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RESEARCH ARTICLE

The Potential Utilization of Biomass as Substitute Renewable Energy in Supporting Energy Security in Central Java

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Abstract

The utilization of rice straw as a renewable energy resource has received growing attention in the context of regional energy security and carbon emission reduction, particularly in Central Java, Indonesia. This review explores the potential of rice straw as a feedstock for bioethanol production, emphasizing its primary lignocellulosic components—α-cellulose, hemicellulose, and lignin—and key conversion stages, including pretreatment, hydrolysis, fermentation, and purification. In addition, the performance of various technologies for converting bioethanol into electricity is critically examined. Among these, Direct Ethanol Fuel Cells (DEFCs) are identified as the most efficient, offering conversion efficiencies of 40–60% and notable environmental advantages over conventional ethanol-fueled combustion generators. The findings suggest that the integration of high-efficiency conversion technologies with the region's abundant rice straw resources could represent a strategic pathway toward a more sustainable and low-emission regional energy system.

Keywords: *rice straw, bioethanol, renewable energy, lignocellulosic biomass, direct ethanol fuel cell, energy conversion.*

1. Introduction

The Directorate General of Electricity at the Ministry of Energy and Mineral Resources reported that Indonesia's per capita electricity consumption in 2023 reached 1,337 kilowatt-hours (kWh) per person. Electricity is a vital need in various sectors of life, where energy consumption continues to increase annually [1]. The majority of power plants in Indonesia utilize coal and natural gas as the primary energy sources in the electricity generation process [2]. The use of coal and natural gas as the main energy sources for power generation faces various challenges such as greenhouse gas emissions that affect the environment, limited reserves due to their non-renewable nature, fuel price fluctuations, and the risk of supply disruptions that can threaten national energy security. The combustion of fossil fuels such as coal, petroleum, and natural gas is the primary source of CO_2 emissions [3]. The increase in carbon dioxide (CO_2) as a greenhouse gas intensifies the greenhouse effect which causes global warming, extreme weather, melting ice, and rising sea levels [4]. According to Musyafiq and Purwanto, at the end of 2019 electricity consumption in Central Java reached around 19,612 GWh with consumption distribution across various sectors such as the domestic sector 9,297 GWh (47.4%), business sector 2,160 GWh (11%), industrial sector 6,881 GWh (35%), and public sector 1,275 GWh (6.6%) [5].

The increase in electricity consumption indicates the importance of expanding energy sources to maintain the sustainability of electricity supply in the future. Indonesia has great potential in the development of renewable energy. The need for renewable energy continues to grow in line with global climate change, the limitations of fossil energy sources, and the increasing awareness of the importance of preserving environmental health [6]. The main renewable energy sources that are widely developed include solar energy, water (hydro), biomass, geothermal (steam), and nuclear energy. Solar energy is energy derived from solar radiation which is then converted into electrical or thermal energy through technologies such as photovoltaic panels or thermal heating systems, such as in Solar Power Plants [7]. Water or hydro energy utilizes the power of water flow to drive turbines and generate electricity, such as in Hydroelectric Power Plants [6]. Biomass is an energy source obtained from organic materials such as agricultural waste and animal waste. This energy can be converted into various other forms of energy such as biogas through biological conversion processes, for example, the production of bioethanol from bagasse waste and biogas production from agricultural waste [8]. Geothermal utilizes heat from within the earth to produce steam which is then used to drive power plant turbines [6]. Nuclear energy is also included in the category of low-carbon energy. Using nuclear fission reactions, nuclear energy can produce large amounts of electricity with very low carbon emissions [9].

Although its potential is very large, the utilization of renewable energy in Central Java until now is still not optimal. The Central Java Province has set a renewable energy mix (EBT) target of 21.32% in 2025 [10]. However, until the end of 2024 the achievement of the EBT mix only reached 18.55%, where this figure is still far from the target that Central Java Province must achieve in 2025. A renewable energy source that has great prospects to be developed is biomass. Biomass is organic material derived from plants or animals and can be processed into energy through various methods into bioethanol, biodiesel, and biogas [11]. As a renewable and environmentally friendly energy source, biomass offers a viable alternative to reduce greenhouse gas emissions and 2dependence on fossil fuels [12]. Especially in the agricultural sector, harvest residues such as rice straw, husks, and other plant stalks are available in abundant quantities [13].

Table 1. Potential Biomass Energy from Agriculture Residue in Indonesia [14].

Raw Material	Production (Ton)	% residue		Potential Residue (tonnage/year)	Caloric Value (kJ/kg)	GJ/year
Paddy	83.037.150	Rise Husk	5%	4.151.858	14,8	61.447.491
		Rice Straw	15%	12.455.573	14,2	176.869.129,5
Corn	30.055.623	Corn Husk	17,53%	5.268.750,71	14,64	771.345.510,42
		Corn Cob	16,32%	4.905.077,67	18,82	92.313.561,82
Palm Oil	42.883.631	Shell	7%	3.001.854	20,5	61.538.010,49
		Husk	13%	5.574.872	19,9	110.939.953,4
		EFB	22%	9.434.399	18,5	174.536.378,2
Coconut	2.840.148	Husk	47,75%	1.356.170,67	19,4	26.309.711
		Shell	14,87%	422.330,01	20,3	8.573.299,154
Rubber	3.630.357	Rubber Tree	74%	2.686.464	19,2	51.580.112,26
Sugar Cane	2.170.948	Bagasse	30%	651.284	18,5	12.048.761,4
		Bagasse Pith	11%	238.804	18	4.298.477,04
		Total				857.589.396

The abundant rice straw in Central Java has great potential as an environmentally friendly biogas feedstock that can reduce dependence on fossil fuels and greenhouse gas emissions [15]. Around 36–62% of rice straw is burned or returned to the soil as compost, 31–39% is used as animal feed, and the remaining 7–16% is used for industrial purposes [13]. Rice straw, as a highly abundant agricultural waste, requires proper management because uncontrolled disposal through land burning practices can cause negative environmental impacts [16], [17]. Anaerobic fermentation allows biogas to be utilized as an energy source, such as electricity, heat, and fuel [18]. Biogas is a gas produced through the anaerobic fermentation of organic materials by bacteria that thrive in oxygen-free environments [19]. Biogas is produced from the anaerobic fermentation of biomass which is a mixture of various gases with methane as its main component comprising around 55–70%, while carbon dioxide accounts for 35–40%, and the rest consists of nitrogen, hydrogen sulfide, and other gases in very small amounts. The composition of these gases depends on the digester temperature and the type of organic material used, so changes in these factors can affect the percentage of gas produced [11].

Rice straw contains three main components namely cellulose, hemicellulose, and lignin. These components interact to form a recalcitrant polymer crystal structure that inhibits lignocellulose hydrolysis [20]. Rice straw biogas can be utilized to generate electricity through a microgrid that supplies energy directly to commercial facilities or small communities. In the context of research in the area, integration with commercial units such as rice mills is considered the most likely [21]. All energy produced will be used within the microgrid, while by-products in the form of compost are sold at a discounted price to farmers who supply straw, or sold at full price to other end users [21]. Rice straw biogas provides many benefits, one of which is reducing greenhouse gas emissions. Biogas from straw reduces methane (CH_4) emissions into the atmosphere, and the process produces biochar for fuel and can also be utilized for power generation [22]. Based on these statements, this aims to identify the components in rice straw that can produce biogas, as well as to understand the electricity generated from rice straw biogas utilization.

2. Raw Material

Straw is an agricultural waste product that holds great potential to be utilized as a biomass source in the development of environmentally friendly renewable energy [16]. Biomass itself has the potential to become an alternative energy source that can gradually replace fossil fuels in various energy production sectors [23]. Among the available sources, rice straw is considered one of the most promising types of biomass to support the utilization of renewable energy as part of efforts to enhance energy security and move toward a more sustainable and environmentally friendly future [24]. This is because straw contains components such as α-cellulose, hemicellulose, pentosans, and lignin which can be processed and utilized effectively as biomass to support sustainable alternative energy production. [25].

Table 2. Nutrition Label Content of Rice Straw Waste [26]

No	Nutrition	Concentration (%)
1.	α-cellulose	28-45%
2.	Hemicellulose	12-32%
3.	Pentosans	23-28%
4.	Lignin	5-24%

The α-cellulose content found in the secondary cell wall of plants functions as the main structural component, providing strength and rigidity to straw [27]. α-Cellulose is insoluble in water and most organic solvents due to its linear structure composed of glucose units, with strong and extensive hydrogen bonds between polymer chains, as well as its high molecular weight and regular crystalline arrangement, which confer exceptional mechanical strength [27]. α-Cellulose can be hydrolyzed into glucose, which can then be fermented into biomass-derived renewable energy [28]. This glucose is subsequently utilized by microbes as a carbon source for growth and for the production of metabolites such as biomass.

Hemicellulose is a heterogeneous polysaccharide found in plant cell walls that functions to fill the space between cellulose fibers and lignin [29]. This polymer is composed of pentose and hexose sugars, such as xylose, glucose, mannose, and galactose, which form its backbone, with arabinose, galactose, glucose, and glucuronic acid present in its side chains [29]. Unlike α-cellulose, hemicellulose is more amorphous and branched, making it more soluble and more easily degraded by enzymes or acids [30]. In biomass processing, hemicellulose can be converted into monomeric sugars through acid or enzymatic hydrolysis, which can then be fermented by microorganisms into biomass-derived products [27]. During the fermentation process, hemicellulose serves as an alternative carbon source to cellulose, potentially enhancing the efficiency of biomass conversion into renewable energy or chemicals. Rice straw represents a highly promising lignocellulosic biomass feedstock due to its substantial pentosan (23–28%) content as a hemicellulose source and lignin (5–24%) as a structural component [31]. The abundant pentosan fraction, primarily xylan, can be effectively hydrolyzed into xylose through alkaline pretreatment (2% NaOH), achieving yields up to 85%, while dilute acid pretreatment (1% H_2SO_4) converts it into value-added furfural [32]. However, the wide variability in lignin content significantly impacts saccharification efficiency. Biological pretreatment using *Phanerochaete chrysosporium* has demonstrated remarkable selectivity, degrading up to 58% of lignin while preserving the pentosan fraction [33].

Rice straw contains key components such as α-cellulose, hemicellulose, pentosans, and lignin, which are the main constituents of lignocellulosic biomass [26]. These components play a crucial role in the conversion process of biomass into bioenergy, particularly bioethanol [15]. Rice straw holds significant potential as a biomass resource capable of replacing fossil-based non-renewable energy and strengthening energy security in Central Java. Through its conversion into biomass fuels such as briquettes and charcoal, as well as its utilization in biomass-based power generation systems, rice straw plays a crucial role in reducing dependence on fossil energy and promoting the transition toward a more sustainable energy system.[34]. The utilization of rice straw with these components can reduce reliance on non-renewable natural resources.

3. Production Process

3.1 Pretreatment Process

Rice straw is one type of lignocellulosic biomass that holds great potential as a raw material for second-generation bioethanol production [15]. However, its utilization requires an initial stage known as pretreatment to overcome the complex and recalcitrant structure of this material [35]. One of the main challenges in converting rice straw into bioethanol is its relatively high lignin content [36].

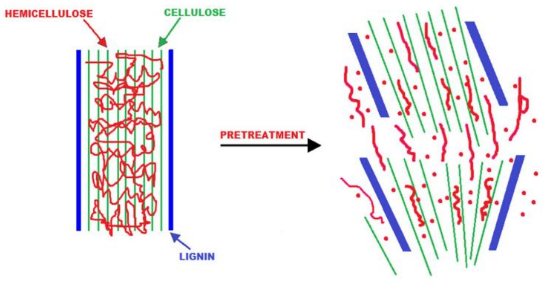

Figure 1. Lignocellulosic structure of rice straw [37]

Ramos (2023) reported that rice straw contains lignin ranging from 5 to 24 percent. Lignin is one of the main components of plant cell walls and is classified as a natural aromatic polymer composed of complex organic compounds with an irregular structure [38]. The rigid and irregular three-dimensional structure of lignin forms a protective matrix around cellulose and hemicellulose, thereby hindering enzymatic access to these carbohydrate components [27]. Lignin also serves as both a physical and chemical barrier by providing structural strength to the cell wall of rice straw and protecting polysaccharides from biological and enzymatic degradation [39].

Pretreatment of rice straw aims to disrupt the lignocellulosic structure, soften or remove lignin known as the delignification process and reduce cellulose crystallinity to make it more easily hydrolyzed [40]. This delignification process is essential because lignin not only blocks enzymatic access but can also non-specifically adsorb hydrolytic enzymes, ultimately reducing the efficiency of the hydrolysis process [41]. Delignification can be performed using alkaline (e.g., NaOH, KOH) or acidic (e.g., H_2SO_4, HCl) solutions under specific concentrations and temperatures to enhance the accessibility of cellulose and hemicellulose [42]. For example, alkaline pretreatment using 2–4% NaOH at 70–90°C for 1–2 hours can remove 60–80% of lignin, while acidic pretreatment with 1–2% H_2SO_4 at 121°C (autoclaving) is more effective in solubilizing hemicellulose, although it also contributes to lignin removal [43]. During pretreatment, lignin degrades and dissolves in the chemical solution, reducing the physicochemical barriers to enzymatic hydrolysis, though residual lignin may still inhibit the process if not completely removed [44]. By increasing the porosity of rice straw, pretreatment enhances the accessibility of cellulolytic enzymes, resulting in hydrolysis efficiencies ranging from 50% to 90%, depending on the method used [45].

3.2 Hydrolysis Process

Hydrolysis is the subsequent step that chemically breaks down complex carbohydrates such as cellulose and hemicellulose into simple sugar monomers using water, facilitated by enzymes or acid/base catalysts [46]. The objective of this process is to convert cellulose and hemicellulose into fermentable sugars, such as glucose and xylose, for the production of bioethanol or other valuable chemicals, with conversion efficiencies that can exceed 80% following effective pretreatment [47].

$$(C_6H_{10}O_5)n + nH_2O \longrightarrow nC_6H_{12}O_6$$

Figure 2. Hydrolysis Process Reaction

After pretreatment, enzymatic hydrolysis is typically performed to convert cellulose into monomeric sugars through the synergistic action of cellulase enzymes: endoglucanase randomly cleaves internal β-1,4-glycosidic bonds, exoglycanase (cellobiohydrolase) releases cellobiose units from chain ends, and β-glucosidase converts cellobiose into glucose [48]. Enzymatic hydrolysis generally achieves 85–95% efficiency under optimal conditions (around 50°C and pH 5) [48]. Alternatively, acid hydrolysis using 1–3% H_2SO_4 at 120–180°C can proceed more rapidly, but often produces inhibitory by-products such as furfural, which can interfere with subsequent fermentation steps [49].

Following pretreatment, enzymatic hydrolysis plays a central role in converting the now more accessible cellulose into simple sugars such as glucose [50]. In this process, endoglucanase initiates the breakdown by randomly cutting glycosidic bonds within cellulose chains, generating new chain ends [51]. Exoglycanase then acts on these ends to release cellobiose, which is subsequently hydrolyzed into glucose by β-glucosidase [52]. Additional enzymes such as LPMOs (lytic polysaccharide monooxygenases) can further assist by oxidizing and cleaving cellulose chains, thereby enhancing the overall efficiency of hydrolysis [51]. The enzymatic hydrolysis process is highly sensitive to temperature and pH, with optimal conditions around 40–50°C and pH 4.5. Lower temperatures reduce enzyme activity, while higher temperatures risk denaturing the enzymes [46]. The glucose obtained from enzymatic or acid hydrolysis is then converted by microorganisms such as *Saccharomyces cerevisiae* into bioethanol, a renewable fuel or into other biochemical compounds such as lactic acid and bioplastics [53]. Through this integrated process of pretreatment, delignification, and hydrolysis, rice straw can be effectively utilized as an environmentally friendly and renewable energy source.

3.3 Fermentation Process

Rice straw is an abundant agricultural waste in Central Java and contains high levels of cellulose and hemicellulose [54]. These two components can be converted into simple sugars which are then fermented by microorganisms into bioethanol [27]. The most commonly used microorganism in this process is Saccharomyces cerevisiae because it can efficiently convert glucose into ethanol under anaerobic conditions [55]. To support this process enzymes such as cellulase and hemicellulase are needed to break down complex compounds into simple sugars [56]. After sugars are formed the microorganisms will use them as substrates and produce ethanol as the main product along with by-products such as carbon dioxide [57].

$$C_6H_{12}O_6 \xrightarrow{\textit{Saccharomyces cerevisiae}} 2C_2H_5OH + 2CO_2$$

Figure 3. Reaction of the Fermentation Process

The fermentation process in converting rice straw into bioethanol generally uses three main techniques namely batch fed-batch, and continuous fermentation [58]. Batch fermentation is carried out in a closed system with all materials added at once and the process runs in one cycle which is suitable for small scale because the system is simple and flexible [59]. The fed-batch technique which is a combination of batch and continuous allows gradual addition of substrates to increase productivity reduce the risk of contamination and suppress inhibitor effects [60]. Meanwhile continuous fermentation allows for the continuous addition of substrates and removal of products resulting in high productivity and shorter processing time making it suitable for large scale industrial production [60]. The choice of fermentation technique depends heavily on the type of substrate microorganisms and production scale. The effectiveness of rice straw fermentation is often hindered by the formation of inhibitors such as organic acids and phenolic compounds during lignocellulose pretreatment which can inhibit the activity of bioethanol producing microorganisms and the risk of microbial contamination that lowers fermentation efficiency [61]. As a solution to this problem various approaches such as chemical and physical pretreatment have been applied to reduce inhibitor content. Rice straw fermentation has been developed from laboratory scale for process optimization to pilot and industrial scale for mass production. Conversion efficiency increases significantly after pretreatment under optimal conditions at 190°C for 60 minutes ethanol yield can reach 71% more than double compared to untreated straw which only produces 32% [62]. Compared to other biomass such as corn or sugarcane waste rice straw has a higher lignin content so it requires more intensive pretreatment and delignification processes [27]. Nevertheless the abundant availability of rice straw and its low raw material cost make it a potential renewable energy source [61]. To further improve fermentation results supporting technologies such as inhibitor detoxification simultaneous saccharification and fermentation (SSF) and consolidated bioprocessing (CBP) have been widely developed. Among these SSF is considered the most advantageous because of its low initial cost and its ability to produce high bioethanol productivity and yield with a shorter processing time [63].

Based on experiments conducted by Salihu (2022) the fermentation process runs optimally at a temperature of 35°C with a pH of 4.5 [64]. The optimal incubation time in the bioethanol fermentation process is around 72.1 hours depending on the type of microorganism and environmental conditions [65]. The concentration of rice straw biomass also needs to be considered because too high a concentration can inhibit nutrient movement and reduce fermentation efficiency whereas if it is too low the ethanol yield becomes uneconomical [66]. Other factors such as temperature pH and fermentation duration greatly affect the final result. Too high a temperature can damage enzymes and reduce microorganism activity while too low a temperature slows down the process [67]. Microorganisms can also be inhibited by toxic compounds such as acetic acid or furfural formed during hydrolysis [68]. Therefore, it is necessary to control conditions properly and select microorganisms that are resistant to inhibitors so that the fermentation process can run effectively and produce an optimal amount of bioethanol.

3.4 Purification Process

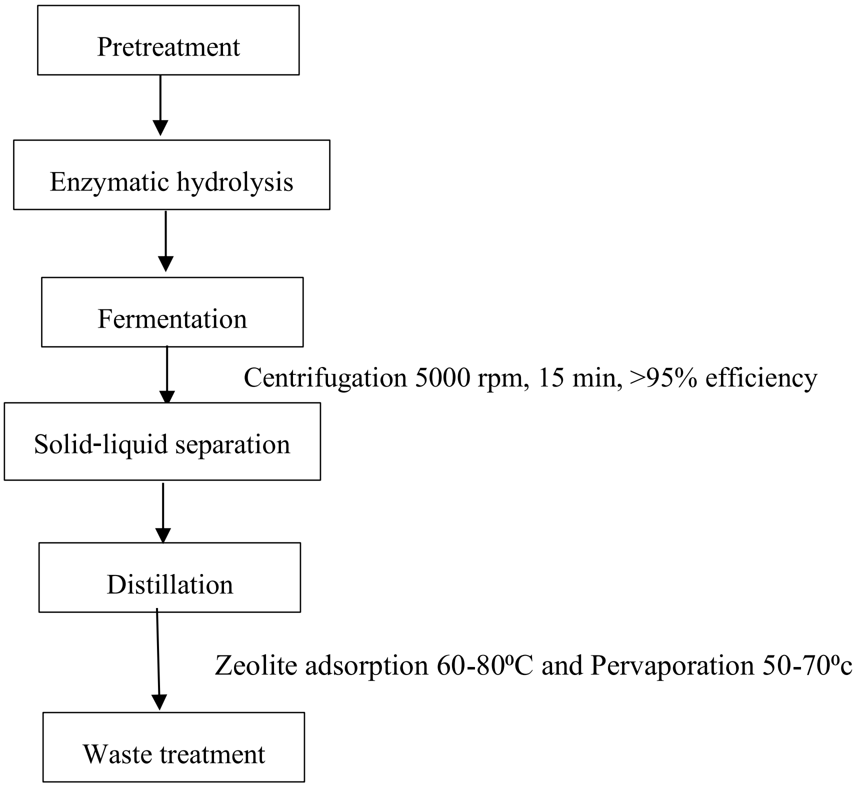

Figure 4. Bioethanol purification from rice straw

After fermentation the separation of yeast cells lignin and solid residues before distillation can be done through centrifugation where centrifugation at 5000 rpm for 15 minutes results in a clearer liquid with separation efficiency over 95 percent or membrane filtration which is more energy efficient but has a risk of clogging if solid content is high [69]. In bioethanol distillation the separation of ethanol from water and impurities reaches optimal efficiency at a temperature of 78 to 82°C which is close to the boiling point of ethanol using a distillation column containing 15 to 20 plates to produce ethanol concentrations above 90 percent and a reflux ratio of 3 to 4 to increase product purity [70]. To achieve ethanol purity above 99.5 percent which is the standard for fuel grade a dehydration process using zeolite 3Å adsorption is the most common method operating optimally at 60 to 80°C with adsorption capacity up to 20 percent of zeolite weight [71]. Pervaporation using hydrophobic membranes such as PDMS offers an energy efficient solution for ethanol dehydration by utilizing vapor selectivity to separate ethanol from water at operating temperatures of 50 to 70°C [72]. Based on the Life Cycle Assessment (LCA) approach, the purification process of bioethanol from rice straw through a combination of centrifugation distillation and zeolite adsorption achieves 85 percent energy efficiency with lower CO_2 emissions compared to conventional methods [73]. The quality of the fermentation results significantly determines purification efficiency where low ethanol content under 10% v/v increases distillation costs due to excessive water evaporation and contaminants such as organic acids and glycerol potentially cause fouling in the distillation column or reduce membrane performance while high solid content over 20 percent worsens initial separation and increases energy demand [74].

The treatment of wastewater and sludge from the fermentation and purification of rice straw bioethanol aims to reduce environmental impact and optimize waste utilization. This waste contains organic materials and nutrients so it can be used as compost or alternative fuel.

Technologies such as anaerobic digestion can produce biogas and reduce waste volume while thermochemical methods such as pyrolysis and gasification convert sludge into energy or industrial raw materials. Proper management supports sustainable and environmentally friendly bioethanol production [75]. Straw residues and fermentation waste can be utilized into liquid and solid organic fertilizers from processed sludge and wastewater as well as produce biogas biochar humic acid bioplastics and industrial enzymes. Through anaerobic digestion this waste can also be converted into renewable energy in the form of environmentally friendly biogas [76]. Bioethanol purification from rice straw requires high energy and costs especially at the distillation stage which requires heat for the condenser and reboiler. The use of technologies such as membranes and high gravity fermentation can help reduce energy consumption and lower operational costs [77]. To improve the quality of bioethanol from rice straw through purification the pretreatment process must be optimized to increase the accessibility of cellulose and hemicellulose the use of more efficient enzymes the fermentation process must be controlled and the distillation and post-fermentation purification processes must be optimized to remove impurities and increase the purity of bioethanol to meet the required quality standards [35]. Bioethanol from rice straw that has been purified for use as fuel must have a minimum ethanol content of 99.5 percent after denaturation and contain methanol and water below the maximum limits of 0.5 percent and 0.7 percent. This standard refers to SNI 7390:2012 which sets the quality and impurity content limits for fuel grade bioethanol [78]. The purification process of bioethanol from rice straw has a significant environmental impact including greenhouse gas emissions water pollution potential and air pollution due to the use of chemicals and energy during the process [79]. In addition, waste from the purification process must be properly managed to avoid soil and water pollution. The use of efficient and environmentally friendly technologies can minimize this impact [80]. The development of environmentally friendly and efficient purification technologies for bioethanol from rice straw can be carried out through non-toxic pretreatment methods such as the laccase-assisted sodium chlorite (LASC) method to reduce lignin without hazardous waste. This process is followed by optimized fermentation including the use of cellulase enzymes from microorganisms that increase hydrolysis efficiency and bioethanol production. Waste from the process can also be used to produce by-products such as biofertilizer making the process more sustainable and environmentally friendly [81].

3.5 *Application of Bioethanol as Renewable Electrical Energy*

Bioethanol is converted into electricity through combustion or by using fuel cells [82]. In combustion systems, bioethanol is vaporized then mixed with air and burned in the combustion chamber of an engine or turbine to generate heat [83]. This thermal energy is used to drive pistons or turbines connected to a generator to produce electricity [84]. Alternatively, bioethanol can be used in a type of fuel cell called Direct Ethanol Fuel Cell which utilizes electrochemical reactions without combustion and directly generates electricity with higher efficiency and lower emissions [85].

The utilization of bioethanol derived from rice straw as a source of electrical energy can be impelemented through several power generation technologies. The table below presents a comparison of these technologies:

Table 3. Comparative Analysis of Bioethanol Utilization Technologies for Power Generation

Technology	Bioethanol Specifications	Conversion Efficiency	Advantages	Disadvantages	References
Bioethanol Generator Set	1. Minimum purity of 95% (hydrous) or 99,5% (anhydrous) if	26%	1. Easy to install. 2. Low capital	1. Low efficiency. 2. Primarily suitable for small to	[86][87][88][89][90][91]

	blended with gasoline. 2. Octane rating (RON) of approximately 108. 3. Water content < 5%. 4. Sulfur content < 10 ppm.		investment.	medium-scale applications.	
Bioethanol Gas Turbine	1. Purity ≥ 99.5%. 2. Calorific value of 26.8 MJ/kg. 3. Alkali metals (Na, K) < 0,1 ppm. 4. Vapor pressure compatible with injection system.	36.38%	1. Cleaner emissions. 2. Capable of operating in Combined Heat and Power (CHP) configuration for improved overall efficiency.	1. NOx emissions remain unavoidable. 2. Higher system cost.	[92][93][94][95][96][97][98][99]
Direct Ethanol Fuel Cell (DEFC)	1. Purity > 99,9%. 2. Ethanol-water composition of 10-20%. 3. Methanol and acetaldehyde < 100 ppm.	40-60%	1. Low greenhouse gas emissions. 2. Quiet operation. 3. High energy efficiency.	1. Technology is still under development. 2. Requires expensive catalysts (Pt/C).	[100][101][102][103][104]

The electrical energy produced from bioethanol depends on the calorific value and the conversion efficiency of the system used. The calorific value of bioethanol is around 24 MJ/L (~6.67 kWh/L). In generator sets the conversion efficiency is around 26% so each liter of bioethanol can generate 1.7–2.3 kWh of electricity [105]. Meanwhile DEFC with higher efficiency (40–60%) can produce 2.7–4.0 kWh of electricity per liter of bioethanol. One ton of straw with a cellulose content of around 40% can produce 200–300 liters of bioethanol through enzymatic hydrolysis and fermentation which if converted using a generator set with 25–35% efficiency will generate around 400–600 kWh of electricity per ton of straw [106].

4. Conclusions

Rice straw represents a highly abundant but underutilized biomass resource with strong potential to enhance regional energy security and sustainability in Central Java. The review shows that through a multi-stage bioconversion process including pretreatment, enzymatic hydrolysis, fermentation, and purification its primary components (α-cellulose, hemicellulose, and lignin) can be effectively transformed into high-purity bioethanol. Beyond its bioethanol yield, the broader significance lies in its alignment with national and global energy transition goals. The integration of advanced technologies such as Direct Ethanol Fuel Cells (DEFCs), which offer higher electrical conversion efficiencies (up to 60%) and minimal emissions, underlines a strategic opportunity to transition from fossil-based systems to cleaner, decentralized bioenergy solutions. These findings highlight the generalisability of rice straw valorization pathways not only for Indonesia but also for other agrarian economies facing similar biomass waste management and energy access challenges. However, to enable large-scale deployment, systemic challenges remain including inconsistent feedstock quality, high purification costs, and technological immaturity in bioethanol-to-electricity conversion systems. Addressing these will require an interdisciplinary approach that combines innovation in bioprocessing, infrastructure development, and supportive policy frameworks. Future research should also incorporate life cycle assessment (LCA), techno-economic analysis (TEA), and sustainability metrics to evaluate environmental and economic trade-offs more comprehensively. In summary, the valorization of rice straw into bioethanol and its subsequent use in high-efficiency power generation technologies offers a promising route to support both clean energy development and rural empowerment. Strengthening integration across the biomass value chain from residue management to energy conversion—can accelerate progress toward a circular, low-carbon energy future.

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