วารสารวิชาการพระจอมเกล้าพระนครเหนือ ปีที่ 36 ฉบับที่ 2 เม.ย.–มิ.ย. 2569
The Journal of KMUTNB., Vol. 36, No. 2, Apr.–Jun. 2026

บทความวิชาการ

เทคโนโลยีการปรับสภาพลิกโนเซลลูโลสสำหรับการผลิตไบโอเอทานอลจากเศษวัสดุเหลือทิ้งทางการเกษตร

ปุณยนุช คุณมณี สุภาวดี สุดสาย และ มาลินี ศรีอริยนันท์
ศูนย์วิจัยอุตสาหกรรมเคมีชีวภาพและวิศวกรรมกระบวนการแบบอัตโนมัติ ภาควิชาวิศวกรรมเคมีและกระบวนการ บัณฑิตวิทยาลัยวิศวกรรมศาสตร์นานาชาติสิรินธรไทย-เยอรมัน มหาวิทยาลัยเทคโนโลยีพระจอมเกล้าพระนครเหนือ
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รับเมื่อ 15 กรกฎาคม 2568 แก้ไขเมื่อ 11 พฤศจิกายน 2568 ตอบรับเมื่อ 25 ธันวาคม 2568 เผยแพร่ออนไลน์ 20 มีนาคม 2569

บทคัดย่อ

การใช้ประโยชน์จากของเสียทางการเกษตรเพื่อการผลิตพลังงานชีวภาพมีบทบาทสำคัญในการส่งเสริมเศรษฐกิจหมุนเวียนและลดผลกระทบต่อสิ่งแวดล้อม ชีวมวลลิกโนเซลลูโลส เช่น ฟางข้าว ซังข้าวโพด และชานอ้อย ถือเป็นวัตถุดิบที่มีศักยภาพสูงในการผลิตเชื้อเพลิงชีวภาพโดยเฉพาะเอทานอลชีวภาพ อย่างไรก็ตามเนื่องจากโครงสร้างที่ซับซ้อนและทนทานของลิกโนเซลลูโลส โดยเฉพาะการมีอยู่ของลิกนินจึงจำเป็นต้องมีการปรับสภาพเบื้องต้น เพื่อเพิ่มการเข้าถึงของเซลลูโลสและเฮมิเซลลูโลสในการย่อยสลายต่อไป บทความปริทัศน์ฉบับนี้ได้รวบรวมและประเมินวิธีการปรับสภาพทางเคมีหลายรูปแบบ ได้แก่ การปรับสภาพด้วยกรด ด่าง ออร์กาโนซอล์ฟ ของเหลวไอออนิก และตัวทำละลายยูเทกติกเชิงลึก โดยเน้นถึงข้อดี ข้อจำกัด และประเด็นด้านสิ่งแวดล้อมของแต่ละวิธี นอกจากนี้ยังกล่าวถึงเกณฑ์ในการเลือกวิธีการปรับสภาพที่เหมาะสมตามชนิดของชีวมวลและผลิตภัณฑ์ปลายทางที่ต้องการ อีกทั้งยังสำรวจแนวคิดของโรงกลั่นชีวภาพในฐานะวิธีการที่ยั่งยืนเพื่อเพิ่มมูลค่าสูงสุดจากเศษเหลือทางการเกษตร โดยการเปลี่ยนให้เป็นพลังงานชีวภาพ สารเคมีชีวภาพ และวัสดุชีวภาพ ซึ่งช่วยเพิ่มประสิทธิภาพในการใช้ทรัพยากร ลดการพึ่งพาเชื้อเพลิงฟอสซิล และส่งเสริมความยั่งยืนด้านสิ่งแวดล้อมในระยะยาว

คำสำคัญ: กระบวนการกลั่นทางชีวภาพ ชีวมวลลิกโนเซลลูโลส เอทานอล การปรับสภาพทางเคมี เศรษฐกิจหมุนเวียน

การอ้างอิงบทความ: ปุณยนุช คุณมณี, สุภาวดี สุดสาย, มาลินี ศรีอริยนันท์, วนารัตน์ ภาคีนุยะ และ วทันยา ไชยสายัณท์, “เทคโนโลยีการปรับสภาพลิกโนเซลลูโลสสำหรับการผลิตไบโอเอทานอลจากเศษวัสดุเหลือทิ้งทางการเกษตร,” *วารสารวิชาการพระจอมเกล้าพระนครเหนือ*, ปีที่ 36, ฉบับที่ 2, หน้า 1–17, เม.ย.–มิ.ย. 2569, เลขที่บทความ 262-098125, doi: 10.14416/j.kmutnb.2026.03.004.

Academic Article

Lignocellulosic Pretreatment Technologies for Bioethanol Production from Agricultural Residues

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DOI: 10.14416/j.kmutnb.2026.03.004
Received 15 July 2025; Revised 11 November 2025; Accepted 25 December 2025; Published online: 20 March 2026

Abstract

The utilization of agricultural waste for bioenergy production plays a crucial role in promoting a circular economy and reducing environmental impacts. Lignocellulosic biomass, such as rice straw, corn cobs, and sugarcane bagasse, is considered a highly promising feedstock for the production of biofuels, particularly bioethanol. However, due to the complex and recalcitrant structure of lignocellulose, especially the presence of lignin, pretreatment is essential to enhance the accessibility of cellulose and hemicellulose for subsequent hydrolysis. This review compiles and evaluates various chemical pretreatment methods, including acid, alkaline, organosolv, ionic liquid, and Deep Eutectic Solvent (DES) pretreatments, highlighting their advantages, limitations, and environmental considerations. Furthermore, it emphasizes criteria for selecting appropriate pretreatment methods based on biomass type and desired end products. The review also explores the biorefinery concept as a sustainable approach to maximizing value from agricultural residues by converting them into bioenergy, biochemicals, and biomaterials. This approach enhances resource efficiency, reduces reliance on fossil fuels, and promotes long-term environmental sustainability.

Keywords: Biorefinery, Lignocellulose Biomass, Ethanol, Chemical Pretreatment, Circular Economy

Please cite this article as: P. Kunmanee, S. Sudsai, M. Sriariyanun, V. Phakeenuya and W. Chaisayan, “Lignocellulosic pretreatment technologies for bioethanol production from agricultural residues,” *The Journal of KMUTNB*, vol. 36, no. 2, pp. 1–17, Apr.–Jun. 2026 (in Thai), Art. no. 262-098125, doi: 10.14416/j.kmutnb.2026.03.004.

1. Introduction

The utilization of agricultural waste for bioenergy production plays a vital role in waste management, environmental protection, and the advancement of alternative energy sources. Agricultural residues, such as rice straw, corn cobs, bagasse, nutshells, animal manure, and by-products from food processing, are valuable forms of biomass that can be converted into energy [1]. If left unmanaged, these wastes can cause serious environmental issues, including air pollution from open burning, foul odors from decomposition, and the release of greenhouse gases that contribute to climate change [2].

Turning agricultural waste into bioenergy aligns with the principles of the circular economy, which promotes efficient resource use, waste minimization, and value recovery. Technologies such as anaerobic digestion for biogas, biomass briquetting for solid biofuels, and transesterification for biodiesel from used cooking oil are practical examples of this approach [3], [4]. These methods reduce reliance on fossil fuels, improve energy efficiency, and help to close the resource loop.

The circular economy framework is supported through practices such as "Reduce" by minimizing waste at the farm and production level, "Reuse" through repurposing plant residues as mulch or animal feed, and "Recycle" by converting organic waste into biofertilizers or renewable energy. These strategies allow farmers and industries to generate additional income, lower energy costs, and contribute to sustainable resource management.

In addition to environmental benefits, such as reduced greenhouse gas emissions and decreased reliance on finite natural resources, bioenergy production from agricultural waste supports community-level economic development [5]. It creates jobs in the renewable energy sector and enhances energy security for rural and agricultural communities. This review aims to provide a comprehensive overview of current technologies, benefits, and challenges associated with converting agricultural waste into bioenergy within the framework of the circular economy. It explores practical applications, policy implications, and future research directions, with the objective of promoting sustainable development through integrated waste-to-energy systems.

2. Bioconversion Process of Lignocellulosic Biomass

Lignocellulose is the primary structural component of plant cell walls, providing mechanical strength, rigidity, and enabling plants to maintain their upright form. It is composed of three main biopolymers: cellulose, hemicellulose, and lignin [6]. Cellulose, a linear polysaccharide of glucose units linked by β-1,4-glycosidic bonds, forms tightly packed crystalline fibers due to strong intermolecular hydrogen bonding, rendering it water-insoluble. Hemicellulose, a branched heteropolymer made up of various sugars such as xylose, arabinose, mannose, and galactose [7], has a more amorphous and flexible structure that facilitates cross-linking between cellulose and lignin, thereby reinforcing the plant cell wall [8]. Lignin, a complex aromatic polymer of phenylpropanoid units, acts as a binding matrix that imparts hydrophobicity, structural rigidity, and resistance to microbial degradation.

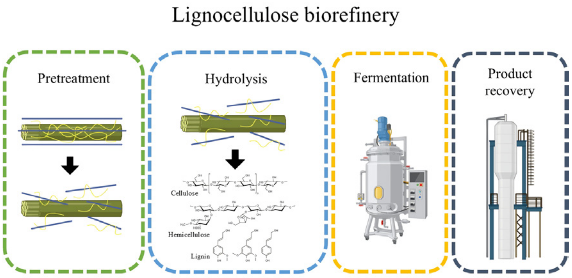

Figure 1 Lignocellulose biorefining process including pretreatment, hydrolysis, fermentation and product recovery.

Lignocellulosic biomass is abundant in agricultural and industrial residues such as rice straw, corn cobs, bagasse, sawdust, and wood chips (Table 1), making it a promising feedstock for producing bioenergy, biochemicals, and biomaterials [9]. However, the recalcitrant nature of lignin poses a significant challenge to biomass conversion, especially in biofuel production. Effective utilization of lignocellulose requires a sequence of processing steps that integrate physical, chemical, and biological technologies [10] (Figure 1).

The conversion process begins with feedstock preparation harvesting, selecting, and reducing biomass particle size to enhance surface area for subsequent treatment. Pretreatment is a critical step designed to disrupt the rigid lignocellulosic matrix, particularly by loosening or removing lignin to increase the accessibility of cellulose and hemicellulose [11]. Pretreatment methods include chemical (acid or alkaline), physical (steam explosion), or biological approaches (lignin-degrading enzymes). Following pretreatment, enzymatic or acid hydrolysis converts polysaccharides into fermentable sugars such as glucose and xylose. These sugars are then fermented by microorganisms, such as yeast or bacteria, to produce biofuels like bioethanol or biogas. Therefore, the bioconversion of lignocellulosic residues not only enhances the value of agricultural waste but also mitigates environmental concerns and supports the development of a circular economy by promoting renewable energy and sustainable resource utilization [9].

The biorefinery operates similarly to a petroleum refinery, where a single raw material yields multiple products, thereby maximizing resource efficiency. Biorefinery processes vary depending on the type of biomass and target products and can be categorized into three main types: biological processes, including microbial fermentation and enzymatic hydrolysis for producing bioethanol and biogas; chemical processes, such as the transesterification of fatty acids to biodiesel or the transformation of bio-based compounds into various chemicals; and physical and thermochemical processes, such as pyrolysis, which heats biomass in an oxygen-free environment to produce bio-oil, and gasification, and converts biomass into syngas for use in the energy and chemical industries [12], [13]. The development of biorefineries is a key strategy for reducing reliance on fossil resources, lowering greenhouse gas emissions, and mitigating pollution from organic waste. Moreover, it increases the value of biomass, supports the bioeconomy, and advances the circular economy by utilizing biological resources efficiently and sustainably, making biorefineries a crucial path toward a long-term sustainable economic system with minimized environmental impact [14].

Table 1 Price of agricultural wastes that have potential to be raw materials for biorefinery

Biomass Type	Price per Ton (Baht)	Reference Year	Reference
Napier Grass	300–500	2021	[15]
Rice Straw	1,000–3,000	2024	[16], [17]
Sugarcane Bagasse	900–1,000	2024–2025	[18]
Sugarcane Leaves	900–1,000	2024–2025	[18]
Water Hyacinth	500–1,160	2020	[19]
Palm Bunches	300	2022	[20]
Palm Leaves	100–200	2016	[20]
Palm Trunk	200–300	2016	[20]
Rice Husk	1,400–1,500	2021	[21]
Corn Cob	300–500	2014	[22]

3. Biomass Pretreatment Processes

Pretreatment is a critical step in processing lignocellulosic biomass, as it enhances its degradability and prepares it for conversion into bioenergy or bioproducts. The necessity for pretreatment arises from the complex and recalcitrant nature of lignocellulose, which is composed of three main components: cellulose, hemicellulose, and lignin. These components are tightly bound, forming a rigid structure that resists enzymatic or microbial degradation. In particular, lignin encapsulates cellulose and hemicellulose, acting as a physical barrier that limits enzyme accessibility. Lignocellulose typically consists of 30–50% cellulose and 20–43% hemicellulose, forming a highly stable structure [23]. Through hydrolysis, these polysaccharides can be converted into fermentable sugars for biofuel and biochemical production.

Pretreatment aims to improve biomass digestibility through four primary mechanisms: 1) disrupting or modifying lignin 2) decreasing cellulose crystallinity 3) solubilizing hemicellulose to expose cellulose fibers and 4) increasing the accessible surface area. Effective pretreatment can substantially enhance enzymatic hydrolysis efficiency, though challenges such as pseudo-lignin formation, sugar degradation, and inhibitor production may occur depending on the severity of processing [24]–[27]. These issues highlight the need to balance efficiency with downstream compatibility.

The selection of a suitable pretreatment strategy depends on several factors, including biomass composition, lignin content, sugar release targets, cost considerations, and environmental sustainability. For example, alkaline pretreatment is often preferred for high-lignin biomass such as bagasse and wood residues, while dilute acid pretreatment is effective for hemicellulose-rich feedstocks [28]. Additional factors such as the potential generation of inhibitory compounds, equipment requirements, and energy input must also be considered when determining the most appropriate pretreatment method.

3.1 Overview of Pretreatment Strategies

Various pretreatment approaches, including thermal, chemical, biological, and physical methods, have been developed to overcome lignocellulosic recalcitrance (Table 2). Physical size reduction increases surface area but often requires substantial energy. Biological pretreatment using lignin-degrading microorganisms is environmentally friendly but slow and less feasible at scale. In particular, biological pretreatment suffers from inherently low delignification efficiency and requires prolonged processing times due to the slow rate of ligninolytic microbial activity. The performance of fungi or lignin-degrading microorganisms is also highly sensitive to factors such as temperature, moisture content, and substrate variability, often leading to inconsistent outcomes. These limitations create significant challenges for scale-up, as industrial biorefineries require stable, fast, and high-throughput operations. Consequently, biological pretreatment is generally considered suitable only for small-scale or complementary applications rather than as a primary pretreatment strategy for commercial processes. Steam explosion provides effective fiber disruption without extensive chemical use but demands high energy. Among these technologies, chemical pretreatment is widely applied because it can achieve strong delignification and markedly enhance hydrolysis yields [29].

3.2 Chemical Pretreatment Methods

3.2.1 Acid Pretreatment

Dilute acid pretreatment (e.g., H_2SO_4, H_3PO_4) efficiently solubilizes hemicellulose, making cellulose more accessible to enzymes. This method is particularly effective for improving sugar release; however, severe conditions may lead to the formation of inhibitors such as furfural and HMF, which negatively affect downstream fermentation [24].

3.2.2 Alkaline Pretreatment

Alkaline pretreatment using agents such as NaOH or NH_3 effectively removes lignin and disrupts the ester linkages between lignin, cellulose, and hemicellulose. This enhances enzyme accessibility, especially in high-lignin biomass. Nevertheless, alkaline processes may generate phenolic inhibitors and often require large volumes of water for washing [28].

3.2.3 Organosolv Pretreatment

Organosolv pretreatment employs organic solvents, often combined with catalysts, to selectively solubilize lignin while preserving cellulose. It can produce high-quality lignin suitable for value-added applications; however, issues related to solvent recovery, cost, and process safety remain key challenges.

3.2.4 Oxidative Pretreatment

Oxidative agents such as ozone or hydrogen peroxide degrade lignin through oxidation reactions. Although these methods achieve significant delignification and improve digestibility, they require high reagent costs and energy input, limiting industrial applicability.

3.2.5 Ionic Liquid (IL) Pretreatment

Ionic liquids dissolve lignocellulosic components and reduce cellulose crystallinity, significantly improving hydrolysis efficiency. Despite their effectiveness, the high cost of ILs, combined with challenges in solvent recycling and process integration, inhibits large-scale deployment.

3.2.6 Deep Eutectic Solvent (DES) Pretreatment

DESs have gained attention as greener, lower-cost solvents capable of solubilizing lignin and improving enzymatic hydrolysis. Their tunable properties allow customization for specific biomass types. However, scalability, long-term solvent

Table 2 Various chemical pretreatment methods of lignocellulosic biomass

Biomass	Chemicals	Condition	Key findings	Reference
Barley Straw	2.0% NaOH	100°C 60 min	84.8% lignin removal, 79.5% hemicellulose removal	[30]
Sugarcane Bagasse	1.5% NaOH	121°C 30 min	87.3% lignin removal, 34% hemicellulose removal	[31]
Hemp	1% NaOH	121°C 60 min	60.0% lignin removal, 11.6% hemicellulose removal	[32]
Cocoa Pod Husk	5% NaOH	30 min at 120°C	57% lignin removal	[33]
Rice Straw	100% Glycerol with 0.25% HCl	1:19 solid content at 190°C with 600 min	Recovery rates: 62.9% cellulose 1.2% hemicellulose 16.3% lignin	[34]
Sugarcane Bagasse	70% Glycerol with 0.72% H_2SO_4	1:10 solid content at 110°C with 420 min	Recovery rates: 79.2% cellulose 1.8% hemicellulose 13.9% lignin	[35]
Sugarcane Bagasse	83% Glycerol with 0.4% HCl	1:6 solid content at 130°C with 15 min	Recovery rates: 54.2% cellulose 3.2% hemicellulose 26.5% lignin	[36]
Corn Cob	100% Glycerol	1:10 solid content at 170°C with 60 min	Recovery rates: 46.5% cellulose 36.6% hemicellulose 12.7% lignin	[37]
Wheat Straw	ChCl-lactic acid (1:2)	pretreatment at 150°C for 6 h, solid loading (1:20 w/v)	The enzymatic saccharification rate was 89.8%	[38]
Sugarcane Bagasse	ChCl/glycerol/ $FeCl_3$	120°C 3 h	The enzymatic saccharification rate was 90.31%	[39]
Corn Cob	ChCl-Ethylene glycol (1:2)	90°C for 24 h, 1:20 w/v	The enzymatic saccharification rate was 85.3%	[40]
Biomass Mixtures	ChCl-lactic acid (1:2)	solid loading of 1:10 w/v, 121°C, 90 min	Recovery rates: 59.7% cellulose 20.87% hemicellulose 9.55% lignin	[41]

stability, and recycling efficiency require further investigation.

Each pretreatment method offers distinct advantages, yet none is optimal for all. Acid pretreatment is effective for hemicellulose removal but may generate sugar-derived inhibitors. Alkaline pretreatment excels in delignification but can produce phenolic compounds that inhibit fermentation. Organosolv and oxidative methods offer high delignification efficiency but face economic and environmental challenges. ILs and DESs provide promising alternatives as green solvents with high tunability, though cost and solvent recyclability remain limiting factors. Future research should focus on minimizing inhibitor formation, improving solvent recovery, optimizing hybrid strategies, and integrating pretreatment into scalable biorefinery systems.

4. Development of Pretreatment Processes

The selection of an appropriate pretreatment method depends on several factors, including the characteristics of the biomass feedstock and the intended conversion objectives. One of the most critical considerations is the type and amount of lignin present in the biomass. For instance, feedstocks with high lignin content, such as wood residues or bagasse, often suit well to alkaline pretreatment or steam explosion [28]. These methods effectively disrupt the lignin matrix and improve cellulose accessibility, thereby enhancing enzymatic hydrolysis.

When the primary objective is the production of fermentable sugars, dilute acid pretreatment (e.g., using sulfuric acid) is particularly effective at hydrolyzing hemicellulose and releasing monomeric sugars such as xylose and arabinose for downstream fermentation [42]. However, the selection process must also consider economic feasibility. Techniques like steam explosion, while effective, are energy-intensive and may incur higher operational costs. Conversely, biological pretreatment is more environmentally friendly and cost-effective, but it typically requires longer processing times and may have lower efficiency.

Environmental sustainability is another important factor in pretreatment selection. Preferred methods should minimize the generation of toxic by-products and align with green processing principles to support eco-friendly biomass utilization. Therefore, a balance between process efficiency, cost, and environmental impact is essential to ensure that the chosen pretreatment method contributes to a sustainable bioconversion system.

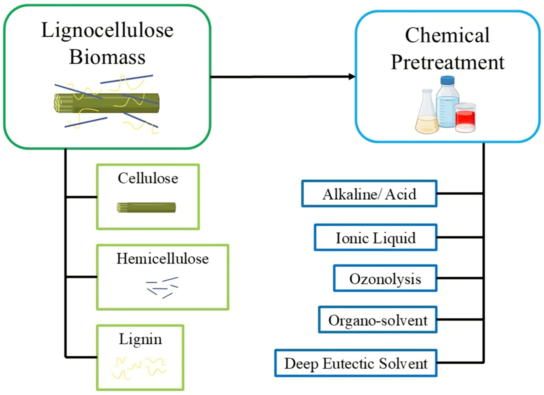

Figure 2 Chemical pretreatment of lignocellulosic biomass.

Chemical pretreatment involves the application of chemical agents to alter the structure of lignocellulosic biomass, thereby improving the accessibility of cellulose and hemicellulose for further processing. Due to the recalcitrant nature of lignocellulose, chemical pretreatment plays a vital role in many biomass conversion technologies. A range of chemical methods is available, with the choice depending on the specific characteristics of the biomass and the desired end products (Figure 2).

Acid pretreatment using diluted sulfuric acid (H_2SO_4) or phosphoric acid (H_3PO_4) effectively breaks down hemicellulose, thereby exposing cellulose and releasing fermentable sugars. This method is suitable for biomass with high hemicellulose content, such as corn and wheat. The use of diluted sulfuric acid in combination with aluminum sulfate was reported to selectively remove hemicellulose. The optimal conditions were 160°C, 1.5% aluminum sulfate, 0.7% sulfuric acid, and a 40-minute reaction time, achieving 98.05% hemicellulose removal while only 9.01% lignin was removed, indicating high specificity [43]. Phosphoric acid (H_3PO_4) pretreatment was effective in degrading hemicellulose and lignin while preserving cellulose structure, thereby increasing the cellulose surface area and enzymatic digestibility. The optimal condition was pretreated with 75% H_3PO_4 at 60°C for 60 minutes, removing approximately 66% of lignin [44].

Alkaline pretreatment, using sodium hydroxide (NaOH) or ammonia (NH_3), disrupts lignin that encases cellulose and hemicellulose, improving accessibility for enzymatic hydrolysis. This method is suitable for lignin-rich biomass, such as wood chips and bagasse. The use of NaOH and ammonia for treating lignocellulosic materials like sawdust, corn stover, and bagasse, showed significant lignin removal and improved enzymatic access [45]. Recent studies reported that soaking aqueous ammonia pretreatment at moderate temperatures (50–90°C) substantially enhanced delignification of corn stover, achieving lignin removal above 55–65% and significantly improving subsequent cellulose digestibility [46].

Organosolv pretreatment uses organic solvents, such as ethanol mixed with acid or base, to separate lignin from cellulose and hemicellulose. The extracted lignin can be further utilized in other industries. Using an ethanol–sulfuric acid mixture on hybrid poplar achieved over 70% lignin removal and yielded high-purity cellulose suitable for enzymatic hydrolysis. The separated lignin also had applications in bioproducts and materials [47]. The uses of solvents like ethanol, methanol, and acetone with mild acids to fractionate lignocellulosic biomass, highlight the high-value lignin produced, suitable for polymer and biocomposite industries, while also enhance enzymatic cellulose hydrolysis [48].

Oxidative pretreatment employs oxidizing agents such as ozone (O_3) or hydrogen peroxide (H_2O_2) to degrade lignin and loosen biomass structure. Although costly, it effectively breaks down lignin. Ozone treatment for 90 minutes at pH 3.0 yielded biomass with 59% cellulose, 22% hemicellulose, and 6% lignin, reducing lignin content by 217%. Hydrolysis reduced sugar content from 19.34 to 2.86 mg/L after heating at 100°C, and fermentation yielded 0.79% (v/v) ethanol [49]. Alkaline hydrogen peroxide (AHP) pretreatment was investigated to address bamboo biomass recalcitrance. The process removed 68.29% of lignin while retained 90.72% glucan and 60.45% xylan. Enzymatic digestibility of glucan and xylan increased significantly to 90.62% and 88.30%, respectively, representing 8.14-fold and 10.07-fold improvements over raw bamboo [50].

IL pretreatment utilizes ILs that dissolve cellulose and lignocellulosic components without degrading cellulose. Although IL has high cost, it is suitable for processes requiring high cellulose integrity. ILs such as [Amim]Cl and [C2mim]OAc could dissolve cellulose, lignin, and hemicellulose from diverse biomass sources (e.g., corn stover, switchgrass, rice straw, and hardwood/softwood), reduce cellulose crystallinity, enhance enzymatic hydrolysis, and enable lignin valorization into bioproducts or polymers [51]. Imidazolium-based ILs, particularly [Emim][OAc], improved enzymatic accessibility for hydrolysis at 45°C, resulting in ethanol yields increased by 2.6-fold for model cellulose, 2.8-fold for pine sawdust, and 3.9-fold for oak sawdust, suggesting a significant advancement in sustainable biorefinery processes [52].

Finally, DESs offer an eco-friendly and cost-effective alternative for lignin and cellulose solubilization while preserving cellulose structure. Pineapple peel waste was utilized as a feedstock for second-generation biofuel production using a DES composed of ethylene glycol and citric acid. This increased glucose contents to 59.85% and xylose to 97.12% were obtained [53]. A green biomass preparation strategy was developed using a combination of betaine–glycerol and choline chloride–oxalic acid (or choline chloride–acetamide) DESs. Corn biomass treated with the DES cocktail exhibited glucan digestibility of 89.51% and xylan digestibility of 75.43%, with enhanced structural porosity and enzymatic access. Fermentation of the pretreated biomass yielded 73.35% ethanol [54]. Therefore, the selection of a suitable chemical pretreatment method must consider biomass type, production goals (e.g., sugar for fermentation or bioproduct manufacturing), cost, energy consumption, and environmental impacts to ensure sustainability of the process.

5. Limitations and Improvement of Pretreatment Methods

Chemical pretreatment, although highly effective in enhancing lignocellulosic biomass digestibility, presents several inherent limitations that affect its technical, economic, and environmental feasibility. One major challenge is the high operational cost, particularly when concentrated or large quantities of acids and alkalis are used. These chemicals not only increase raw material expenditures but also generate substantial waste streams that require complex management. Residual chemicals remaining in biomass such as traces of strong acids or alkalis pose environmental risks and often necessitate additional neutralization or wastewater treatment steps, further increasing processing costs.

Another critical limitation involves the formation of inhibitory compounds. Previous studies have shown that both alkali and dilute acid pretreatments produce inhibitors detrimental to enzymatic hydrolysis and microbial fermentation [55]. Alkali pretreatment typically generates higher levels of lignin-derived compounds, including phenolics and ferulic acid. In contrast, dilute acid pretreatment tends to produce sugar-derived inhibitors such as furfural (from pentoses) and hydroxymethylfurfural (HMF, from hexoses). Even at low concentrations, these inhibitors can significantly reduce enzyme activity and fermentation efficiency, negatively impacting overall bioconversion yields.

Harsh reaction conditions, including high temperature, high pressure, or excessive chemical loading, may also degrade cellulose or other valuable components of the biomass. This degradation reduces the amount of recoverable cellulose available for saccharification, ultimately lowering conversion efficiency. The energy-intensive nature of many chemical pretreatment processes further exacerbates these limitations. Techniques requiring elevated temperatures or pressures increase both energy demand and operating costs, making them economically unfavorable for large-scale applications. For example, studies on low-temperature alkaline hydrogen peroxide pretreatment demonstrated reduced energy use and lower waste generation; however, the use of chemicals such as NaOH and H_2O_2 still requires careful handling and generates waste streams that must be treated appropriately

[56]. Moreover, the relatively long reaction time limits the suitability of such processes for industrial deployment.

6. Improvements and Future Directions for Pretreatment Technologies

Addressing the limitations outlined above is essential to develop effective, economical, and environmentally responsible pretreatment systems. A key improvement strategy involves the adoption of greener chemicals such as ILs and DESs which can dissolve and fractionate lignocellulosic biomass without causing extensive cellulose or hemicellulose degradation. These solvents reduce reliance on harsh chemicals and offer potential advantages in terms of recyclability and reduced inhibitor formation, thereby directly mitigating challenges associated with conventional chemical pretreatments.

Improving waste management through solvent recycling and energy recovery is another critical direction. Designing pretreatment systems that allow efficient chemical reuse can substantially reduce both operational and environmental costs. Integrated biorefinery approaches, such as recovering energy from byproducts or valorizing lignin into high-value chemicals, can further improve economic feasibility while minimizing waste.

Advances in low-energy pretreatment technologies also offer promising solutions. Methods that operate under ambient or near-ambient conditions, without requiring high temperatures or pressures, can significantly reduce energy consumption. For instance, low-pressure separation techniques or low-energy catalytic systems help maintain pretreatment effectiveness while improving overall sustainability.

Additionally, ensuring the long-term quality and safety of biomass-derived products requires thorough evaluation of chemical residues and potential contaminants. Future research should prioritize pretreatment strategies that balance efficiency with environmental integrity, minimize the formation of inhibitory compounds, and ensure compatibility with downstream enzymatic and fermentation processes. Developing scalable, cost-effective, and environmentally sound pretreatment technologies will be essential to advancing lignocellulosic bioenergy and bioproduct industries.

7. Conclusion

The utilization of agricultural waste for bioenergy production plays a crucial role in promoting a circular economy and reducing environmental impacts. These alternative energy sources reduce dependence on fossil fuels, lower greenhouse gas emissions, and add value to waste materials while minimizing pollution from open burning. In the conversion of lignocellulosic biomass, material preparation and pretreatment are essential for breaking down rigid lignin structures. Methods such as acid or alkali treatment and high-pressure steam are used to disrupt the biomass matrix, improving hydrolysis efficiency. Although pretreatment can be costly and may cause issues like pseudo-lignin formation, ongoing advancements aim to enhance conversion efficiency. Integrating the biorefinery concept further increases the value of biomass by enabling the co-production of bioenergy, biochemicals, and biomaterials. This supports efficient resource use, reduces fossil fuel reliance, and contributes to greenhouse gas mitigation in a sustainable and economically viable way.

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