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Sustainable Valorization of Rice Straw for Bioethanol Production Using *Saccharomyces cerevisiae*: A Circular Bioeconomy Approach

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A B S T R A C T

The utilization of rice straw waste as a renewable feedstock for bioethanol production presents an innovative approach to sustainable agricultural waste management and green energy development. This study aimed to evaluate the conversion process of rice straw into bioethanol through four main stages: material preparation, hydrolysis, fermentation, and distillation. One kilogram of dried rice straw was used as the primary substrate, enriched with 8% molasses and 5% *Saccharomyces cerevisiae* as the fermentative inoculum. Hydrolysis was conducted by boiling for 1 hour, resulting in 32.5 g/L of reducing sugars. Fermentation was performed at ambient temperature (±30°C) for 30 days, yielding an ethanol concentration of 65% (v/v) as measured by the pycnometer method, with a sugar conversion efficiency of 78%. Distillation at 78–80°C produced 250 mL of ethanol distillate from 1500 mL of fermented broth. The results indicate that rice straw has significant potential as a bioethanol feedstock, not only as an alternative renewable energy source but also as a natural solvent for applications in industries such as perfumery. This research highlights the importance of integrated rice straw valorization in reducing environmental pollution, enhancing economic value, and promoting the transition toward a circular and sustainable agricultural economy.

Contribution to Sustainable Development Goals (SDGs):
SDG 7 – Affordable and Clean Energy
SDG 12 – Responsible Consumption and Production
SDG 13 – Climate Action
SDG 9 – Industry, Innovation, and Infrastructure

1. INTRODUCTION

1.1. Research Background

West Sumatra is one of Indonesia's primary rice-producing regions, contributing significantly to national food security. Padang Pariaman Regency, particularly Nagari Padang Toboh Ulakan, is not only recognized as a major rice cultivation area but also generates substantial agricultural waste in the form of rice straw. According to the Ministry of Agriculture [1], each hectare of rice field produces approximately 12–15 tons of straw per harvest season. With over 30,000 hectares of cultivated land, the potential generation of rice straw waste in this region can reach several hundred thousand tons annually. This enormous quantity of residual biomass presents major challenges in terms of waste management and valorization. Without proper handling, rice straw can become an environmental burden, contributing to pollution and the loss of potential economic value. Currently, the utilization of rice straw in Padang Toboh Ulakan remains minimal. A small portion is used as livestock feed, while open-field burning remains the most common disposal practice. This

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method not only wastes a valuable lignocellulosic resource but also has severe environmental consequences. The burning of rice straw releases large amounts of greenhouse gases—carbon dioxide (CO_2), carbon monoxide (CO), and methane (CH_4)—which contribute to global warming, air pollution, and respiratory health issues [2]. Moreover, open burning reduces soil fertility by depleting essential organic matter and nutrients, threatening long-term agricultural sustainability. Rice straw is primarily composed of lignocellulosic materials, including cellulose (32–47 %), hemicellulose (19–27 %), and lignin (5–24 %) [3]. This biochemical composition provides a strong foundation for its conversion into bioethanol, an environmentally friendly renewable energy source [4]. However, the high lignin content acts as a structural barrier, limiting enzymatic access to cellulose and hemicellulose during hydrolysis and fermentation. Pretreatment of the raw material is therefore essential to break down lignin, enhance sugar release, and improve bioethanol yield [5,6].

Lignin, cellulose, and hemicellulose are the main structural components of lignocellulosic biomass that can be converted into simple sugars through pretreatment and hydrolysis. These sugars can subsequently be fermented by microorganisms, such as Saccharomyces cerevisiae, to produce bioethanol. Bioethanol is a clean and renewable alternative to fossil fuels, capable of reducing dependence on conventional energy sources and lowering greenhouse gas emissions [7].

The chemical structures of cellulose, hemicellulose, and lignin determine the conversion efficiency of rice straw into fermentable sugars [8]. This composition makes rice straw a promising feedstock for bioethanol production through sequential pretreatment, hydrolysis, and fermentation processes. The development of second-generation bioethanol from agricultural residues aligns with Indonesia's national energy policy under MEMR Regulation No. 25 of 2013, which mandates the blending of fossil fuels with biofuels such as biodiesel and bioethanol. Depending on process conditions and microbial strains, rice straw can yield bioethanol concentrations ranging from 60% to 80% [3].

Bioethanol derived from lignocellulosic materials is more sustainable than first-generation bioethanol from food crops (e.g., corn or cassava), as it does not compete with food supply and supports both food and energy security [4,9]. Beyond its role as an alternative energy source, bioethanol also has diverse industrial applications in cosmetics, pharmaceuticals, and fine chemicals. Biomass-derived ethanol exhibits physicochemical properties comparable to synthetic ethanol, enabling its use as a natural solvent or raw material in value-added products. Consequently, rice straw in Nagari Padang Toboh Ulakan possesses dual economic potential—as a renewable energy source and as an industrial feedstock—creating opportunities for product diversification and local economic growth. From a socio-economic perspective, developing bioethanol from rice straw supports community empowerment and rural sustainability. Through technology transfer, training, and farmer participation, local communities can be directly engaged in bioethanol production chains, generating additional income and improving livelihoods. Such efforts contribute to the realization of a circular economy, transforming agricultural residues into valuable resources with both environmental and economic benefits. This approach is also consistent with Indonesia's green economy framework and the national renewable energy target of 23 % by 2025, as stipulated in Presidential Regulation No. 22 of 2017 on the National Energy Policy [10]. Considering the vast availability of rice straw and the challenges associated with its management, this research aims to provide a practical and sustainable solution through the conversion of rice straw waste into bioethanol. The study conducted in Nagari Padang Toboh Ulakan exemplifies how integrating science, technology, policy, and community participation can transform agricultural waste into renewable energy and economic opportunities for West Sumatra.

2. MATERIALS AND METHODS

2.1.1. Materials

The primary raw material used in this study was rice straw obtained from Nagari Padang Toboh-Ulakan, Padang Pariaman Regency, West Sumatra, Indonesia. The straw was air-dried, chopped into smaller fragments, and used as the primary substrate for bioethanol production. Molasses was employed as an additional carbon source to enhance microbial fermentation, while *Saccharomyces cerevisiae* served as the inoculum for the fermentation process. Distilled water was used throughout all experimental stages as a solvent and washing medium. The pH of the fermentation medium was adjusted within the range of 5.0–5.5 using a buffer solution to provide optimal conditions for yeast metabolism.

2.1.2. Equipment

The equipment used in this study included a mechanical stirrer, a heating apparatus, and an analytical balance (Shimadzu ATX224R) for precise weighing. Essential glassware such as Erlenmeyer flasks, pipettes, beakers, filter paper, and a desiccator were used for handling and processing samples. The fermentation and distillation systems were the core units employed to convert rice straw biomass into bioethanol. For sample preparation, a grinder (Herb Maksindo MKS-ML 2500) was used to obtain fine straw particles, while a food dehydrator (GETRA ST-02) facilitated moisture removal. Heating was conducted using a hot plate (Velp Scientifica, code F20500551), and the concentration of liquid samples was performed using a rotary evaporator (BUCHI). Ethanol purity was analyzed using a pycnometer and a densitometer.

2.1.3. Research Design and Experimental Procedure

A total of 1 kg of dried rice straw was used as the main substrate. The straw was first cleaned, chopped, and dried to a uniform moisture level. The hydrolysis process was initiated by boiling the prepared straw in distilled water for one hour to break down the cellulose and hemicellulose into fermentable sugars. The resulting hydrolysate was filtered and supplemented with 8% (v/v) molasses as an additional sugar source to support microbial activity. Subsequently, 5% (v/v) *Saccharomyces cerevisiae* inoculum was added to initiate fermentation.

The fermentation process was carried out at ambient temperature (approximately 30°C) for a period of 30 days under semi-anaerobic conditions. During this stage, yeast converted the reducing sugars present in the hydrolysate into ethanol. The progress of fermentation was monitored by measuring the sugar concentration and ethanol content at regular intervals. The ethanol yield (% v/v) was determined using the pycnometer method. In contrast, sugar consumption efficiency (%) was

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calculated based on the reduction of initial sugar levels measured as reducing sugars using the DNS method.

After completion of fermentation, the fermented broth was subjected to distillation at a temperature range of 78–80°C. This step aimed to separate and purify the ethanol produced from the fermentation mixture. The volume of the distillate was recorded, and the ethanol purity was verified using the pycnometer. The obtained bioethanol yield and conversion efficiency were calculated to evaluate the performance of the process.

This experimental design integrated four main stages—material preparation, hydrolysis, fermentation, and distillation—to assess the feasibility of rice straw as a sustainable feedstock for bioethanol production. The study emphasised process simplicity and scalability, aligning with the concept of sustainable waste valorisation and the circular bioeconomy.

3. RESULT AND DISCUSSION

3.1. Preparation of materials

Rice straw obtained from Nagari Padang Toboh-Ulakan was thoroughly cleaned to remove impurities, air-dried, and finely chopped to improve the accessibility of cellulose and hemicellulose during subsequent processing. Pretreatment is a critical initial step in converting rice straw into bioethanol, as it facilitates the hydrolysis and fermentation processes [5,6]. The presence of lignin in rice straw can hinder acid penetration during hydrolysis and inhibit microbial growth during fermentation; therefore, partial lignin removal (delignification) is essential to enhance cellulose accessibility [6,9].

3.1.1. Hydrolysis

Hydrolysis of rice straw was performed by mixing 1 kg of the dried material with 3000 mL of water, boiling for 1 hour, and then cooling to room temperature. Hydrolysis decomposes complex carbohydrates (cellulose and hemicellulose) into fermentable sugars. Dilute acid or mild thermal/alkaline combinations are commonly used to increase sugar release while minimising inhibitor formation [11,4]. The process in this study produced a final pH of 5.2 and a reducing sugar concentration of 32.5 $g \cdot L^{-1}$ — an increase of approximately 25 % relative to pre-hydrolysis levels (26.1 $g \cdot L^{-1}$). The measured sugar release is comparable to ranges reported for dilute-acid or optimized alkaline pretreatments of straw biomass [5,6,11]. Figure 1 indicates a significant increase in reducing sugar concentration after hydrolysis.

3.1.2. Fermentation

After hydrolysis, 8% (v/v) molasses was added as an auxiliary carbon source and 5% (w/v) *Saccharomyces cerevisiae* was used as inoculum. Fermentation proceeded at ambient temperature (~30 °C) for one month under semi-anaerobic conditions. Throughout fermentation, medium pH decreased from 5.2 to 3.9, consistent with active yeast metabolism and ethanol production. Reducing sugars declined markedly as the yeast consumed them. The ethanol yield determined by the pycnometer/density method at 25 °C was 65% (v/v), and the sugar conversion efficiency was calculated to be 78%. The use of molasses as a co-substrate to supplement carbon sources and maintain yeast vigor is a common, cost-effective strategy in small-scale processes [12]. Previous studies have reported that lignocellulosic hydrolysates may contain inhibitory compounds formed during pretreatment, potentially reducing ethanol yields. However, strategies such as the use of co-substrates, detoxification steps, or employing resilient yeast strains can significantly improve fermentation performance [13–15].

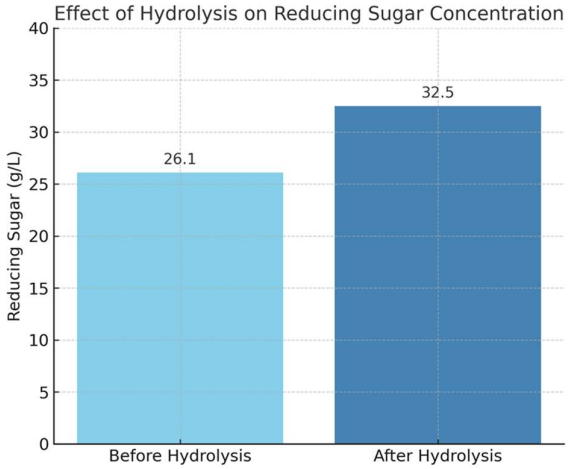

Figure 1. Effect of hydrolysis on reducing sugar concentration in rice straw hydrolysate

Figure 2 shows the ethanol yield and sugar conversion efficiency obtained in this study. The ethanol yield reached 65%, while the sugar conversion efficiency was 78%. These values are within the reported range for yeast-based fermentation of rice straw hydrolysates under moderate pretreatment conditions [12–15].

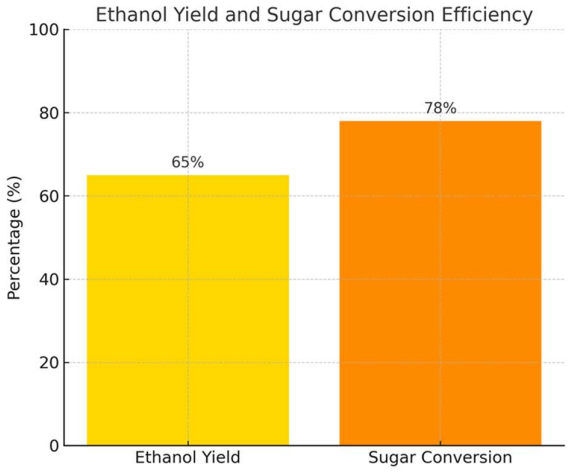

Figure 2. Ethanol yield and sugar conversion efficiency obtained from the fermentation of rice straw hydrolysate supplemented with molasses.

3.1.3. Distillation Process and Ethanol Recovery

Distillation of the fermented broth was conducted at a controlled temperature range of 78–80 °C to recover ethanol by exploiting the differences in boiling points between ethanol and water. From a total fermented volume of 1500 mL, approximately 250 mL of

distillate was obtained with an ethanol concentration of 65% (v/v), corresponding to a recovery efficiency of about 65%. This recovery rate aligns with previous studies emphasizing that temperature control and optimized reflux ratios are critical for maximizing ethanol yield and purity [4,5].

Precise management of distillation parameters—such as vapor–liquid equilibrium, condensation rate, and column efficiency—is essential to minimize ethanol loss and prevent degradation of volatile organic compounds. The integration of energy recovery systems, such as heat exchangers and multi-effect distillation setups, can further enhance ethanol recovery and improve process energy efficiency [16-10].

The ethanol recovery efficiency achieved in this study is depicted in Figure 3, which illustrates the proportional distribution between recovered ethanol (16.7%) and remaining broth (83.3%). The graphical representation highlights both the effectiveness of the distillation process and potential avenues for optimization through energy-integrated design.

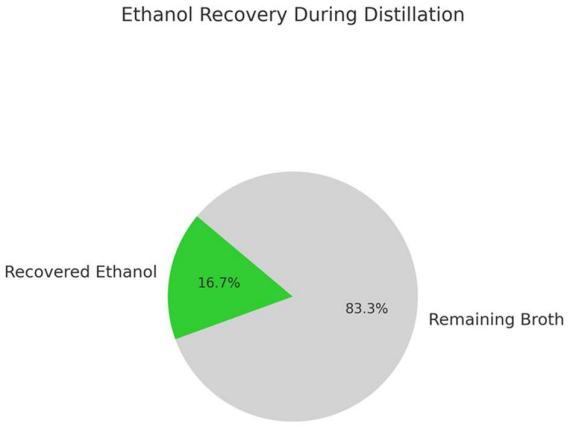

Figure 3. Ethanol recovery during distillation indicates the proportion of ethanol recovered and the remaining broth.
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4. CONCLUSION

This study confirmed that rice straw from West Sumatra possesses high potential as a raw material for bioethanol production. Through mild hydrolysis, fermentation with *Saccharomyces cerevisiae*, and controlled distillation, a bioethanol concentration of 65% (v/v) was achieved with 78% sugar conversion efficiency. The findings indicate that efficient bioethanol production can be achieved without the use of hazardous chemicals, making the process safer, more sustainable, and economically feasible for small-scale operations. The utilization of rice straw as a feedstock for bioethanol production not only supports renewable energy development but also provides an environmentally sound alternative to open-field burning practices. Furthermore, the produced ethanol holds potential as a natural solvent for the fragrance and cosmetic industries, expanding its value beyond the energy sector. Future studies should focus on optimizing enzymatic hydrolysis and scaling up the process using integrated bioreactor systems. Combining this approach with life cycle assessment (LCA) and techno-economic analysis would provide a comprehensive understanding of its industrial viability and environmental benefits.

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