.M. Comparative Techno-Economic, Uncertainty and Life Cycle Analysis of Lignocellulosic Biomass Solvent Liquefaction and Sugar Fermentation to Ethanol. *ACS Sustain. Chem. Eng.* **2018**, *6*, 16515–16524. [\[CrossRef\]](#)
51. Haldar, D.; Purkait, M.K. Lignocellulosic Conversion into Value-Added Products: A Review. *Process Biochem.* **2020**, *89*, 110–133. [\[CrossRef\]](#)
52. Pinto, A.S.S.; Elias, A.M.; Furlan, F.F.; Ribeiro, M.P.A.; Giordano, R.C.; Farinas, C.S. Strategies to Reduce the Negative Impact of Inhibitors in Biorefineries: A Combined Techno-Economic and Life Cycle Assessment. *J. Clean. Prod.* **2022**, *345*, 131020. [\[CrossRef\]](#)
53. Zhu, Q.; Dong, H.; Yan, D.; Gao, D.; Xu, K.; Cheng, X.; Xin, J.; Lu, X. High Concentration Bioethanol Production from Corn Stalk via Enhanced Pretreatment with Ionic Liquids. *Chem. Eng. Sci.* **2024**, *283*, 119375. [\[CrossRef\]](#)
54. Zhou, M.; Feng, Y.; Li, H.; Tian, X. Sustainable Structural Polysaccharides Conversion: How Does DES Pretreatment Affect Cellulase Adsorption, Thereby Improving Enzymatic Digestion of Lignocellulose? *Carbohydr. Polym.* **2024**, *326*, 121593. [\[CrossRef\]](#)
55. Yu, H.; Hou, J.; Yu, S.; Liu, S.; Li, L.; Wu, Q.; Liu, Y.; Jiang, J.; Nie, S. Comprehensive Understanding of the Non-Productive Adsorption of Cellulolytic Enzymes onto Lignins Isolated from Furfural Residues. *Cellulose* **2019**, *26*, 3111–3125. [\[CrossRef\]](#)
56. Yuan, T.; Zeng, J.; Wang, B.; Cheng, Z.; Chen, K. Lignin Containing Cellulose Nanofibers (LCNFs): Lignin Content-Morphology-Rheology Relationships. *Carbohydr. Polym.* **2021**, *254*, 117441. [\[CrossRef\]](#)
57. Yu, H.; Xu, Y.; Ni, Y.; Wu, Q.; Liu, S.; Li, L.; Yu, S.; Ji, Z. Enhanced Enzymatic Hydrolysis of Cellulose from Waste Paper Fibers by Cationic Polymers Addition. *Carbohydr. Polym.* **2018**, *200*, 248–254. [\[CrossRef\]](#) [\[PubMed\]](#)
58. Ashraf, M.T.; Schmidt, J.E. Process Simulation and Economic Assessment of Hydrothermal Pretreatment and Enzymatic Hydrolysis of Multi-Feedstock Lignocellulose—Separate vs Combined Processing. *Bioresour. Technol.* **2018**, *249*, 835–843. [\[CrossRef\]](#) [\[PubMed\]](#)
59. Zheng, J.-L.; Zhu, Y.-H.; Zhang, W.; Sun, G.-T.; Zhu, M.-Q. Life Cycle Assessment and Techno-Economic Analysis of Joint Extraction of *Eucommia* Powder, Gum, Water-Soluble Polysaccharide and Alkali-Extractable Polysaccharide from *Eucommia* Leaves. *Process Biochem.* **2023**, *124*, 235–244. [\[CrossRef\]](#)
60. Alibaba. Price for Choline Chloride. Available online: <https://chinese.alibaba.com/product-detail/Industrial-RICE-Liquid-Glucose-Syrup-Ingredient-2007683040.html> (accessed on 2 March 2025).
61. Azzouz, A.; Hayyan, M. Techno-Economic Feasibility Analysis: The Missing Piece in the Puzzle of Deep Eutectic Solvents. *Sustain. Mater. Technol.* **2024**, *39*, e00795. [\[CrossRef\]](#)

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