

COMPARATIVE EVALUATION OF CHEMICAL PRETREATMENTS FOR SIMULTANEOUS REMOVAL OF SILICA AND LIGNIN FROM RICE STRAW

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This study investigates the efficacy of various chemical pretreatments for the concurrent removal of silica and lignin from rice straw. The impact of different alkali (NaOH, Ca(OH)₂, and lime) and acid (H₂SO₄), at varied concentrations, on rice straw composition was assessed. Fourier transform infrared (FTIR) spectroscopy and field emission scanning electron microscopy (FE-SEM) were employed to analyze the morphological and chemical changes in treated and untreated rice straw. The results showed that H₂SO₄ pretreatment exhibited the most pronounced effect on rice straw morphology, with significant removal of lignin and silica. Chemical proximate analysis and characterization of lignin, hemicelluloses, cellulose, hollocellulose, ash and silica content of the dry matter of both untreated and treated rice straw were performed using the standard TAPPI Methods T257cm/85 (Technical Association of the Pulp and Paper Industry). Proximate analysis revealed that H₂SO₄ treatment achieved the highest reduction in silica and ash content. The findings of this study highlight the potential of chemical pretreatment for enhancing the suitability of rice straw as a feedstock for various applications.

Keywords: silica, lignin, cellulose, chemical treatment, rice straw

INTRODUCTION

Rice (*Oryza sativa*) is a staple crop cultivated extensively worldwide, particularly in Asia and Africa, serving as a primary food source for a significant portion of the global population. Large-scale rice production generates vast quantities of non-food biomass, mainly in the form of straw and husks. Approximately 8×10^{11} kg of rice straw and 1.5×10^{11} kg of husks are produced annually,^{1,2} yet only about 20% of this biomass is utilized for applications such as biofuel production, biorefineries, biopolymers, paper, fertilizers, organic acids, and animal feed. The majority is burned in the field or left to decompose, practices that not only waste valuable resources, but also contribute to greenhouse gas emissions, pollution, and soil nutrient imbalance.^{3,4} These issues highlight the urgent need for sustainable utilization strategies for rice straw and husks.

Rice straw is a lignocellulosic material composed of cellulose, hemicelluloses, lignin, and

a high proportion of silica, along with trace micronutrients. While cellulose and hemicelluloses represent potential sources of fermentable sugars, the significant silica content makes rice straw more challenging to process than other agricultural residues. Silica accumulates in rice plants as monosilicic acid and is deposited in the cell wall, where it interacts with hemicelluloses and lignin through Si–O–C linkages.⁵ This intimate integration of silica within the lignocellulosic network imparts mechanical strength to the biomass, but creates considerable obstacles for enzymatic hydrolysis and chemical pretreatment. Moreover, silica deposition reduces digestibility in livestock feed and causes corrosion and operational inefficiencies in industrial bioreactors. Consequently, farmers often resort to open-field burning due to its convenience and low cost, despite its adverse environmental effects.

The recalcitrance of rice straw arises not only from its silica content, but also from the complex architecture of its lignocellulosic matrix. Cellulose microfibrils are tightly embedded in a network of hemicelluloses and lignin, with silica further reinforcing this structure. This configuration hampers access to individual polymers, limiting their efficient recovery. Pretreatment, therefore, plays a critical role in disrupting this matrix, enabling silica removal, delignification, and enhanced enzymatic digestibility. Recent studies have specifically targeted desilication and selective component recovery from rice straw. For instance, Do *et al.* developed a two-step pH-controlled precipitation process that achieved up to 94% silica removal, while simultaneously recovering high-purity lignin.⁶ Similarly, innovative pretreatment methods have been reported to improve silica separation, while maintaining cellulose integrity and boosting sugar yields.^{7,8} These approaches emphasize the importance of tailoring pretreatment strategies to address the unique challenges posed by rice straw, particularly its high silica content.

Despite significant advances, most previous research has emphasized delignification, with relatively limited attention to silica removal. This gap underscores the necessity of developing integrated chemical pretreatment strategies capable of simultaneously removing lignin and silica, without compromising carbohydrate recovery. The present study aims to address this research gap by systematically evaluating the effects of different alkali- and acid-based pretreatments on rice straw. Particular emphasis is placed on assessing component removal efficiencies, structural alterations, and preservation of cellulose and hemicelluloses. Advanced analytical techniques, including field emission scanning electron microscopy (FE-SEM) and Fourier transform infrared (FTIR) spectroscopy, are employed to characterize morphological and chemical changes in treated and untreated rice straw.

EXPERIMENTAL

Collection of raw materials and chemicals

Locally sourced rice straw from Hisar, Haryana, India, served as the raw material for this study. To investigate the pretreatment of rice straw, a range of chemicals, *viz.* D-xylose, cellulose, sodium hydroxide (NaOH), calcium carbonate (CaCO₃), anthrone, sodium chlorite, acetone, 5-parabromoaniline,

hydrochloric acid, acetic acid, sulfuric acid (98% w/v), nitric acid, and hydrofluoric acid (48%), were used. All chemicals and reagents purchased from Hi-Media and Rankem were of high purity and of analytical reagent (AR) grade.

Sample preparation

The procured rice straw was initially processed using a mechanical chopper to obtain uniform pieces of approximately 5–7 cm in length. The chopped straw was then transported to the laboratory in sterile plastic bags. To remove impurities, such as dirt and sand, the rice straw was washed with tap water. Subsequently, the straw was air-dried at ambient temperature for 5–6 days to achieve a consistent weight and moisture content below 15%. Once dried, the rice straw was pulverized into fine particles, passing through a 40-mesh screen, to facilitate chemical analysis. The processed straw sample was stored in a plastic ‘Ziploc’ bag at room temperature until further use.

Extraction of acetone extractives

The acetone extractive content of rice straw was determined according to TAPPI standard procedures (TAPPI T204 cm-97). Approximately 2.0 g of oven-dried, ground sample (40–60 mesh) was weighed into G1 glass crucibles and subjected to Soxhlet extraction with acetone for 6 h at a reflux rate of 10–12 cycles per hour. After extraction, the solvent was evaporated, and the residue was dried in an oven at 105 ± 2 °C until constant weight was obtained. The percentage of acetone extractives was calculated on a dry weight basis.

Optimization of chemical pretreatment for rice straw

Considering the recalcitrant nature of lignocellulosic biomass, acid pretreatments were employed to hydrolyze the cell walls, particularly the hemicellulose component. This step is crucial for the cost-effective conversion of biomass into fermentable sugars. To release cellulose from its complex with hemicelluloses and lignin, various pretreatment methods were explored. Chemical pretreatments using alkali and acid reagents have gained significant attention due to their simplicity and efficiency. In order to achieve selective hydrolysis, it is essential to determine the optimal concentration of alkali or acid, reaction temperature, and other critical parameters through experimentation.

A range of alkaline and acidic reagents, including sodium hydroxide (NaOH), calcium hydroxide Ca(OH)₂, lime, and sulfuric acid (H₂SO₄), were utilized to break down the complex components of rice straw, such as lignin, cellulose, hemicelluloses, and silica. The key parameters influencing the production of desired products were identified as alkaline/acid concentration, biomass loading ratio, temperature, and reaction duration. This study investigated the effect of

varying alkali/acid concentrations (1.5% to 3.5% w/v) on rice straw pretreatment under standardized conditions (100 °C, 4 hours, and 1:4 alkali/acid to sample loading ratio). The pretreatment process involved dissolving the alkali/acid in distilled water, followed by slow addition to the rice straw. After treatment, the rice straw was separated from the pretreatment solution (black liquor) using a Buchner funnel. The treated rice straw was then air-dried at room temperature for 5-6 days. A comprehensive compositional analysis was performed on both untreated and treated rice straw samples.

Proximate analysis of rice straw

The lignin, cellulose, hemicelluloses, holocellulose, ash, and silica content of both untreated and treated rice straw were determined using standard TAPPI Methods (Technical Association of the Pulp and Paper Industry). The TAPPI Test Method T257cm/85 was employed to prepare the raw material for chemical proximate analysis. To facilitate chemical analysis, various reagents were used to react with the rice straw. The straw was pulverized into fine particles (passing a 40-mesh screen) to ensure uniform analysis. Delignification of the ground powder was achieved using a sodium chlorite-acetic acid solution, following the procedure outlined by Wise *et al.*⁹ The resulting lignin-free residue was used to calculate the holocellulose content. The cellulose content was determined using the method developed by Updegroff *et al.*, which involves the acetolysis of cellulose to form acetylated cellulodextrins.¹⁰ These were then dissolved and hydrolyzed into glucose molecules, which were subsequently converted into hydroxymethylfurfural. The intensity of the resulting color was measured at 630 nm. The hemicellulose content was quantified by converting hemicelluloses into furfural through boiling in 3.85N hydrochloric acid, followed by titration using a bromate-bromide reagent. The lignin content was determined by hydrolyzing and solubilizing lignin using sulfuric acid, followed by filtration, oven-drying (105 °C), and weighing. Calculations were performed to determine the lignin content.

Morphological analysis of rice straw using field-emission scanning electron microscopy (FE-SEM)

The surface morphology of both untreated and processed rice straw powder was examined using a Field-Emission Scanning Electron Microscope (JSM-7610F Plus). This advanced electron microscope enabled the visualization of extremely fine rice straw particulates resulting from the pretreatment process. Prior to imaging, samples were mounted on carbon-paste-coated brass stubs and sputter-coated with a Pd-Pt layer to enhance conductivity. Untreated rice straw was also imaged as a control sample. High-resolution images of the native and treated rice straw surfaces were captured at various magnifications ranging from

500X to 10000X. The acquired images were subsequently analyzed using PC-SEM JDEL software to gain insights into the morphological changes induced by the pretreatment process.

Fourier transform infrared (FTIR) spectroscopy for biomass characterization

FTIR spectroscopy was employed to investigate changes in the functional groups and bond strengths between sugar molecules and lignin in untreated and treated rice straw. The analysis was performed using an FTIR spectrometer (Model MB3000) in accessory mode (A-I mode), with a detector (Model 114690-131082) set to a resolution of 16 and a detector gain of 81. The spectral data were collected over the range of 500–4000 cm⁻¹, with four scans performed for each sample.

The crystallinity of cellulose was evaluated following the method described by Nelson and O'Connor, which relates specific infrared absorption bands to cellulose crystallinity.¹¹ The absorbance ratio of the band at 1429 cm⁻¹ (CH₂ scissoring vibrations in crystalline cellulose) to that at 897 cm⁻¹ (C–H deformation in amorphous cellulose) was used to calculate the crystallinity index (CrI) according to the equation:

$$Cr = \frac{A_{1429}}{A_{897}} \quad (1)$$

where A_{1429} and A_{897} are the absorbance intensities at 1429 cm⁻¹ and 897 cm⁻¹, respectively. Additionally, the band at ~2900 cm⁻¹ was attributed to C–H and CH₂ stretching vibrations in cellulose. The acquired spectral data were processed using Origin 6.1 software to facilitate peak analysis and interpretation.

RESULTS AND DISCUSSION

Optimization of rice straw pretreatment for enhanced valorization

To overcome the recalcitrant nature of rice straw, this study employed a chemical pretreatment strategy, utilizing a diverse array of chemicals, such as alkalis, acids, organosolv agents (including formic and acetic acid), and eutectic solvents, aiming at disrupting its complex structure and facilitating the extraction of lignin and silica.

Chemical composition of rice straw

The proximate analysis of rice straw revealed its major constituent components. To prevent interference from extractives, rice straw was initially subjected to extractive-free treatment. The extractive content was determined based on the initial weight of rice straw. The analysis showed that the holocellulose content in rice straw was comparable to that of other wood and non-wood biomass, with a value of 70.6% (Table

1). This finding is consistent with previous reports by Kaur *et al.*¹² The rice straw was found to be rich in polysaccharides, comprising 33.3% cellulose and 37.9% hemicelluloses. The lignin content was determined to be 13.3%. However, the high ash and silica content in rice straw poses significant challenges to its utilization. The present study found that the rice straw contained 18.8% ash, with a silica content of 85.6%.

Optimization of mild chemical pretreatment of rice straw

Rice straw was subjected to pretreatment using various alkaline and acidic reagents, including NaOH, Ca(OH)₂, CaO, NH₃, and H₂SO₄, at concentrations ranging from 1.5% to 3.5%. The efficacy of NaOH pretreatment in delignification was evaluated, revealing significant reductions in lignin content at concentrations of 1.5% (27.8%) and 2.0% (31.5%) compared to untreated rice straw (13.3%) (Table 1). Further increases in NaOH concentration to 2.5% and 3.5% resulted in enhanced lignin reduction (33.8% and 36.84%, respectively). However, the destruction of polysaccharides, including cellulose and hemicelluloses, increased with rising NaOH concentrations, rendering the rice straw unsuitable

for various industrial applications at higher alkali concentrations. The ash content of rice straw decreased substantially up to a 2.5% NaOH concentration. Silica reduction in ash was observed at concentrations of 2.5% (18.10%), 3.0% (18.45%), and 3.5% (18.5%). No significant differences in chemical composition were noted at higher alkali concentrations. Consequently, 2.5% NaOH was identified as the optimal concentration for pretreatment.

Previous studies have demonstrated the efficacy of sodium hydroxide in removing lignin and hemicelluloses, thereby increasing the surface area and porosity of processed straw biomass.¹³ An alkali assisted biphasic pretreatment process under mild condition with NaOH loading ratio of 0.1-1.0% (w/v) was reported to lead to lignin removal of 82.16% at 80 °C and 78.15% at 55 °C.¹⁴ Furthermore, response surface methodology has been employed to investigate the effects of NaOH concentration, temperature, and treatment time on rice straw to maximize glucose yield.¹⁵ A detailed proximate analysis of NaOH-treated straw at various concentrations is presented in Table 2.

Table 1
Proximate analysis of untreated rice straw

Parameter	Present study	Kaur <i>et al.</i> ¹²
Acetone extractives (%)	2.5	2.42
Cellulose (%)	32.6	33.3
Hemicelluloses (%)	37.9	27.3
Holocellulose (%)	70.6	66.4
Lignin (%)	13.3	13.0
Ash (%)	18.8	12.6
Silica in ash (%)	85.6	92.8

Table 2
Proximate analysis of NaOH pretreated rice straw

NaOH	0%	1.5%	2.0%	2.5%	3.0%	3.5%
Lignin (%)	13.3	9.6	9.1	8.8	8.5	8.4
Hemicelluloses (%)	37.9	35.8	35.5	34.8	33.8	33.2
Cellulose (%)	32.6	30.7	30.5	29.8	27.7	27.5
Ash (%)	18.8	16.8	16.5	15.3	15.1	15.0
Silica (%)	85.6	74.2	72.3	70.1	69.8	69.7

Optimization of lignin reduction using Ca(OH)₂ pretreatment

The pretreatment of rice straw with Ca(OH)₂ resulted in significant lignin reduction, with an optimal reduction of 32.33% achieved at 3.5%. A gradual increase in lignin degradation was

observed as the Ca(OH)₂ concentration was increased from 1.5% to 2.5%. Specifically, Ca(OH)₂ concentrations of 2.5%, 3.0%, and 3.5% resulted in lignin reductions of 27.06%, 30.07%, and 32.33%, respectively, indicating a positive correlation between Ca(OH)₂ concentration and

lignin removal efficiency. Additionally, ash and silica content were reduced by 14.89% and 14.71%, respectively, at the optimal $\text{Ca}(\text{OH})_2$ concentration of 3.5%. Notably, the pretreatment had no significant impact on the cellulose and hemicellulose content.

Proximate analysis revealed that the optimal concentration of $\text{Ca}(\text{OH})_2$ for maximizing silica and lignin reduction is 3.5%. A detailed account of the proximate analysis results for $\text{Ca}(\text{OH})_2$ pretreatment is presented in Table 3.

The pretreatment of rice straw with calcium oxide (CaO) at a concentration of 2.5% yielded notable reductions in ash and silica content, reaching 12.7% and 12.0%, respectively. Concurrently, lignin, cellulose, and hemicellulose contents decreased by 18.7%, 4.9%, and 3.6%,

respectively. However, further increases in CaO concentration did not result in significant additional reductions (Table 4).

The treatment of rice straw with ammonia (NH_3) at a concentration of 2.0% resulted in the maximum lignin reduction of 18.7%. Further increases in NH_3 concentration did not yield significant additional reductions. The impact of NH_3 treatment on cellulose content was concentration-dependent, with reductions of 2.4%, 3.0%, 3.6%, 6.4%, and 7.6% observed at concentrations of 1.5%, 2.0%, 2.5%, 3.0%, and 3.5%, respectively. Optimal degradation of cellulose and hemicelluloses occurred at 2.0% NH_3 concentration, accompanied by 6.3% ash removal and 11.3% silica removal.

Table 3
Proximate analysis of $\text{Ca}(\text{OH})_2$ pretreated rice straw

$\text{Ca}(\text{OH})_2$	0%	1.5%	2.0%	2.5%	3.0%	3.5%
Lignin (%)	13.3	10.2	10.1	9.7	9.3	9.0
Hemicelluloses (%)	37.9	37.0	36.3	36.0	35.7	34.4
Cellulose (%)	32.6	31.9	31.4	31.0	30.2	29.1
Ash (%)	18.8	17.5	17.1	16.6	16.2	16.0
Silica (%)	85.6	75.4	75.1	74.3	74.0	73

Table 4
Proximate analysis of CaO pretreated rice straw

CaO	0%	1.5%	2.0%	2.5%	3.0%	3.5%
Lignin (%)	13.3	11.0	11.1	10.8	10.3	10.1
Hemicelluloses (%)	37.9	36.9	36.5	36.0	35.3	35.0
Cellulose (%)	32.6	31.8	31.3	31.0	29.9	29.8
Ash (%)	18.8	17.3	16.9	16.4	16.3	16.1
Silica (%)	85.6	75.9	75.5	75.3	75.1	75.0

Table 5
Proximate analysis of NH_3 pretreated rice straw

NH_3	0%	1.5%	2.0%	2.5%	3.0%	3.5%
Lignin (%)	13.3	11.0	10.8	10.5	10.4	10.1
Hemicelluloses (%)	37.9	37.1	36.5	36.3	35.8	35.3
Cellulose (%)	32.6	31.8	31.6	31.4	30.5	30.1
Ash (%)	18.8	18.1	17.6	17.3	17.0	16.5
Silica (%)	85.6	76.3	75.9	75.3	75.1	75.0

Table 6
Proximate analysis of H_2SO_4 pretreated rice straw

H_2SO_4	0%	1.5%	2.0%	2.5%	3.0%	3.5%
Lignin (%)	13.3	9.9	9.7	9.1	8.9	8.3
Hemicelluloses (%)	37.9	33.3	32.1	31.9	31.1	30.6
Cellulose (%)	32.6	29.7	29.6	29.4	29.1	28.6
Ash (%)	18.8	17.1	16.6	16.1	15.9	15.1
Silica (%)	85.6	66.3	65.5	64.5	64.31	64.1

Based on these findings, 2.0% NH_3 concentration was determined to be the optimal treatment condition. A comprehensive analysis of NH_3 treated straw at varying concentrations is presented in Table 5. The treatment of rice straw with sulfuric acid (H_2SO_4) resulted in significant lignin reduction, with concentrations of 1.5%, 2.0%, 2.5%, 3.0%, and 3.5% yielding reductions of 25.5%, 27.0%, 31.5%, 33.08%, and 37.6%, respectively. Although the maximum reduction occurred at 3.5% H_2SO_4 , it was not substantially different from the reduction achieved at 2.5% H_2SO_4 . Furthermore, the pretreatment with 2.5% H_2SO_4 resulted in a 14.3% reduction in ash content and a 24.6% reduction in silica content (Table 6). In a related context, previous studies have demonstrated the efficacy of sodium hydroxide in removing lignin and hemicelluloses, thereby enhancing the surface area and porosity of the pretreated straw biomass. Moreover, response surface methodology has been employed to investigate the effects of sodium hydroxide concentration, temperature, and treatment time on rice straw, with the aim of optimizing glucose production.¹⁶

A comparative examination of the proximate analysis results following alkaline and acidic pretreatments revealed that H_2SO_4 pretreatment

was the most effective method for removing silica and lignin from rice straw. Acidic pretreatment is a widely adopted approach for straw biomass, as it disrupts the complex bonds between hemicelluloses, lignin, and cellulose, thereby enhancing hemicellulose hydrolysis and lignin removal. This, in turn, facilitates the subsequent saccharification and fermentation processes.¹⁷ Sulfuric acid pretreatment at higher concentration remains a key method for commercial-scale lignocellulosic biomass processing.¹⁸ However, it was observed that H_2SO_4 pretreatment had a slightly higher impact on cellulose and hemicellulose degradation compared to alkaline treatment.

Surface morphological analysis using FE-SEM

The scanning electron micrographs revealed significant changes in surface morphology due to chemical and enzymatic treatments. The pretreatment was found to have a profound impact on the structural integrity of rice straw. All chemically treated samples exhibited irregular surface morphologies at 10,000X magnification, characterized by increased porosity and fissures. In contrast, the untreated rice straw displayed a compact structure (Fig. 1(a)).

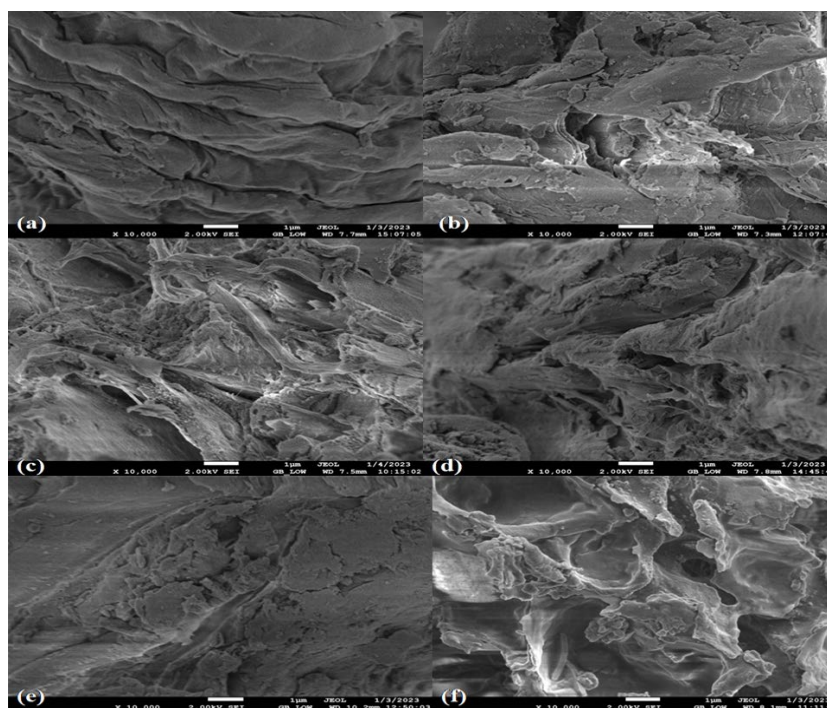


Figure 1: Scanning electron microscopic images of: (a) untreated rice straw, (b) rice straw treated with CaO , (c) NaOH , (d) $\text{Ca}(\text{OH})_2$, (e) NH_3 , (f) H_2SO_4

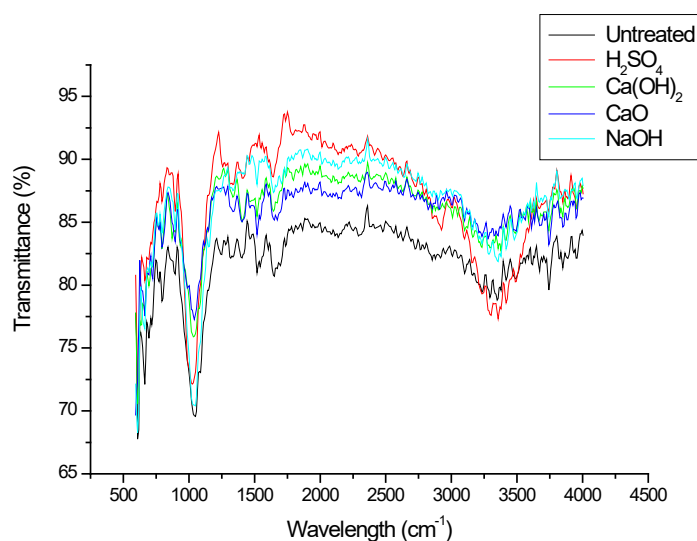


Figure 2: FTIR spectra of untreated and chemically treated rice straw

Table 7
Crystallinity index of untreated and chemically pretreated rice straw

Sample	Abs (1429 cm ⁻¹)	Abs (897 cm ⁻¹)	CrI
Untreated (UT)	0.0813	0.0922	0.8820
NaOH-treated	0.0518	0.0662	0.9010
Ca(OH) ₂ -treated	0.0659	0.0746	0.7833
H ₂ SO ₄ -treated	0.0513	0.0735	0.9990
CaO (lime)	0.0680	0.0785	0.6983

The treatment with CaO resulted in minimal changes to the surface structure (Fig. 1(b)), whereas the NaOH pretreatment had a more pronounced effect, causing significant rupture of the rice straw cell wall, as evident from both the FE-SEM images and proximate analysis (Fig. 1(c)).

Comparative analysis of SEM images from alkaline and acidic pretreatments revealed that H₂SO₄ showed the most profound impact on rice straw morphology. The fibrous structure was extensively opened, indicating that H₂SO₄ penetrated the cell wall and deeper layers, consistent with the proximate analysis results showing maximum lignin and silica removal.

FTIR spectroscopic analysis

To investigate the structural modifications in rice straw following various treatments, ATR-FTIR spectroscopy was employed, and the resulting spectra are presented in Figure 2. The FTIR spectra exhibited a prominent absorption band between 3445 and 3250 cm⁻¹, attributed to the stretching vibrations of hydroxyl (OH) bonds in carbohydrates and lignin. Specific absorption

peaks at 3428 cm⁻¹, 3340 cm⁻¹, and 3272 cm⁻¹ were associated with hydrogen bonding within and between molecules. Additional peaks at 3305 cm⁻¹ and 3405 cm⁻¹ indicated intermolecular hydrogen bonding.¹⁹ A band at 2892 cm⁻¹ corresponded to the stretching vibrations of CH groups in various bond types.^{20,21} A peak at 1648 cm⁻¹ was linked to aromatic vibrations in lignin.²²

Of particular importance, the band at 1429 cm⁻¹ was assigned to CH₂ scissoring vibrations of crystalline cellulose, while the band at 897 cm⁻¹ was attributed to C–H deformation vibrations of amorphous cellulose. According to Nelson and O'Connor,¹¹ the absorbance ratio of these two bands provides a reliable estimation of cellulose crystallinity in lignocellulosic biomass. In the present study, this method was employed to calculate the crystallinity index (CrI) of untreated and pretreated rice straw samples.

Untreated rice straw exhibited a CrI of 0.8820, reflecting the dominance of amorphous fractions associated with hemicelluloses and lignin. Following the H₂SO₄ pretreatment, the CrI increased, indicating selective removal of amorphous components and relative enrichment

of crystalline cellulose. The pretreatment with NaOH and Ca(OH)₂ resulted in moderate changes in CrI, while the CaO pretreatment produced a comparatively smaller increase, suggesting preferential degradation of hemicelluloses, without substantial exposure of crystalline domains.

The absorption bands between 1243 and 1317 cm⁻¹ were associated with vibrations in lignin's structure.²³ Hemicelluloses were characterized by a C=O stretching vibration at 1725–1735 cm⁻¹.^{24,25} The Si–O bond was observed at 792 cm⁻¹ with a bending mode.^{25,26} The band at 3321 cm⁻¹ showed changes after H₂SO₄ treatment, possibly indicating a decrease in phenolic compounds. Additional peaks at 1140 cm⁻¹ and 1029 cm⁻¹, related to the stretching of C–O–C bonds, became more pronounced after H₂SO₄ treatment, suggesting the breakdown of specific sugars during pretreatment.²⁷

Overall, the FTIR spectroscopic analysis revealed not only significant alterations in the chemical structure of rice straw after pretreatment, but also quantifiable changes in cellulose crystallinity, confirming the structural reorganization of the biomass matrix.

CONCLUSION

The results demonstrated that the H₂SO₄ pretreatment was the most effective method for removing silica and lignin from rice straw, followed by the NaOH treatment. The findings of this study highlight the importance of optimizing pretreatment conditions to enhance the accessibility of cellulose and hemicelluloses for enzymatic hydrolysis. In conclusion, this study has implications for the development of efficient and sustainable biorefinery processes for the conversion of rice straw into valuable biofuels and biochemicals. Future studies can build upon these findings to optimize pretreatment conditions and develop scalable processes for the utilization of rice straw as a renewable biomass feedstock.

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