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Bioethanol as a Renewable Energy Solution: Opportunities and Challenges in Agricultural Waste Utilization

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Abstract
In the face of climate change challenges and declining fossil energy resources, bioethanol is emerging as an environmentally friendly renewable energy solution. This article aims to review the potential, opportunities, and challenges in utilizing agricultural waste as the main raw material for bioethanol production. By analyzing various recent studies, it is found that agricultural wastes such as rice straw, corn cob, and bagasse have significant carbohydrate content for conversion into ethanol. Second-generation bioethanol production technologies utilizing lignocellulose offer higher efficiency than previous generations but face technical and economic challenges, including complex pretreatment requirements and high production costs. This review shows that bioethanol utilization can reduce dependence on fossil fuels while providing a sustainable solution for waste management. Policy support, technological innovation, and cross-sector collaboration are needed to accelerate the development of agricultural waste-based bioethanol, especially in developing countries such as Indonesia.

Keywords: *Bioethanol, agricultural waste, energy*

1. Introduction

The global economy is presently heavily reliant on multiple fossil energy sources, including oil, coal, and natural gas. These energy sources are utilized for the generation of fuels, electricity, and other commodities (1). The overconsumption of fossil fuels, particularly in major urban centers, has led to elevated pollution levels in recent decades. The concentration of greenhouse gases in the Earth's atmosphere has risen significantly. In light of climate change and diminishing fossil fuel resources, bioethanol is developing as a viable renewable energy alternative. Bioethanol, derived from biomass, particularly agricultural waste, provides a cleaner and more sustainable substitute for fossil fuels (2) .

Due to the potential of biomass, numerous technologies are advancing to convert biomass into biofuels, which significantly reduces carbon emissions and dependence on oil, as its production is derived from renewable and organic sources (3). As seen in Figure 1(4), the United States generates almost 50% of global bioethanol, but Europe accounts for merely 6%; additionally, each European nation's contribution is below 5%, with Brazil being the second-largest producer of bioethanol.

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Agricultural byproducts, including straw, crop residues, and agricultural trash, possess significant potential as feedstock for bioethanol production. Mchenry et al. assert that employing agricultural waste, such as cassava byproducts, for bioethanol production can yield substantial economic and environmental advantages, particularly in landlocked nations with constraints on exporting agricultural goods (5).

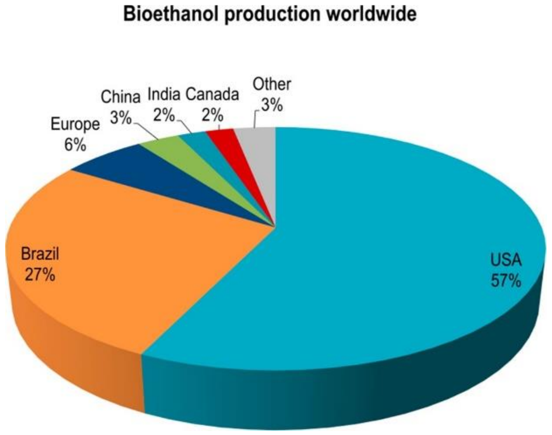

Figure 1. Bioethanol production worldwide

In Indonesia, plentiful agricultural residues, including empty fruit bunches (EFB) and straw, can be converted into bioethanol by hydrolysis and fermentation methods. Aznury et al. demonstrated that cellulosic waste, abundantly available in Indonesia, may be efficiently transformed into bioethanol by appropriate acid treatment and fermentation duration (6). This indicates a significant possibility to establish an agricultural waste-derived bioethanol business in Indonesia, which might enhance national energy security and diminish reliance on fossil fuel.

Nonetheless, despite this considerable promise, substantial hurdles exist in the advancement of bioethanol from agricultural waste. The primary problems are the intricate conversion procedure and elevated production expenses. Mahbubul observes that in Bangladesh, despite significant potential for bioethanol production from agricultural waste, technological and infrastructural challenges remain substantial obstacles (7). Furthermore, Bahlawan's research indicated that while breadfruit peels possess potential as a bioethanol source, obstacles in conversion and processing must be resolved to enhance production efficiency (8).

Furthermore, challenges in processing agricultural waste into bioethanol also include environmental and social aspects. Adewuyi emphasized that the development of biofuels, including bioethanol, must consider environmental impacts and sustainability, especially in developing countries with limited resources (2). Consequently, it is essential to formulate policies and strategies that facilitate the production of bioethanol from agricultural waste, considering sustainability and socio-economic implications.

This article seeks to examine the opportunities and challenges associated with the use of agricultural waste for bioethanol production. This article will analyze recent studies to elucidate the potential of bioethanol as a renewable energy alternative and the necessary measures to address current obstacles (3). It is anticipated that this article would aid in the formulation of more sustainable and eco-friendly energy policies in Indonesia and other emerging nations.

2. Methods

This article uses a systematic approach to collect, evaluate and compile information from various relevant sources. The aim is to provide a comprehensive overview of the potential and challenges of bioethanol as a renewable energy solution, particularly from agricultural waste.

3. Results and Discussion

3.1. Definition of Bioethanol

Bioethanol is an alternative fuel generated via fermentation from biomass, encompassing many feedstock sources, including starch-, sugar-, and cellulose-rich plants. The bioethanol manufacturing method entails the transformation of organic matter into ethanol facilitated by microorganisms, including yeast. Sadimo et al. assert that bioethanol addresses fossil energy scarcity while possessing environmentally sustainable and renewable characteristics, rendering it a compelling choice for energy sustainability (9).

Bioethanol can be synthesized from several basic materials, encompassing agricultural and organic waste. Susmiati highlighted the potential of agricultural and organic waste as bioethanol feedstock in Indonesia, along with the technology that may be created for its production (10). In this instance, bioethanol functions as an alternative that diminishes reliance on fossil fuels and enhances the value of waste produced by the agricultural industry.

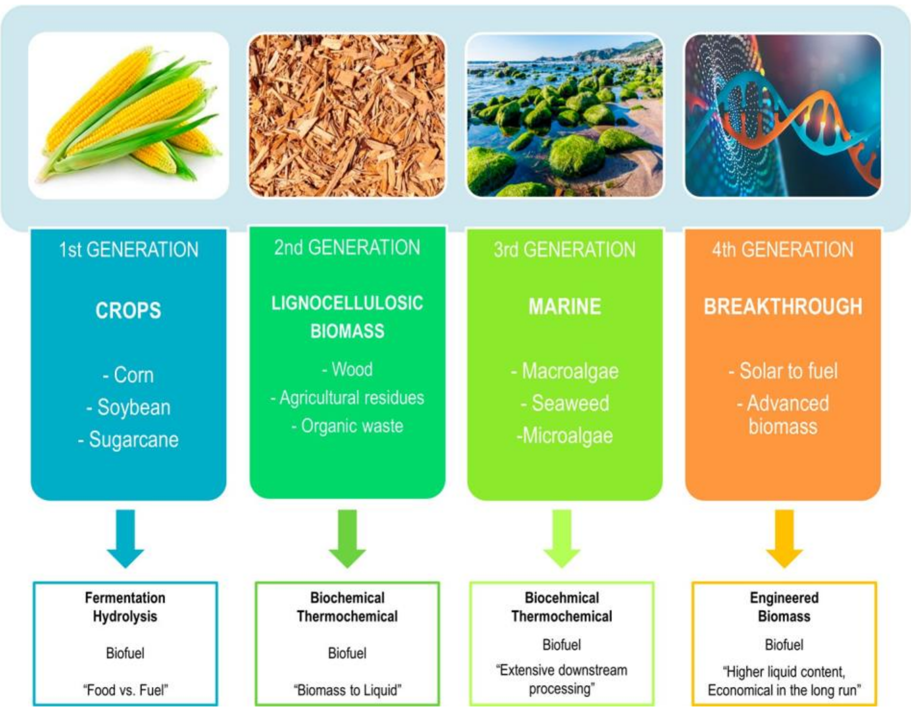

Figure 2. Bioethanol fuel generation

Bioethanol derived from edible feedstocks like corn and sugarcane is referred to as first-generation (1G) bioethanol, but bioethanol produced from lignocellulosic feedstocks is classified as second generation (2G) bioethanol. Examples of lignocellulosic biomass include transitional grasses, maize stalks, wood, herbaceous plants, wastepaper and paper products, agricultural and forestry residues, pulp and paper mill trash, municipal solid waste, and food sector waste. Lignocellulosic biomass comprises cellulose, hemicellulose, lignin, protein, ash, and trace extractives (7). Lignocellulosic biomass is regarded as a feedstock for bioethanol production owing to its comparatively cheap procurement cost, accessibility, and sustainability of supply. This biomass can enhance existing bioethanol production rates and is projected to yield around 442 billion liters of bioethanol every year worldwide. Second-generation bioethanol possesses a superior capacity to mitigate greenhouse gas emissions in comparison to first-generation bioethanol. Third generation (3G) bioethanol is derived from algae as the feedstock. Algae bioethanol is gaining popularity likely because of its high carbohydrate content and the lack of lignin in most accessible algae. Utilizing this type of feedstock is anticipated to lower pretreatment expenses by obviating the intricate process of lignin extraction (11). Fourth-generation (4G) bioethanol is produced by altering the genes of E. coli through metabolic engineering or systems biology techniques (4). An overview of bioethanol generation is presented in Figure 2 (12).

The production of bioethanol often encompasses multiple phases, namely hydrolysis, fermentation, and distillation. Novelia elucidates that bioethanol is generated via the fermentation of biomass facilitated by microorganisms, serving as an alternative fuel to supplant petroleum and other fossil energy sources (11). This approach not only mitigates greenhouse gas emissions but also offers economic advantages to the community by utilizing previously neglected agricultural trash.

Additionally, bioethanol can be generated from particular waste materials, including banana peels and maize cobs, which possess elevated carbohydrate content. Gafiera et al. shown that banana peels possess monosaccharides that can be transformed into bioethanol by fermentation (13). Furthermore, research conducted by Ruhibnur et al. demonstrated that corn cobs can be converted into bioethanol using appropriate fermentation methods (14). This indicates that other agricultural byproducts can be employed for bioethanol production, hence minimizing waste and enhancing sustainability.

In the realm of bioethanol production in Indonesia, various obstacles and opportunities warrant consideration. Bioethanol possesses significant promise as a renewable energy source; yet its production necessitates efficient and eco-friendly technology. Consequently, additional research and development are required to enhance the bioethanol production process from diverse agricultural waste sources, thereby contributing to national energy security and environmental sustainability (8).

3.2. Source of Bioethanol Source

Bioethanol is a renewable energy source derived from diverse agricultural byproducts. The production method entails the transformation of organic matter into ethanol by fermentation, utilizing many forms of agricultural waste (15).

As previously stated, bioethanol produced from agricultural waste is classified as second-generation bioethanol and is the most favored feedstock for bioethanol production due to its year-round availability. The global output of these agro wastes is illustrated in Table 1

(16). Asia is the primary source of rice straw and wheat straw, but corn straw and bagasse are predominantly produced in the Americas. Their chemical composition also varies (Table 2) (17), with cellulose as the main component.

Table 1. Amount of agricultural waste (million tons) reportedly available for bioethanol

Agro waste	Africa	Asia	Europe	America	Oceania
Rice straw	20.9	667.6	3.9	37.2	1.7
Wheat straw	5.34	145.20	132.59	62.64	8.57
Corn straw	0.00	33.90	28.61	140.86	0.24
Bagasse	11.73	74.88	0.01	87.62	6.49

Table 2. Chemical composition of agricultural waste

Substrate	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Protein (%)	Ash(%)
Rice Straw	32-47	19-27	5-24	-	12.4
Wheat straw	35-45	20-30	8-15	3.1	10.1
Corn straw	42.6	21.3	8.2	5.1	4.3
Baggase	65(total carbohydrates)		18.4	3	2.4

The generation of bioethanol from agricultural waste is a possible alternative for diminishing reliance on fossil fuels and managing waste responsibly. Diverse forms of agricultural waste can serve as feedstock for bioethanol production, and studies indicate that numerous such wastes possess considerable potential. A potential source of bioethanol is sorghum stalks (Sorghum bicolor). Research conducted by Kartini and Pandebesie demonstrated that sorghum stalks possess a substantial total sugar content, nearly comparable to that of sugarcane juice, so rendering them suitable for bioethanol synthesis with a consortium of Saccharomyces cerevisiae yeast and Pichia stipites (3). In addition, corn waste, such as stalks and corn husks, also have great potential.

Jusman reported that processing corn waste can provide economic opportunities for communities, and this waste can be further processed to produce bioethanol (18). Cassava crop residues and sugarcane tops are viable feedstock for bioethanol production. Asmara observed that the plentiful cassava stalks and sugarcane tops in Way Kanan Regency have not been well utilized, indicating significant potential for their conversion into bioethanol (6). Furthermore, Susmiati's research indicates that the conversion of agricultural and organic waste into bioethanol can be achieved by several processes, including Separate Hydrolysis and Fermentation (SHF) and Simultaneous Saccharification Fermentation (SSF) (14). Additional agricultural residues, such as rice straw, can also be employed for bioethanol production. Studies indicate that rice straw can be converted into bioethanol via fermentation, offering additional value to farmers who frequently encounter excessive agricultural waste.

Table 3. The amount of rice straw available worldwide and theoretical ethanol yields (1)

Country	Rice straw availability (million MT)	Theoretical ethanol yield (billion liters)
Africa	20.93	8.83
Asia	667.59	281.72
Europe	3.92	1.65
North America	10.95	4.62
Central America	2.77	1.17
South America	23.51	9.92

Rice straw is one of the most plentiful lignocellulosic agricultural wastes globally. The annual production is around 731 million tons, distributed over Africa, Asia, Europe, and the Americas (Table 3). This quantity of rice straw may generate 205 billion liters of bioethanol annually (19). In Asia, rice straw constitutes the predominant residue generated in substantial volumes, totaling 667.59 million tons. A total of 668 million tons can provide 282 billion liters of ethanol, contingent upon the availability of technology. Nonetheless, the majority of this rice straw is incinerated in the fields. This energy wastage appears unjustifiable, considering the elevated fuel costs and the significant necessity to mitigate greenhouse gas emissions and air pollution (20).

Straw and husk, byproducts of rice farming, have significant energy potential. While the utilization of rice husk technology is well-established in numerous Asian nations, rice straw is infrequently employed as a renewable energy resource. A primary reason for the favored utilization of husk is its accessibility, as it is abundantly accessible at rice mills. The collecting of rice straw is labor-intensive and its availability is restricted to the harvest period (21). The collection logistics can be executed through baling; however, the substantial expense of the equipment renders it impractical for the majority of rice producers. Therefore, the technique for utilizing rice straw for energy must be highly efficient to offset the substantial costs associated with straw harvesting (9).

Utilizing diverse agricultural wastes for bioethanol production can diminish reliance on fossil fuels while also enhancing the value of trash produced by the agricultural sector. Consequently, it is imperative to persist in research and development within this domain to enhance the efficiency and sustainability of bioethanol production.

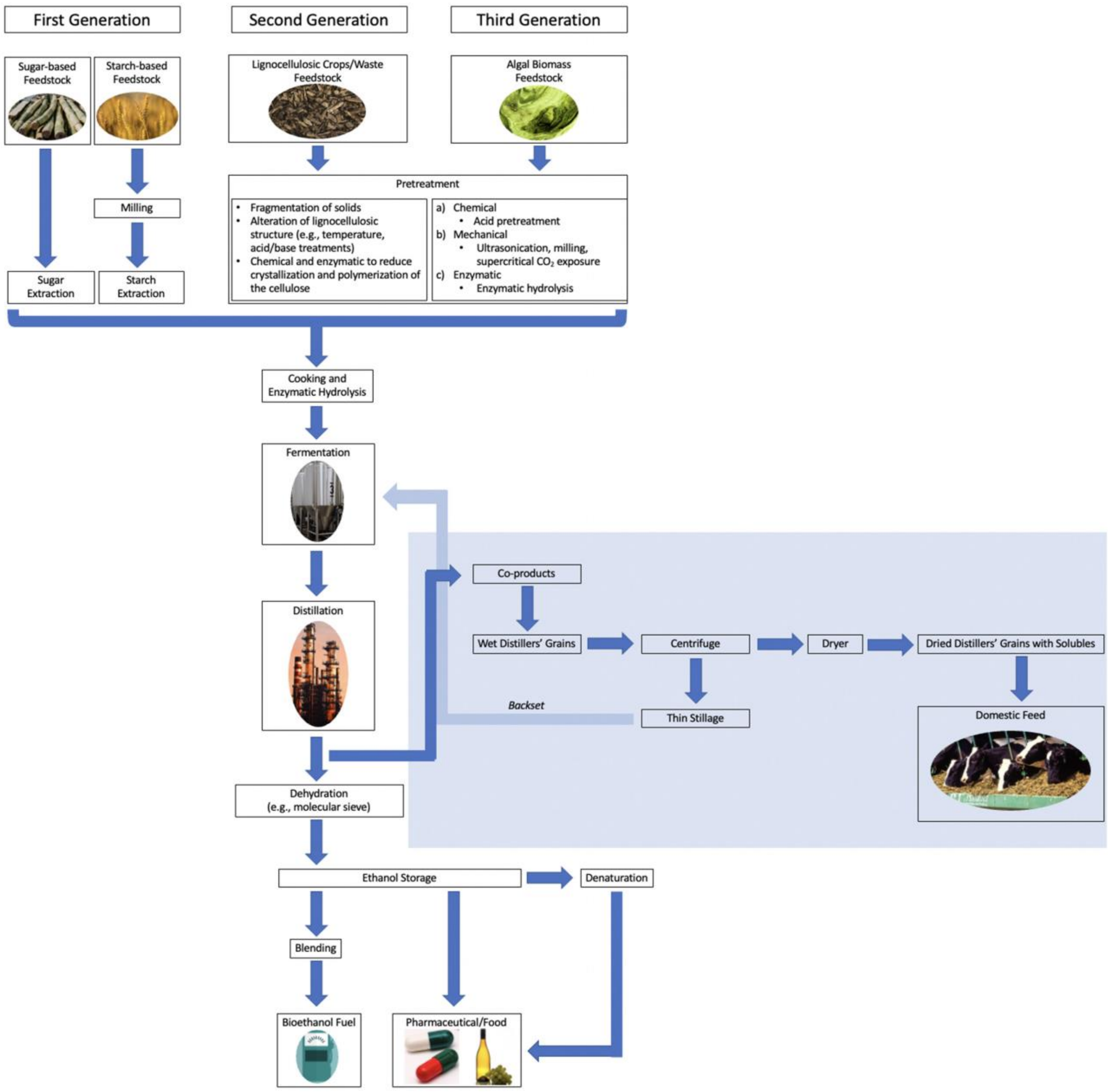

Figure 1. General flow chart of bioethanol production

Industrial bioethanol production is presently categorized into three generations according to the type of feedstock utilized (Figure 3) (17). The procedures involved in all biofuel production encompass: (1) pretreatment, (2) hydrolysis (although not necessary in sugarcane fermentation), and (3) the conversion of sugars to bioethanol via fermentation. Certain feedstocks necessitate pretreatment conditions (e.g., lignocellulosic feedstocks and algal biomass) to liberate fermentable sugars into the medium. In the absence of pretreatment, the advancement of fermentation may be hindered by a restricted supply of fermentable sugars for metabolic processes. The genetics of the feedstock can influence differences in sugar concentration and impact the production of fermented ethanol (15). Research is currently underway on fourth-generation bioethanol production techniques that employ genetically modified organisms to enhance fermentation efficiency. This method has not yet been executed on an industrial basis. The stages of bioethanol synthesis from various feedstocks encompass pretreatment, hydrolysis, fermentation, and ethanol recovery. The following processes are delineated below:

3.2.1. Pretreatment

The primary processing hurdle in biofuel production is the pretreatment of biomass. Lignocellulosic biomass comprises three primary components: hemicellulose, lignin, and cellulose. Pretreatment procedures pertain to the dissolving and separation of one or more components of biomass. This renders the residual solid biomass more amenable to subsequent chemical or biological processing (12). Lignocellulosic complexes have a matrix of cellulose and lignin interconnected by hemicellulose chains. Pretreatment is conducted to decompose the matrix, thereby diminishing the crystallinity of cellulose and augmenting the proportion of amorphous cellulose, which is the form most conducive to enzymatic degradation (22).

Diverse pretreatment methods have been established to enhance the accessibility of cellulose and hemicellulose by altering the structure of lignin and modifying the physical and chemical properties of biomass. Frequently employed techniques include physical, chemical, and biological preparation. Physical techniques, like grinding and torrefaction, enhance surface area and diminish particle size, consequently augmenting enzyme accessibility (23,24). Chemical pretreatments, such as acidic, alkaline, and ionic liquid treatments, efficiently solubilize hemicellulose and partially eliminate lignin, which is essential for enhancing sugar yield during hydrolysis (25–27). Alkali pretreatment has been demonstrated to markedly enhance the enzymatic hydrolysis of diverse lignocellulosic substrates, such as agricultural leftovers and waste paper (28).

Biological pretreatment, utilizing microbes or enzymes, provides an eco-friendly alternative that functions under gentler settings and generates fewer harmful by-products than chemical procedures (29,30) . These technologies can efficiently breakdown lignin and enhance biomass digestibility, however they often necessitate extended processing durations (29).

The selection of pretreatment method is determined by the biomass type and the intended efficiency of the bioethanol production process. Research indicates that the integration of torrefaction and alkaline pretreatment can synergistically enhance sugar and bioethanol yield from wood waste (24). The amalgamation of many pretreatment tactics might enhance the overall process, mitigating the constraints of singular methods (19,24).

Pretreatment of lignocellulosic biomass is essential for effective bioethanol production. Pretreatment enhances the yield of fermentable sugars and bolsters the economic feasibility of bioethanol as a renewable energy source. Continued research aimed at optimizing pretreatment procedures remains crucial for the advancement of bioethanol manufacturing technology (31,32).

3.2.2. Hydrolysis

Hydrolysis is an essential phase in the bioethanol production process, particularly when utilizing lignocellulosic biomass as feedstock. This technique seeks to transform intricate polysaccharides, including cellulose and hemicellulose, into monosaccharides that can be

fermented into ethanol. Hydrolysis primarily occurs through two methods: enzymatic hydrolysis and acid hydrolysis. Every approach possesses advantages and disadvantages that influence the efficiency and ultimate yield of bioethanol production (33–35).
Enzymatic hydrolysis employs particular enzymes, such as cellulases, to cleave the glycosidic linkages in cellulose. These enzymes can be sourced from diverse organisms, including fungi and bacteria. Research indicates that enzymes derived from Trichoderma viride and Aspergillus niger enhance the hydrolysis efficiency of diverse biomass types, such as sorghum stalks and agricultural trash (3,36) In this context, enzymes function more efficiently under specific conditions, such as optimal pH and temperature, which can enhance the conversion rate of carbs to sugars (37,38).

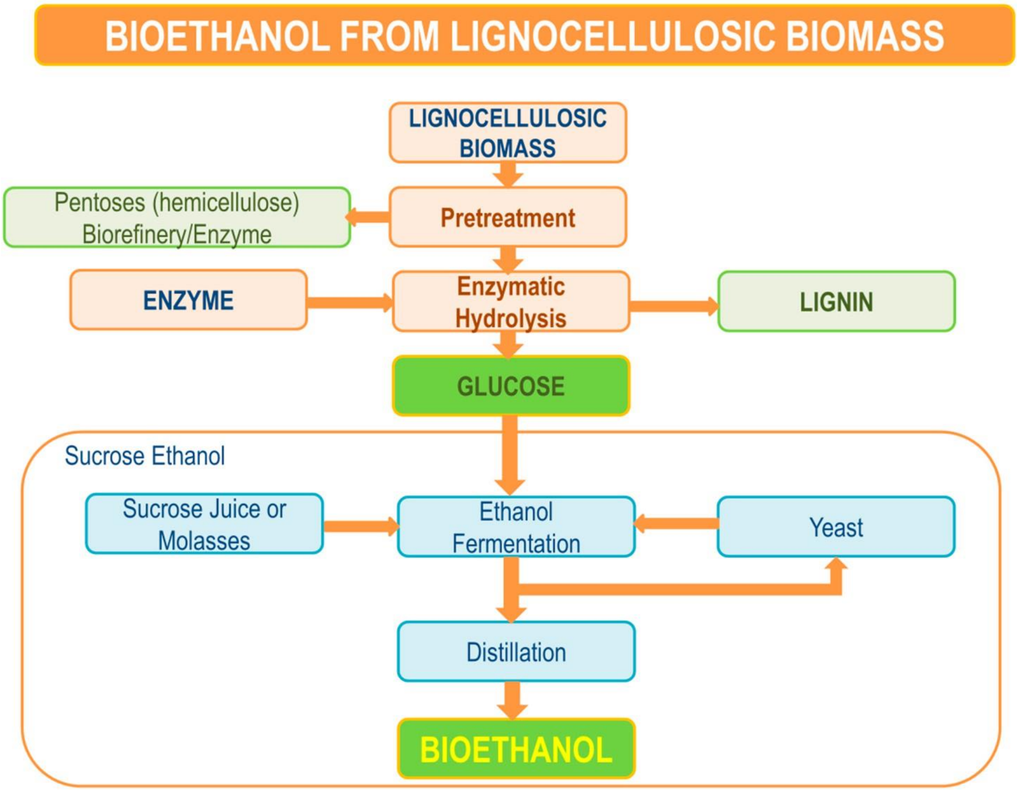

Figure 4. Enzymatic hydrolysis pathway

Figure 4 illustrates the overall enzymatic hydrolysis mechanism. Conversely, acid hydrolysis employs acids, such as HCl or H2SO4, to decompose polysaccharides. This approach is generally more rapid than enzymatic hydrolysis; however, it may generate undesirable byproducts and necessitates a neutralizing step post-process (1,39). Research indicates that acid hydrolysis at specific concentrations can provide substantial quantities of sugar, however it may compromise the integrity of the resultant sugar (1,40).
A promising method is Simultaneous Saccharification and Fermentation (SSF), wherein enzymatic hydrolysis and fermentation occur concurrently. This approach enhances conversion efficiency by decreasing the time needed for ethanol production and mitigating the hindrance caused by product accumulation (13,41). In SSF, the utilization of yeast, particularly Saccharomyces cerevisiae, is prevalent due to its superior fermentation capacity for sugars derived from hydrolysis (11).

The ideal conditions for hydrolysis, whether enzymatic or acidic, are primarily contingent upon the specific type of biomass utilized. Research indicates that the brown seaweed Sargassum duplicatum possesses significant potential for bioethanol production due to its elevated cellulose content and reduced lignin, facilitating hydrolysis (34). Moreover, additional research indicates that agricultural waste, including rice husks, can be efficiently digested with enzymes derived from Aspergillus niger, yielding sugars suitable for fermentation into bioethanol (36).

In the realm of bioethanol production from agricultural waste, it is crucial to contemplate pretreatment processes preceding hydrolysis. Pretreatment seeks to enhance cellulose accessibility by diminishing lignin and hemicellulose, therefore augmenting hydrolysis efficiency (42,43). Numerous pretreatment techniques, including steam explosion and deep eutectic solvents, have been examined to enhance hydrolysis yield and bioethanol generation.

3.2.3. Fermentation Process

The fermentation process in bioethanol production is a crucial phase that influences the ultimate yield of the product. Fermentation is the process of transforming carbohydrates into ethanol by the action of microbes, typically utilizing yeast from the genus Saccharomyces, such as Saccharomyces cerevisiae. This process can be executed by multiple techniques, including concurrent and discrete fermentation, utilizing diverse carbohydrate-rich feedstocks. A extensively studied technique is simultaneous fermentation and saccharification (SSF), wherein enzymatic hydrolysis and fermentation occur concurrently. This technology is demonstrated to enhance the efficiency of bioethanol synthesis from diverse sources, including rice bran and bagasse (44,45). A study by Haryani et al. demonstrated that the SSF process yields higher ethanol concentrations in a reduced timeframe compared to SHF (Separated Hydrolysis and Fermentation) (18).

Another element influencing fermentation yield is the kind of batch, which encompasses batch, fed-batch, and continuous fermentation (Table 4) (12). The ideal fermentation batch type is contingent upon the kinetics of the employed microorganisms and the raw ingredients utilized. In batch fermentation, bacteria are typically introduced into a predetermined volume of medium within the fermenter. As nutrients are utilized and microbes proliferate, by-products will accumulate. Fermentation concludes with the depletion of nutrients. The fixed initial food input and the ongoing consumption of nutrients by microorganisms result in a continuously changing culture environment (46).

This fermentation often yields a standard growth curve with a lag phase, exponential phase, stationary phase, and death phase. The lag phase is the initial critical period of microbial development in batch fermentation, during which the organisms adapt to the new environment. During the exponential phase, organisms reproduce at a consistent rate, resulting in an exponential increase in microbial growth (logarithmic growth phase). The rate of cell proliferation is sometimes limited by substrate availability, which may arise from deficits in medium constituents (e.g., nutrient imbalance) or high substrate concentrations (e.g., surplus sugar) (47), resulting in long fermentation times and reduced ethanol yields (48). Subsequent to the exponential phase, microorganisms will transition into a stationary phase, when the quantity of proliferating and deceased cells attains balance, attributable to nutrient depletion in the medium (e.g., sugars) or the accumulation of poisonous by-products (e.g., ethanol toxicity) (49). Upon completion of fermentation, a death phase may ensue as the viability of cells diminishes. Nonetheless, several companies circumvent the lag phase by cultivating yeast in smaller vessels under optimal circumstances, then introducing a substantial inoculum to the primary fermentation (50). This circumvents the exponential period and can enhance fermentation efficiency. Nevertheless, batch fermentation is typically cost-effective, presents a reduced risk of contamination, and allows for simpler sanitation and control of raw materials compared to other fermentation methods. Batch fermentation is more cost-effective than fed-batch and continuous fermentation. Fermentation has reduced cell density (51), Nutrients are not supplied during the exponential growth phase. Increased downtime arises from the routine cleaning and sterilization of vessels between consecutive fermentation batches. Batch fermentation is mostly utilized in extended, small-scale, or solid-state fermentation processes (47).

Table 4. Comparison between batch, fed-batch, and continuous fermentation under submerged/liquid conditions (46,51).

Batch	Fed-Batch	Continuous
Microorganisms are provided with a fixed volume of medium (nutrients and other ingredients). Culture environment is consistently changing as nutrients are consumed.	Media is inoculated with microorganisms which then grow under a batch regime for a certain amount of time, then nutrients are added incrementally throughout the fermentation.	Fresh media is continuously added to the fermenter, replacing the consumed nutrients. Ethanol, used media, and toxic metabolites are continuously removed.
Advantage		
• Low cost, • Low risk of contamination, • Less control required, • Easier sterilization	• Maintenance of maximum viable cell concentration, • Extended lifespan of cells, Higher ethanol accumulation, • By-product accumulation is limited, • Control of factors (e.g., pH, temperature, dissolved oxygen)	• Less downtime for vessel cleaning, • Increased productivity, • Lower cost, • Higher degree of control, • Ability to automate, more cost-efficient and less sensitive to human error.
Disadvantage		
• Lower cell densities, • ethanol production, • Longer downtime between batches due to cleaning, vessel setup, and sterilization	• Increased costs for process control, • Longer downtime between batches due to cleaning, vessel setup, and sterilization	• Less control for non-growth-related products, • Cell aggregation can prevent optimum steady-state growth,

		• Long growth periods can increase the risk of contamination, • Can be difficult to maintain filamentous organisms due to viscosity and heterogeneity of the medium

Fermentation, especially in raw materials that have high lignocellulose content, such as oil palm empty fruit bunches (45). Research has increasingly concentrated on the utilization of different microorganisms to enhance bioethanol output. Nugraheni and Mastur emphasized the promise of Zymomonas mobilis as a substitute for Saccharomyces cerevisiae in the fermentation of sugarcane molasses, potentially enhancing bioethanol production output (52). Moreover, fluctuations in fermentation parameters, including pH and duration, substantially influence the ultimate output. Hartina et al. demonstrated that fluctuations in pH and fermentation duration influence bioethanol yield from molasses, achieving best outcomes at specific pH levels and fermentation times (53). Nutritional elements significantly influence the fermentation process. The incorporation of additives like urea and NPK can augment yeast proliferation and hence elevate ethanol production levels (24,54). In this context, research by Fitria and Lindasari showed that the addition of proper starter inoculation can increase bioethanol yield from pineapple peel waste (54).

Conclusions

Bioethanol derived from agricultural waste is a highly promising approach for the shift to renewable energy. Agricultural waste, prevalent in numerous areas, can serve as the primary feedstock, enhancing the value of a hitherto untapped resource. Second-generation bioethanol production systems demonstrate considerable effectiveness in the utilization of lignocellulosic biomass; yet, they necessitate additional advancements to enhance scalability and reduce production costs. Principal challenges encompass the intricacy of the conversion process, inadequate infrastructure, and societal and regulatory opposition. To advance bioethanol production, strategic measures are required, including enhancing research and technological innovation, incorporating renewable energy legislation, and informing the public about the advantages of bioethanol. Through a coordinated strategy, bioethanol can serve as a crucial component in enhancing national energy security, particularly in emerging nations, while offering sustainable solutions for both the environment and the economy.

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Conflicts of Interest

The authors declare no conflict of interest.

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