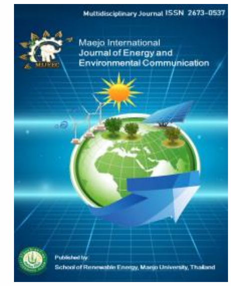
Maejo International Journal of Energy and Environmental Communication

Journal homepage: https://ph02.tci-thaijo.org/index.php/MIJEEC



ARTICLE

Sustainable management of rice straw addressing burning issues and harnessing bioethanol potential

Warangkhana Khaodee[1], Panupat Chaiworn[2,*]

[1]Department of Chemistry, Faculty of Science and Technology, Chiang Mai Rajabhat University, Chiang Mai 50300, Thailand
[2]Department of Physics and General Science, Faculty of Science and Technology, Chiang Mai Rajabhat University, Chiang Mai 50300, Thailand

ARTICLEINFO

Article history:
Received 24 October 2023
Received in revised form
21 November 2023
Accepted 24 November 2023

Keywords:
Lignocellulosic Biomass
Agricultural Residues
Rice Straw Management
Environmental Impact
Bioethanol Production

ABSTRACT

Asian rice feeds half the world and produces hundreds of millions of tons of rice straw. Farms burning rice straw in open fields release harmful chemicals and greenhouse gases, impair soil quality, and affect health. No viable alternatives make open-field burning bans difficult to enforce. Rice straw bioethanol could replace fossil fuels and greenhouse gases. Optimizing bioethanol production requires pretreatment, hydrolysis, fermentation, and distillation. Chemically, rice straw offers bioenergy and industrial potential. Bioconversion and animal feed are conceivable due to their high dry matter (93.23%) and crude protein (27.13%). Its 35.10% crude fiber and 69.10% neutral detergent fiber indicate high cellulose and hemicellulose content, making it ideal for biofuel production. Enzymatic hydrolysis is aided by low acid detergent lignin (4.27%) but hampered by high silica (11.20%). Multiple pretreatment methods were investigated to improve enzymatic digestibility. Grinding and steam explosion enhanced lignocellulosic surface area. NaOH and H_2SO_4 stripped lignin and hemicellulose to reveal cellulose. The highest fermentable sugar concentrations after enzymatic hydrolysis were from alkali-steam explosion pretreatment. *Saccharomyces cerevisiae* fermentation produced the maximum ethanol from combination pretreatment. Steam-exploded straw yielded 25.8 g/L, alkali- and acid-treated 30 g/L, and alkali-steam explosion 35 g/L. This study found that rice straw's sustainable bioethanol potential benefits the environment and economy. More research should optimize pretreatment and fermentation to scale up and profit from bioethanol.

1. Introduction

Rice is a vital staple grain that nourishes more than half of the world's population. Asia, which accounts for almost 90% of global rice production, has substantial difficulties managing rice straw, the leftover biomass from harvesting the grain (Kumar et al., 2013). Every year, rice farming produces enormous amounts of rice straw, totaling hundreds of millions of tons globally. Properly handling and managing this waste has become a crucial concern, requiring effective and environmentally friendly approaches (Bhatt et al., 2023). Historically, rice straw has been handled by burning it in open fields, a method that has been widely used in agriculture due to its simplicity and cost efficiency. Farmers sometimes use incinerating

* Corresponding author.
E-mail address: Panupat_cha@g.cmru.ac.th (Chaiworn P.)

rice straws to swiftly clear their fields in preparation for the upcoming planting season, therefore circumventing the arduous and time-consuming task of manually removing the straw. Nevertheless, this approach has significant environmental and health risks, leading to an increasing demand for alternate management strategies.

The act of burning rice straw in open fields has significant and wide-ranging environmental and health consequences. The prompt emission of particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NOx), and volatile organic compounds (VOCs) into the atmosphere deteriorates air quality, leading to the formation of smog and causing respiratory problems in impacted populations. In addition, the burning of rice straw emits substantial amounts of greenhouse gases (GHGs), specifically carbon dioxide (CO_2) and methane (CH_4), which contribute to the intensification of global warming and climate change (Kaushal & Prashar, 2021). The environmental influence also affects the health of the soil. Repeated incineration of rice straw results in the depletion of precious organic matter and vital nutrients in the soil, ultimately causing a decline in soil fertility (Anand et al., 2023). This loss can negatively impact agricultural productivity in the long run, leading to a harmful cycle of reliance on chemical fertilizers to sustain yields.

Public health concerns due to the harmful emissions from burning rice straw, particularly in young and elderly populations, have led to restrictions in several countries. However, implementing sustainable methods remains challenging due to a lack of practical options and support (Ali et al., 2020). Governments and institutions are promoting alternative management solutions through research, subsidies, and technical support. These include integrating rice straw into soil, composting, and transforming it into animal feed. However, these methods have unique challenges, such as pest and disease control, optimal composting conditions, and the production of bioethanol, a sustainable energy resource derived from rice straw (Hassan et al., 2021).

The EU's bioenergy sector is the primary source of renewable energy, with solid biofuels accounting for 68.4% of the total. Bioethanol production primarily uses cereal components like corn and sugarcane (Nguyen et al. 2020a; Unpaprom et al., 2019). Biofuels can reduce greenhouse gas emissions by up to 95% compared to fossil fuels, aligning with UN targets. Rice straw, a significant source of agricultural waste, can be converted into bioethanol, a clean fuel alternative to gasoline (Hassan et al., 2021). The process involves pretreatment, hydrolysis, fermentation, and distillation to transform rice straw into sugars (Khammee et al. 2021; Nguyen et al. 2020b; Vu et al., 2018). The process reduces CO_2 emissions from automobile engines and promotes energy security and environmental sustainability. The use of rice straw for bioethanol production also helps reduce greenhouse gas emissions, as the carbon dioxide released during combustion is balanced by the carbon dioxide absorbed by rice plants.

Lignocellulosic biomass-derived bioethanol is gaining worldwide recognition as a viable energy option for achieving a sustainable energy society (Nguyen et al. 2022). It effectively tackles issues such as the depletion of fossil fuels, global warming, and the conservation of natural resources (Bhuyar et al., 2021; Junluthin et al., 2021). Lignocellulosic biomass is derived from agricultural, forestry, and industrial waste. The high cellulose and hemicellulose content of rice straw makes it a favorable feedstock for the generation of bioethanol. Despite significant research efforts, the commercialization of ethanol production from rice straw is impeded by the exorbitant expenses associated with the collection, preservation, processing, and fermentation systems (Harun et al., 2022). An urgent need exists to develop a highly efficient ethanol production system utilizing plentiful biomass, such as rice straw, in order to provide a new and sustainable energy source. The structure of rice straw is heterogeneous and complicated, characterized by rigid cellulose fibers arranged in a crystalline structure, together with intertwined lignin and hemicellulose.

Pretreatment via physical and/or chemical means is essential in the bioconversion of lignocellulose to ethanol (Ratchawet & Chaiworn, 2022). This process is important to disrupt the robust structure of lignocellulose and facilitate the production of fermentable sugars by the action of biocatalysts such as cellulase, xylanase, and ligninase (Pradechboon & Junluthin, 2022). Several physical treatments encompass steaming, steam explosion, grinding, milling, and irradiation. Chemical therapies encompass alkali, acid, and ammonia treatments. Among these options, alkali treatments using NaOH, KOH, CaOH, and Na_2CO_3 are the most efficient. These treatments break the ester bonds between lignin, hemicellulose, and cellulose, removing lignin and a portion of the hemicellulose (Junluthin et al., 2022; Manmai et al., 2021; Saetang & Tipnee, 2022). Consequently, the cellulose fibers expand and establish enhanced interaction with cellulose.

Enzymatic hydrolysis plays a vital role in the bioethanol manufacturing process following pretreatment (Bhuyar et al., 2022). A large range of hydrolysis enzyme reagents are available globally, and each pre-treated biomass requires specialized reagents that are appropriate for efficient hydrolysis (Kongchan et al., 2022). Nevertheless, a limited number of research have effectively optimized the selection of reagents as well as the estimation of the mixing ratio (Manmai et al., 2019). The task of choosing the right cellulase is difficult because of the variations in structure among different biomass sources and the inconsistent enzymatic capabilities of commercially available cellulase reagents (Manmai et al., 2022). Efficient ethanol production from lignocellulosic biomass, such as rice straw, requires the use of microbes that can ferment xylose due to its high presence in the biomass. These strains can release cellulase enzymes (namely endo-β-glucanase, cellobiohydrolase, and β-glucosidase) and xylanase enzymes (specifically endo-β-xylanase and β-xylosidase) while directly metabolizing polysaccharides. In addition, they exhibit tolerance towards fermentation inhibitors such as furfural and 5-HMF that are generated during pretreatment at high temperatures and pressures (Harun et al., 2022).

A portion of the rice straw is utilized as livestock feed, while the remaining portion is incinerated in the field, leading to an escalation in air pollution. The process of producing bioethanol from rice straw includes pretreatment, enzymatic hydrolysis, and fermentation. In the process of bioethanol manufacturing, cellulosic material derived from agricultural leftovers is gathered from the field and then transported to the plant for further processing. Alkaline chemical pretreatment techniques are employed to extract bioethanol from rice straw, improving its manufacturing potential (Sahu et al., 2022).

Hence, the management of rice straws is a crucial concern in the realm of sustainable agriculture and environmental preservation. The harmful effects of open field burning require investigating and implementing alternate management measures. Out of these options, manufacturing bioethanol from rice straw is a particular approach with physical, chemical, and combination treatments noteworthy as a viable solution that can tackle waste management problems while also contributing to the creation of renewable energy.

2. Material and methods

2.1 Rice straw collection and preparation

Rice straw was obtained from paddy fields situated in Agronomy, Maejo University, Chiang Mai, Thailand, where it was gathered during the summer. The rice straw that was gathered was dried in the open air to decrease the amount of moisture it contained. It was then cut by hand into little pieces that were about 5 cm long. This was done to make it easier to process the straw later on. The processed rice straw was kept in a dry and cool location until it was needed for future use.

2.2 Rice straw pretreatment

In order to improve the process of breaking down rice straw using enzymes, many pretreatment techniques were assessed. These approaches included physical, chemical, and combination treatments. The subsequent pre-treatment techniques were employed: The rice straw was pulverized using a hammer mill to decrease particle size and enhance the surface area accessible for enzyme activity. The rice straw underwent steam explosion treatment at a temperature of 200°C for a duration of 5 minutes, after which rapid decompression was used to disrupt the lignocellulosic structure.

Chemical Pretreatment: Alkali Treatment: Rice straw was immersed in a 2% NaOH solution at a temperature of 90°C for a duration of 2 hours. Subsequently, the straw that had undergone treatment was cleansed using distilled water in order to balance the pH level and eliminate any remaining contaminants. The rice straw underwent acid treatment by subjecting it to a 1% H_2SO_4 solution at a temperature of 120°C for a duration of 1 hour. Subsequently, the straw was extensively rinsed with distilled water to eliminate any remaining traces of acid. Alkali-Steam Explosion: Initially, rice straw underwent treatment with a 2% NaOH solution, as previously mentioned. Subsequently, it was subjected to steam explosion using identical parameters.

2.3 Enzymatic hydrolysis

The rice straw that had been treated beforehand was exposed to enzymatic hydrolysis using a commercially available cellulase enzyme mixture (Celluclast 1.5L, Novozyme) in order to transform cellulose and hemicellulose into sugars that can be fermented. The hydrolysis process was carried out in 250 mL Erlenmeyer flasks, each containing 5 grams of pretreatment rice straw, 50 milliliters of 50 millimolar citrate buffer with a pH of 4.8, and 20 filter paper units per gram of enzyme. The flasks were placed in a shaking incubator and subjected to a temperature of 50°C and a rotation speed of 150 rpm for a duration of 72 hours. Regularly spaced samples were collected to quantify the quantity of reducing sugars using the dinitrosalicylic acid (DNS) technique (Miller, 1972).

2.4 Fermentation

The rice straw slurry, which had been broken down by hydrolysis and contained sugars that could be fermented, was used for fermentation with the yeast *Saccharomyces cerevisiae*. The fermentation process was conducted in 250 mL Erlenmeyer flasks with a working volume of 100 mL. The flasks contained the hydrolysate, which was enriched with yeast extract (0.5%), peptone (1%), and ammonium sulfate (0.1%). The pH was initially set to 5.0, and the flasks were then contaminated with an active yeast culture. The fermentation process was carried out at a temperature of 30°C, with agitation at a speed of 150 revolutions per minute, for a duration of 48 hours. The ethanol percentage in the fermentation broth was quantified.

2.5 Analytical techniques

The moisture content of rice straw was assessed by subjecting samples to a drying process in an oven at a temperature of 105°C until a stable weight was obtained. The DNS method was utilized to determine the concentration of reducing sugars during hydrolysis, with glucose serving as the reference standard. Both the ethanol levels and sugar content were quantified. Next, employ an ebulliometer to approximate the quantity of ethanol produced (Vu et al., 2018; Khammee et al., 2021; Ratchawet & Chaiworn, 2022). The phenol-sulfuric acid and DNS standard methods were used to analyze total sugar and reducing sugar, respectively, following the protocols established by Miller (1959) and Dubois et al. (1956).

2.6 Statistical analysis

The studies were performed three times, and the findings were presented as the average value plus or minus the standard deviation. The statistical analysis was conducted using the SPSS program, and significance was evaluated at a threshold of $p < 0.05$.

3. Results and discussion

3.1 Rice straw's chemical composition and its implications for industrial use

The chemical composition of rice straw provides valuable insights into its potential for bioenergy production and other industrial uses (Singh & Patel, 2022). With a high dry matter content of 93.23%, rice straw is predominantly organic, making it an excellent candidate for bioconversion processes (Table 1). Its notable crude protein content of 27.13%, unusually high for agricultural residues, also positions it as a beneficial source of protein for animal feed, in addition to its bioenergy applications. Rice straw's substantial amounts of crude fiber (35.10%) and neutral detergent fiber (69.10%) indicate significant levels of cellulose and hemicellulose, key targets for enzymatic hydrolysis in biofuel production. The presence of acid-detergent fiber (42.97%) and a relatively low level of acid-detergent lignin (4.27%) further suggest that rice straw has less lignin to impede enzymatic access to cellulose, enhancing its suitability for ethanol production.

The composition also includes a noteworthy silica content of 11.20%, which poses challenges in handling and processing due to its abrasive nature, potentially impacting mechanical processing equipment. The ash content, at 12.10%, hints at substantial mineral content, which could influence combustion properties when used as fuel. The levels of calcium (0.935%), phosphorus (0.105%), sodium (0.20%), and potassium (2.60%) in rice straw. These characteristics underline rice straw's adaptability for diverse applications, including sustainable agricultural practices and bioenergy production. Continued research aimed at optimizing the conversion processes for rice straw could maximize its utility, fostering more sustainable and economically viable applications (Das et al., 2023). This could facilitate a shift towards more circular and environmentally conscious economic practices, leveraging rice straw as a key resource in various sectors.

Table 1 Chemical composition of rice straw

Component	Value (%)
Dry matter (DM)	93.23± 0.12
Crude protein (CP)	27.13± 0.05
Crude fiber	35.10± 0.17
Neutral detergent fiber (NDF)	69.10± 0.05
Acid detergent fiber (ADF)	42.97± 0.07
Acid detergent lignin (ADL)	4.27 ± 0.21
Extractable biogenic silica (EBSi)	11.20± 0.03
Ash	12.10± 0.29
Calcium (Ca)	0.935 ± 0.14
Phosphorus (P)	0.105 ± 0.08
Sodium (Na)	0.20± 0.11
Potassium (K)	2.60± 0.03

3.2 Evaluation of the effectiveness of pretreatment

An assessment was conducted to determine the efficacy of several pretreatment techniques in improving the enzymatic digestibility of rice straw by disrupting its intricate lignocellulosic structure. Pretreatment is an essential stage in the bioconversion process, as it facilitates the decomposition of the inflexible composition of lignocellulosic biomass, hence enhancing the accessibility of cellulose and hemicellulose for enzymatic hydrolysis.

3.2.1 Physical preprocessing

Utilizing a hammer mill to grind the rice straw properly reduced particle size, enhancing the surface area accessible for enzymatic activity. Merely employing this mechanical procedure proved inadequate in effectively dismantling the lignin structure, which serves as a shield for the cellulose and hemicellulose (Kumari & Singh, 2022). Grinding is an uncomplicated and economical pretreatment technique that primarily seeks to enhance the surface area of the biomass without causing major changes to the chemical composition of the lignocellulosic matrix. The steam explosion technique includes exposing rice straw to high-pressure steam and then quickly releasing the pressure. The procedure was carried out at a temperature of 200°C for a duration of 5 minutes. The abrupt decrease in pressure resulted in a tangible disturbance of the lignocellulosic framework, rendering cellulose and hemicellulose more readily available to enzymes. The pretreatment method proved to be more efficient than grinding alone, as demonstrated by the higher production of reducing sugars during the subsequent enzymatic hydrolysis process (Unpaprom et al., 2019). The steam explosion technique is commonly employed as a pretreatment method, which efficiently breaks down the lignin structure and improves the ability of enzymes to break down the biomass.

3.2.2 Chemical pretreatment

The rice straw underwent an alkali treatment by immersing it in a 2% NaOH solution at a temperature of 90°C for a duration of 2 hours. The application of this treatment led to significant dissolution of lignin and enhanced cellulose accessibility. Washing the sample with distilled water after treatment was necessary to balance the pH and eliminate any remaining compounds that might hinder the activity of enzymes. The efficacy of alkali treatment was demonstrated by the increased hydrolysis yields compared to untreated straw (Harun et al., 2022). The application of alkali treatment is highly efficient in cleaving ester bonds present in lignin and hemicellulose, eliminating lignin and hemicellulose. Consequently, this process enhances the accessibility of cellulose for enzymatic hydrolysis.

Acid Treatment: In this procedure, rice straw underwent treatment with a 1% concentration of H_2SO_4 at a temperature of 120°C for a duration of 1 hour. The acid hydrolysis process mainly focused on hemicellulose, breaking it down into sugars that can be fermented and partially eliminating lignin. It was required to be thoroughly washed after treatment in order to remove acid residues and prevent the inhibition of following enzymatic operations (Sahu et al., 2022). Although acid treatment is successful, it necessitates cautious handling because of the caustic properties of sulfuric acid. The application of acid treatment successfully breaks down hemicellulose into xylose and other sugars. However, it can also create inhibitory substances, such as HMF, impacting the fermentation procedure.

3.2.3 Pretreatment combination

The alkali-steam explosion method consists of treating the substance with a 2% NaOH solution at 90°C for 2 hours and then subjecting it to steam at 200°C for 5 minutes. The combined effect of chemical and physical disruption led to the greatest improvement in cellulose accessibility compared to all other investigated approaches (Chandrasiri et al., 2022). Combining these pretreatment methods resulted in the largest production of fermentable sugars during the enzymatic hydrolysis process, demonstrating its superior effectiveness. Combining alkali treatment with a steam explosion is advantageous to achieve a more efficient breakdown of the lignocellulosic structure and improve the effectiveness of enzymatic hydrolysis. This collaborative approach enhances the advantages of both strategies. The efficacy of several pretreatment methods on rice straw is delineated in Table 2.

Table 2 Efficacy of different pretreatment methods on rice straw

Pretreatment method	Description	Process conditions	Expected impact on lignocellulose	Resulting sugar yield increase
Physical Pretreatment				
Grinding	Mechanical reduction of particle size using a hammer mill.	Ambient conditions, variable time.	Increases surface area for enzyme action does not significantly alter chemical structure.	Moderate
Steam Explosion	High-pressure steam treatment followed by rapid decompression.	200°C for 5 minutes.	Physically disrupts the structure, enhancing enzyme access to cellulose and hemicellulose.	High
Chemical pretreatment				
Alkali Treatment	Soaking in NaOH solution to solubilize lignin.	2% NaOH at 90°C for 2 hours.	Removes lignin and breaks ester bonds, increasing cellulose accessibility.	Very High
Acid Treatment	Treatment with sulfuric acid to hydrolyze hemicellulose.	1% H2SO4 at 120°C for 1 hour.	Targets hemicellulose, producing fermentable sugars and partially removing lignin.	High
Combined pretreatment				
Alkali-Steam Explosion	Combination of alkali treatment and steam explosion.	2% NaOH at 90°C for 2 hours, followed by 200°C steam for 5 minutes.	Maximizes disruption of lignocellulosic matrix, enhancing overall enzymatic digestibility.	Highest

Table 3 Reducing sugar yields from enzymatic hydrolysis of pretreated rice straw

Pretreatment method	Reducing sugar yield (g/L)	Hydrolysis conditions
Physical Pretreatment	85	Steam explosion; 50°C, 150 rpm, 72 hours, 20 FPU/g enzyme
Chemical Pretreatment	Alkali: 100 Acid: 90	Alkali (NaOH); Acid (H2SO4); 50°C, 150 rpm, 72 hours, 20 FPU/g enzyme
Combined Pretreatment	110	Alkali + Steam explosion; 50°C, 150 rpm, 72 hours, 20 FPU/g enzyme

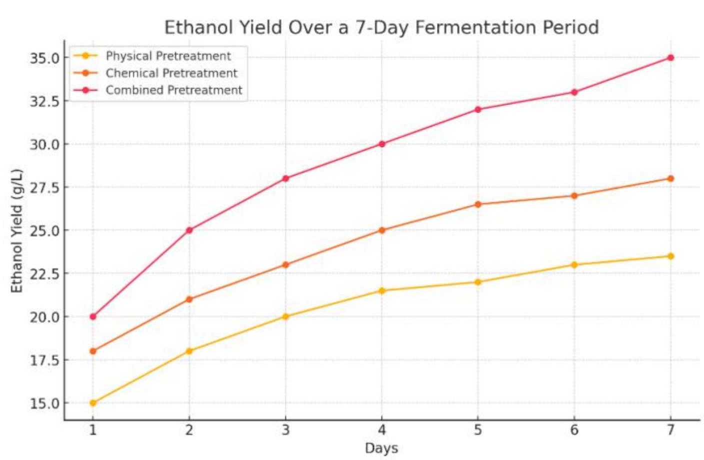


Figure 1 Ethanol production from the rice straw with different pretreatments

3.3 Enzymatic hydrolysis

After being pretreated, a commercial cellulase enzyme mixture was used to hydrolyze the rice straw enzymatically. In order to transform cellulose and hemicellulose into fermentable sugars, the hydrolysis process was optimized. An essential stage in the bioconversion process is enzymatic hydrolysis, which transforms the biomass that has been pretreated into simple sugars that may be fermented to produce ethanol (Pradechboon & Junluthin, 2022). 250 mL Erlenmeyer flasks containing 5 g of rice straw that had been prepared, 50 mL of 50 mM citrate buffer (pH 4.8), and 20 FPU/g of enzyme were used to carry out the reaction. For 72 hours, the flasks were kept in a shaking incubator set at 50°C and 150 rpm. The dinitrosalicylic acid (DNS) method was used to quantify the concentration of reducing sugars in samples obtained at regular intervals. Different reducing sugar yields were obtained depending on the pretreatment technique (Ratchawet & Chaiworn, 2022). Reducing sugar yields from enzymatic hydrolysis of pretreated rice straw are shown in Table 3.

Physical Pretreatment: At a high concentration of 85 g/L, the hydrolysates from steam-exploded straw displayed moderate yields of reducing sugars. Chemical Pretreatment: Alkali-treated straw hydrolysates showed greater sugar yields than acid-treated straw at maximal concentrations of 100 g/L and 90 g/L, respectively. Higher sugar yields were a result of the alkali treatment's ability to remove lignin and increase cellulose accessibility effectively. Significant sugar yields were also obtained by acid treatment, but handling was necessary due to inhibitory chemicals. Combined Pretreatment: With a peak concentration of 110 g/L, the alkali-steam explosion approach produced the largest output of reducing sugars. The combination pretreatment efficiently disturbed the lignocellulosic matrix, leading to the maximum sugar yields and enzymatic hydrolysis efficiency. These findings emphasize the significance of pretreatment in promoting rice straw enzymatic hydrolysis, with the combined alkali-steam explosion approach exhibiting the highest efficacy. The total yield of fermentable sugars and the effectiveness of enzymatic hydrolysis are strongly impacted by the selected pretreatment technique.

3.4 Fermentation Performance

S. cerevisiae was used to ferment the sugars that could be fermented after enzymatic hydrolysis. This stage involves yeast and other microbes converting simple carbohydrates into ethanol, which is essential to bioethanol synthesis (Junluthin et al., 2022; Manmai et al., 2021; Saetang & Tipnee, 2022). The total ethanol yield and production efficiency are strongly impacted by this process' efficacy. The hydrolysate was placed in 250 mL Erlenmeyer flasks with a 100 mL working volume and allowed to ferment. As supplements, 0.5% yeast extract, 1% peptone, and 0.1% ammonium sulfate were added to this medium. The pH was first changed to 5.0. An active yeast culture was added to the flasks, and they were then incubated at 30°C with 150 rpm of shaking, then determined the ethanol in the fermentation broth 48 hours later (Figure 1).

Physical Pretreatment: Moderate ethanol yields were seen in the hydrolysates obtained from the physically processed straw (grinding and steam explosion). The performance of steam-exploded straw was significantly higher, with a peak ethanol concentration of 25.8 g/L. Compared to grinding alone, this approach boosted the hydrolysates' fermentability, which raised the ethanol yields because of the greater accessibility of the substrate.

Chemical Pretreatment: The ethanol concentrations in the hydrolysates of straw treated with alkali were higher than those treated with acid, peaking at 30 g/L. Increased cellulose accessibility and more efficient lignin removal are responsible for the alkali treatment's superior efficiency, allowing for a higher sugar conversion to ethanol. Significant ethanol yields were also obtained via acid treatment, but handling was necessary to lessen the impact of inhibitory chemicals.

Combined Pretreatment: Hydrolysates from straw processed with steam explosion and alkali showed the highest percentage of ethanol, peaking at 35 g/L. The simultaneous application of chemical and physical pretreatment in this process optimized the availability of sugar and the effectiveness of enzymatic hydrolysis, resulting in increased ethanol production.

In order to assess the fermentation's sustainability over an extended duration, the experiment was prolonged to a duration of seven days. Under the identical fermentation conditions mentioned above, ethanol concentrations were routinely checked. This comprehensive evaluation aids in comprehending the kinetic behaviour of yeast and the possibility of long-term, continuous ethanol generation. Finding the best pretreatment technique and fermentation conditions to maximize ethanol yield depends on these observations' outcomes, which are critical for optimizing the bioethanol production process. Gaining such insights is essential to increasing production in a business setting.

3.5 Effective Rice Straw Management for Sustainability

This study emphasizes the importance of efficient pretreatment in maximizing the hydrolysis and fermentation processes to generate bioethanol from rice straw. The combined alkali-steam explosion pretreatment showed the highest efficiency of the procedures examined. It greatly increased the number of fermentable sugars and hence improved ethanol output. Using rice straw to produce bioethanol provides significant advantages for the environment and the economy, a similar concept to Alengebawy et al. (2023). This method helps to reduce the negative environmental effects linked to open-field burning, such as air pollution and the release of greenhouse gases. Additionally, it offers a sustainable energy option that can decrease dependence on fossil fuels. The findings affirm the viability of bioethanol production as a sustainable approach to managing rice straw, in line with the goals of sustainable agriculture and the advancement of renewable energy (Sharma et al., 2020). The open-field burning of rice straw is prevalent in several rice-producing areas since it is straightforward and economically efficient. Nevertheless, this practice has notable environmental and health consequences, including air pollution, emissions of greenhouse gases, and respiratory ailments (Singh et al., 2021; Parihar et al., 2023). Transforming rice straw into bioethanol presents a sustainable substitute for burning rice straw in open fields. This process offers a useful energy source while also diminishing environmental damage.

Adopting sustainable management approaches, such as producing bioethanol from rice straw, effectively tackles the urgent problems of environmental degradation and public health hazards caused by conventional open-field burning. This method enhances environmental well-being and offers farmers financial benefits by transforming agricultural waste into a viable energy source (Sain, 2020; Zaidi, 2021). Bioethanol production from rice straw has several environmental advantages, such as decreased greenhouse gas emissions, enhanced air quality, and improved soil health. The economic advantages encompass the generation of fresh sources of income for farmers, the establishment of novel sectors, and the stimulation of rural progress. The advantages of producing bioethanol from rice straw make it a compelling and environmentally friendly substitute for conventional waste management methods.

The utilization of rice straw for bioethanol production taps into the considerable potential of this plentiful agricultural residue as a viable source of feedstock for bioenergy. This approach facilitates decreasing greenhouse gas emissions, enhances energy security, and fosters rural development by generating novel economic prospects. Bioethanol is an environmentally friendly and renewable energy source that can help decrease reliance on fossil fuels and mitigate greenhouse gas emissions. Utilizing bioethanol as a fuel for transportation can effectively address climate change and enhance air quality (Illankoon et al., 2023). Using rice straw for bioethanol production facilitates the advancement of a circular economy, wherein agricultural waste is transformed into valuable commodities, diminishing waste and augmenting resource efficacy (Jiradechakorn et al., 2023; Saini et al., 2023). The key points of the sustainable management of rice straw for bioethanol production are shown in Table 4.

Table 4 Key points of the sustainable management of rice straw for bioethanol production

Aspect	Details
Pretreatment Efficiency	Combined alkali-steam explosion pretreatment exhibited the highest efficiency in hydrolysis and fermentation processes.
Environmental Benefits	Reduces air pollution and greenhouse gas emissions from open-field burning.
	Enhances soil health and promotes a circular economy by converting agricultural waste into valuable products.
Economic Benefits	Creates new revenue streams for farmers.
	Promotes rural development through the creation of new industries.
Health Benefits	Reduces respiratory diseases caused by air pollution from open-field burning.
Sustainable Agriculture	Aligns with the objectives of sustainable agriculture by managing agricultural waste effectively.
Renewable Energy Source	Provides a renewable energy source, reducing reliance on fossil fuels.
Climate Change Mitigation	Contributes to the reduction of greenhouse gas emissions and mitigates climate change.
Energy Security	Promotes energy security by providing a sustainable and renewable energy source.
Circular Economy	Supports the development of a circular economy by converting rice straw into bioethanol, thus reducing waste and enhancing resource efficiency.
Bioethanol as Transportation Fuel	Use of bioethanol as a transportation fuel improves air quality and reduces dependence on fossil fuels.
Environmental and Economic Incentives	Provides incentives for farmers to adopt sustainable practices by converting waste into valuable energy resources, thus addressing environmental degradation and public health risks.

This table highlights the multifaceted benefits of bioethanol production from rice straw, emphasizing its role in sustainable agriculture, environmental protection, economic development, and renewable energy promotion.

3.6 Challenges and future directions

Bioethanol production's scalability and economic feasibility from rice straws need further investigation. Future research should optimize pretreatment conditions, improve enzyme efficiency, and develop cost-effective fermentation processes (Wang et al., 2023). Additionally, integrating advanced biotechnological approaches, such as genetic engineering of microorganisms for enhanced fermentation efficiency, could further improve bioethanol yields. The scalability of bioethanol production from rice straw is a significant challenge, as it requires large-scale infrastructure and investment (Aziz et al., 2023). The economic feasibility of the process depends on the availability of low-cost feedstock, efficient pretreatment and hydrolysis processes, and favourable market conditions for bioethanol. Future research should address these challenges to make bioethanol production from rice straw commercially viable.

4. Conclusion

This study demonstrates the potential of using rice straw for bioethanol production through effective pretreatment, enzymatic hydrolysis, and fermentation. The combined alkali-steam explosion pretreatment method proved the most effective, yielding fermentable sugars and ethanol concentrations. Rice straw is a viable bioenergy and industrial material due to its high dry matter, crude protein concentration, cellulose and hemicellulose, and low lignin content. Grinding, steam explosion, and NaOH and H_2SO4 pretreatment have been tested to improve enzymatic digestibility. The alkali-steam explosion approach produced the highest fermentable sugar concentrations during enzymatic hydrolysis. Saccharomyces cerevisiae fermentation yielded the most ethanol from this combination pretreatment, reaching 35 g/L. Rice straw can be a sustainable bioethanol source with environmental and economic benefits. Rice straw bioethanol reduces greenhouse gas emissions, improves soil health, and generates additional cash for farmers. Bioethanol production is difficult to scale up and make profitable. Optimizing pretreatment and fermentation, boosting enzyme efficiency, and incorporating sophisticated biotechnological techniques should be future studies. These hurdles must be overcome to maximize bioethanol production and ensure economic viability, promoting sustainable agriculture and energy. Implementing this technology can reduce greenhouse gas emissions, promote energy security, and support rural development, making it an attractive and sustainable alternative to traditional waste management practices.

Acknowledgement

The authors gratefully appreciate the gratitude is also extended to the Agronomy division, Faculty of Agriculture

Production, Maejo University, for providing the rice straw and Faculty of Science and Technology, Chiang Mai Rajabhat University, Chiang Mai 50300, Thailand research facilities support.

References

Alengebawy, A., Ran, Y., Ghimire, N., Osman, A. I., & Ai, P. (2023). Rice straw for energy and value-added products in China: a review. Environmental Chemistry Letters, 21(5), 2729-2760.

Ali, W., Mao, K., Zhang, H., Junaid, M., Xu, N., Rasool, A., Feng, X., & Yang, Z. (2020). Comprehensive review of the basic chemical behaviours, sources, processes, and endpoints of trace element contamination in paddy soil-rice systems in rice-growing countries. Journal of hazardous materials, 397, 122720.

Anand, A., Gautam, S., & Ram, L. C. (2023). Feedstock and pyrolysis conditions affect suitability of biochar for various sustainable energy and environmental applications. Journal of Analytical and Applied Pyrolysis, 170, 105881.

Aziz, T., Shah, Z., Sarwar, A., Ullah, N., Khan, A. A., Sameeh, M. Y., Haiying, C., & Lin, L. (2023). Production of bioethanol from pretreated rice straw, an integrated and mediated upstream fermentation process. Biomass Conversion and Biorefinery, 1-11.

Bhatt, R., Paul, T., Singh, P. K., Tomar, G., Rai, D., Raghavan, M., Tiwari, A., & Tiwari, H. (2023). Crop Residue Management Options in Rice-Wheat Cropping Systems: A Case Study of the Indian Experience. International Journal of Plant & Soil Science, 35(23), 510-520.

Bhuyar, P., Trejo, M., Dussadee, N., Unpaprom, Y., Ramaraj, R., & Whangchai, K. (2021). Microalgae cultivation in wastewater effluent from tilapia culture pond for enhanced bioethanol production. Water Science and Technology, 84(10-11), 2686-2694.

Bhuyar, P., Trejo, M., Mishra, P., Unpaprom, Y., Velu, G., & Ramaraj, R. (2022). Advancements of fermentable sugar yield by pretreatment and steam explosion during enzymatic saccharification of Amorphophallus sp. starchy tuber for bioethanol production. Fuel, 323, 124406.

Chandrasiri, Y. S., Weerasinghe, W. M. L. I., Madusanka, D. T., & Manage, P. M. (2022). Waste-based second-generation bioethanol: a solution for future energy crisis. International Journal of Renewable Energy Development, 11(1), 275-285.

Das, P. P., Sontakke, A. D., & Purkait, M. K. (2023). Rice straw for biofuel production. Green Approach to Alternative Fuel for a Sustainable Future, 153-166.

Dubois M, Gilles KA, Hamilton JK, Rebers PT, Smith F (1956) Colorimetric method for determination of sugars and related substances. Analytical Chemistry 28(3), 350-356.

Harun, S. N., Hanafiah, M. M., & Noor, N. M. (2022). Rice straw utilisation for bioenergy production: A brief overview. Energies, 15(15), 5542.

Hassan, M. K., Chowdhury, R., Ghosh, S., Manna, D., Pappinen, A., & Kuittinen, S. (2021). Energy and environmental impact assessment of Indian rice straw for the production of second-generation bioethanol. Sustainable Energy Technologies and Assessments, 47, 101546.

Illankoon, W. A. M. A. N., Milanese, C., Collivignarelli, M. C., & Sorlini, S. (2023, April). Value chain analysis of rice industry by products in a circular economy context: A review. In Waste (Vol. 1, No. 2, pp. 333-369). MDPI.

Jiradechakorn, T., Chuetor, S., Kirdponpattara, S., Narasingha, M., & Sriariyanun, M. (2023). Performance of combined hydrochemo-mechanical pretreatment of rice straw for bioethanol production. Energy Reports, 9, 180-185.

Junluthin, P., Pimpimol, T., & Whangchai, N. (2021). Efficient conversion of night-blooming giant water lily into bioethanol and biogas. Maejo International Journal of Energy and Environmental Communication, 3(2), 38-44.

Kaushal, L. A., & Prashar, A. (2021). Agricultural crop residue burning and its environmental impacts and potential causes–case of northwest India. Journal of Environmental Planning and Management, 64(3), 464-484.

Khammee, P., Ramaraj, R., Whangchai, N., Bhuyar, P., & Unpaprom, Y. (2021). The immobilization of yeast for fermentation of macroalgae Rhizoclonium sp. for efficient conversion into bioethanol. Biomass Conversion and Biorefinery, 11, 827-835.

Kongchan, W., Unpaprom, Y., Dussadee, N., & Ramaraj, R. (2022). Bioethanol production from low-grade konjac powder via combination of alkaline and thermal pretreatments. Maejo International Journal of Energy and Environmental Communication, 4(3), 27-31.

Kumari, D., & Singh, R. (2022). Rice straw structure changes following green pretreatment with petha wastewater for economically viable bioethanol production. Scientific Reports, 12(1), 10443.

Kumar, A., Nayak, A. K., Sharma, S., Senapati, A., Mitra, D., Mohanty, B., Prabhukarthikeyan, S. R., Sabarinathan, K. G., Indra, M. A. N. I., Garhwal, R.S., & Panneerselvam, P. (2023). Rice straw recycling: A sustainable approach for ensuring environmental quality and economic security. Pedosphere, 33(1), 34-48.

Manmai, N., Bautista, K., Unpaprom, Y., & Ramaraj, R. (2019). Optimization of combined pre-treatments on sugarcane leaves for bioethanol production. Maejo International Journal of Energy and Environmental Communication, 1(1), 30-39.

Manmai, N., Unpaprom, Y., Ramaraj, R., & Wu, K. T. (2021). Transformation of lignocellulose from corn stove for bioethanol production. Maejo International Journal of Energy and Environmental Communication, 3(1), 44-48.

Manmai, N., Balakrishnan, D., Obey, G., Ito, N., Ramaraj, R., Unpaprom, Y., & Velu, G. (2022). Alkali pretreatment method of dairy wastewater based grown *Arthrospira platensis* for enzymatic degradation and bioethanol production. Fuel, 330, 125534.

Miller, G. L. (1972). Use of DNS reagent for determination of reducing sugars. Analytical Chemistry 31, 426-428.

Nguyen, T. V. T., Unpaprom, Y., & Ramaraj, R. (2020a). Enhanced fermentable sugar production from low grade and damaged longan fruits using cellulase with algal enzymes for bioethanol production. Emergent Life Sciences Research, 6, 26-31.

Nguyen, T. V. T., Unpaprom, Y., Tandee, K., Whangchai, K., & Ramaraj, R. (2020b). Physical pretreatment and algal enzyme hydrolysis of dried low-grade and waste longan fruits to enhance its fermentable sugar production. Biomass Conversion and Biorefinery, 12, 1669–1677.

Nguyen, T. V. T., Unpaprom, Y., Manmai, N., Whangchai, K., & Ramaraj, R. (2022). Impact and significance of pretreatment on the fermentable sugar production from low-grade longan fruit wastes for bioethanol production. Biomass Conversion and Biorefinery, 12, 1605-1617.

Parihar, D. S., Narang, M. K., Dogra, B., Prakash, A., & Mahadik, A. (2023). Rice residue burning in northern India: an assessment of environmental concerns and potential solutions–a review. Environmental Research Communications, 5(6), 062001.

Pradechboon, T., & Junluthin, P. (2022). Alkali pretreatment and enzymatic saccharification of blue-green alga Nostochopsis lobatus for bioethanol production. Maejo International Journal of Energy and Environmental Communication, 4(1), 23-28.

Ratchawet, A., & Chaiworn, P. (2022). Pretreatment of barley straw with acid and alkaline solutions to boost the efficiency of fermentable yield enzymatic degradation in the separated fermentation technique for ethanol production. Maejo International Journal of Energy and Environmental Communication, 4(2), 64-69.

Saetang, N., & Tipnee, S. (2022). Influence of nanoparticles inclusion on the production of bioethanol from corn stalks and leaves. Maejo International Journal of Energy and Environmental Communication, 4(2), 23-28.

Sain, M. (2020). Production of bioplastics and sustainable packaging materials from rice straw to eradicate stubble burning: A Mini-Review. Environment Conservation Journal, 21(3), 1-5.

Saini, S., Kuhad, R. C., & Sharma, K. K. (2023). Valorization of rice straw biomass for co-production of bioethanol, biopesticide and biofertilizer following an eco-friendly biorefinery process. Process Safety and Environmental Protection, 173, 823-836.

Sahu, T. K., Sahu, V. K., Mondal, A., Shukla, P. C., Gupta, S., & Sarkar, S. (2022). Investigation of sugar extraction capability from rice paddy straw for potential use of bioethanol production towards energy security. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 44(1), 272-286.

Sharma, A., Singh, G., & Arya, S. K. (2020). Biofuel from rice straw. Journal of Cleaner Production, 277, 124101.

Singh, R., & Patel, M. (2022). Effective utilization of rice straw in value-added by-products: A systematic review of state of art and future perspectives. Biomass and Bioenergy, 159, 106411.

Singh, G., Gupta, M. K., Chaurasiya, S., Sharma, V. S., & Pimenov, D. Y. (2021). Rice straw burning: a review on its global prevalence and the sustainable alternatives for its effective mitigation. Environmental Science and Pollution Research, 28(25), 32125-32155.

Unpaprom, Y., Saetang, N., & Tipnee, S. (2019). Evaluation of mango, longan and lychee trees pruning leaves for the production of biogas via anaerobic fermentation. Maejo International Journal of Energy and Environmental Communication, 1(3), 20-26.

Vu, P. T., Unpaprom, Y., & Ramaraj, R. (2018). Impact and significance of alkaline-oxidant pretreatment on the enzymatic digestibility of *Sphenoclea zeylanica* for bioethanol production. Bioresource Technology, 247, 125-130.

Wang, J., Ma, D., Lou, Y., Ma, J., & Xing, D. (2023). Optimization of biogas production from straw wastes by different pretreatments: Progress, challenges, and prospects. Science of The Total Environment, 166992.

Zaidi, S. T. (2021). Rice Crop Residue burning and alternative measures by India: A Review. Journal of Scientific Research, 65(1), 132-137.