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Optimizing the Cellulose Hydrolysis Process from Petioles and Midribs of Kepok Banana Trees into Glucose

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A B S T R A C T

Agricultural waste from banana petioles and midribs represents an underutilized lignocellulosic biomass, particularly in Bojonegoro Regency, East Java. This study aims to optimize the cellulose hydrolysis process from this waste into glucose using sulfuric acid as a catalyst via the Response Surface Methodology (RSM). This study used the most abundant banana variety in the area, the Kepok banana. The variables tested included temperature (70–110°C) and reaction time (20–100 minutes). The glucose content of the hydrolysis product was measured using a sugar refractometer. The glucose content data were then converted to per cent cellulose conversion, which served as the basis for the optimization process. The results showed that temperature and time significantly influenced glucose conversion, with optimal conditions at 110°C for 100 minutes. The optimization model demonstrated a good fit, with an R^2 value exceeding 0.95. This research confirms the potential of utilizing local banana petiole and midrib waste as a glucose source, providing a scientific basis for sustainable, large-scale production.

Contribution to Sustainable Development Goals (SDGs):
SDG 7 (Affordable and Clean Energy)
SDG 9 (Industry, Innovation, and Infrastructure
SDG 12 (Responsible Consumption and Production)
SDG 13 (Climate Action)
SDG 15 (Life on Land):

1. INTRODUCTION

1.1. Research Background

Bananas are one of the largest fruit products in Indonesia, according to data from the Central Statistics Agency (BPS). East Java Province ranks first among Indonesian provinces in banana production, with Bojonegoro Regency serving as a major banana-farming centre. However, this high production volume is also accompanied by an increase in banana plant biomass waste, particularly from the stalks to the ribs of banana leaves (petioles and midribs), which remain largely untapped. Banana stems are used as stilts for banana trees or as rope for handicrafts. These plant parts are generally discarded or left to rot, creating environmental problems and potentially becoming neglected organic waste. However, banana stems and midribs can be processed into value-added products if managed appropriately. Unfortunately, attention to the processing of biomass waste from these parts remains very limited, especially in banana-producing areas such as Ojonegoro Regency [1].

This waste actually has a high lignocellulose content, with the primary composition consisting of cellulose, hemicellulose, and lignin. One type of banana tree commonly found in Bojonegoro is the Kepok banana. The cellulose content of banana stem waste is relatively high, reaching 80% [2]. Cellulose is a glucose polymer that can be hydrolyzed to produce simple sugars, such as glucose. The conversion of cellulose to glucose is crucial for supporting the development of the bioenergy, food, pharmaceutical, and renewable chemical industries [3].

Cellulose hydrolysis can be carried out enzymatically or chemically. However, the cost and reaction-time limitations of the enzymatic process make chemical approaches using acid catalysts more desirable for industrial-scale applications[4]. In this context, dilute sulfuric acid is often used due to its availability and its ability to accelerate the depolymerization of cellulose. The efficiency of cellulose conversion to glucose during hydrolysis is highly dependent on operating parameters, including temperature, reaction time, acid concentration, and substrate characteristics [5]. Therefore, a process optimization approach is required that can evaluate variable interactions and determine optimal conditions. One method commonly used in this case is Response Surface Methodology (RSM), which can model complex relationships among variables and formulate predictive models to achieve optimal results [6].

Several previous studies have used a similar approach to utilize biomass waste from banana plants. Previous research conducted by [7] studied the kinetics of hydrolysis of kepok banana peels into glucose using a sulfuric acid catalyst. It concluded that increasing temperature and time had a positive effect on glucose levels. However, that study did not reach temperatures above 100°C and did not focus on conversion optimization. Therefore, this study will optimize the hydrolysis of cellulose from petioles and midribs of kepok banana trees using the RSM method, while observing the effects of temperature and hydrolysis time on cellulose conversion to glucose.

1.2. Literature Review

1.2.1. Petiole and Midrib of Banana Tree

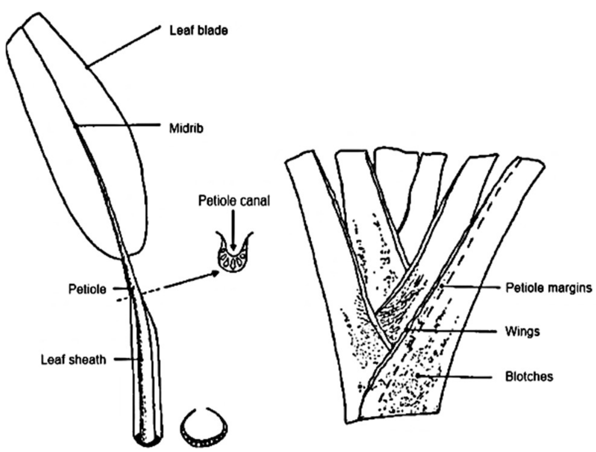

Figure 1. Petiole and Midrib of Banana Tree

Banana plants have several parts, including the stalk and leaf veins, as shown in the image above, indicated by the names petiole and midrib. The stalk and leaf veins of bananas (Musa Paradisiaca) are among the least popular parts of the banana plant. They are often considered useless waste. Waste petioles and midribs from banana trees are typically burned and discarded, contributing to environmental pollution [8]. Banana stalks and leaf veins contain cellular tissue with interconnected pores, which become solid when dried [2]. The margins of banana petioles also vary in color among specific banana cultivars. These colours range from green to reddish-purple to bluish-purple. The margins of the petioles range in width from less than 1 cm to more than 1 cm, and some have colored edges or not. In addition to the margins, margin identification can also be seen from the length of the petioles. The length of the petiole to midrib can range between 100 cm and 200 cm, depending on the type and growth of each banana tree.

1.2.2. Cellulose Hydrolysis

Cellulose is the main component of higher plants. Cellulose $(C_6H_{10}O_5)n$ is very abundant in nature. Plants, bacteria, fungi, and algae can produce cellulose. Cellulose is an organic polymer widely found in nature and is a homopolymer of glucose. Homopolysaccharides are composed of D-glucose monomer units linked by 1,4-glucosidic bonds. The degree of polymerization (i.e., the number of glucose units) of cellulose varies between 2,000 and 20,000. Cellulose forms microfibrils with inter- and intramolecular bonds, rendering it insoluble in most solvents, including water, and highly resistant to enzymatic and hydrolytic degradation. Cellulose in dry conditions is hygroscopic (easily absorbs and releases water vapour) and hard and brittle. Cellulose becomes soft if it contains a lot of water. So the function of water is as a softener. There are two types of cellulose microfibrils: crystalline and amorphous. Crystalline cellulose has greater strength than its amorphous form [9]. Cellulose can be hydrolyzed to produce reducing sugars. These sugars can then be fermented to produce bioethanol [10].

In the hydrolysis reaction, cellulose is converted to cellobiose, which then breaks down into glucose. Cellulose can be hydrolyzed to produce sugars. The hydrolysis process can be assisted mechanically by grinding. Grinding cellulose can increase its degradation rate by reducing crystallinity and increasing its surface area. Lignocellulose with high crystallinity is more difficult to degrade than amorphous structures. The following is a cellulose hydrolysis reaction that produces glucose.

$$(C_6H_{10}O_5)_n + n\,H_2O \xrightarrow{hidrolis} n\,(C_6H_{12}O_6)$$

The cellulose hydrolysis process can use catalysts such as enzymes or acids. Enzymatic hydrolysis takes significantly longer than acid hydrolysis. Therefore, to shorten the time, an acid hydrolysis method using dilute sulfuric acid as the catalyst is used. This is because dilute sulfuric acid can effectively hydrolyze cellulose. In addition, from a cost perspective, dilutedulfuric acid is more economical [11].

1.3. Research Objective

This study aims to determine the optimal conditions for the hydrolysis of cellulose into glucose using petiole and midrib cellulose from kepok banana trees obtained from Bojonegoro Regency, East Java, by testing the effects of hydrolysis time and temperature.

2. MATERIALS AND METHODS

This research was conducted in May 2025 using raw materials, namely petioles and midribs from kepok banana trees collected in Bojonegoro Regency, East Java. This research also employed other chemicals, including a sulfuric acid solution (H_2SO_4) as a hydrolysis catalyst, distilled water, and a NaOH solution for delignification. This research was conducted in the Chemical Engineering laboratory of UPN "Veteran" East Java using equipment including a blender/crusher, oven, 80 mesh sieve, analytical balance, beaker, thermometer, magnetic stirrer, glass funnel, stirring rod, Erlenmeyer flask, pH meter, table cooler, stand and clamp, water bath, three-neck flask, and sugar refractometer. The primary raw material, before the delignification process, will be pretreated with Petioles and midribs from harvested kepok banana trees, cleaned of dirt, cut into 0.5 cm-thick pieces, dried in an oven, and ground into powder using a blender. The resulting powder was then sieved with an 80-mesh sieve and stored in an airtight container.

Delignification was performed to separate lignin and hemicellulose from the cellulose in the sample. This process used a 1N NaOH solution with a powder-to-solution weight ratio of 1:20 at 70°C for 1 hour. The sample was then washed to a neutral pH and dried again at 100°C. Next, the hydrolysis process was carried out by mixing 10 grams of delignified cellulose powder with 20 mL of 20 N H_2SO_4 solution, which was then diluted to 250 mL with distilled water. The hydrolysis process was carried out at temperatures (70, 80, 90, 100, and 110°C) and reaction times (20, 40, 60, 80, and 100 minutes). After hydrolysis, the solution was filtered and neutralised with NaOH to a pH of 7. The glucose content of the hydrolysis product was then tested using a sugar refractometer. Glucose level data will then be used to calculate reaction conversion, which will be optimised using the Response Surface Methodology (RSM) with a Central Composite Design (CCD), and analysed using Design-Expert software version 13.0.5 (Stat-Ease Inc., USA).

3. RESULT AND DISCUSSION

3.1. Petiole and Midrib Powder Test Results of Kepok Banana Trees Before and After Delignification

Based on the test results, lignin content decreased and cellulose content increased in banana leaf stalk and vein powder after delignification (Table 1). According to Ref. [12], during durin lignification, lignin degrades and dissolves, as indicated by a reddish-black colour in the resulting liquor. Lignin is one of the main components of plant cell walls, which form a rigid structure. Its presence can inhibit access to cellulose during hydrolysis, so lignin removal from the lignocellulose structure is an important step to increase cellulose conversion. An increase in cellulose content characterizes the open lignocellulose structure. This indicates that the delignification process has removed some lignin, making the lignin structure more open and the cellulose more readily hydrolyzable.

Table 1. Cellulose and Lignin Content in Samples Before and After Delignification

Before Delignification (%)		**After Delignification (%)**	
Cellulose	**Lignin**	**Cellulose**	**Lignin**
76.35	10.29	80.18	7.30

3.2. Glucose Content from Hydrolysis

Table 2. Glucose Content of Hydrolysis Results

Hydrolysis Temperature (°C)	Glucose Content of Hydrolysis Results of Petiole and Midrib of Kepok Banana Tree (%)				
	20 min	40 min	60 min	80 min	100 min
70	6.5	7.0	7.5	7.8	8.2
80	6.7	7.4	7.7	8.0	8.5
90	7.4	7.8	8.4	8.6	9.4
100	7.5	8.2	8.7	9.5	11.1
110	8.4	8.9	9.6	10.7	12.0

The glucose concentration obtained from the hydrolysis of banana petiole and midrib was significantly influenced by both temperature and hydrolysis time. Glucose levels increased with increasing reaction temperature from 70°C to 110°C and reaction time from 20 to 100 minutes. This increase indicates that the hydrolysis process continues to occur effectively up to 110°C, with no slowdown. According to [12], at higher temperatures, the β-1,4-glycosidic bonds in the cellulose structure break more quickly due to increased kinetic energy. Increasing the temperature can accelerate the chemical reaction and enhance the dissolution of the cellulose fraction from the complex lignocellulose structure, thereby increasing the glucose content obtainable from hydrolysis. These data highlight the importance of optimising temperature and time in the hydrolysis process to maximise glucose levels without causing further degradation. These results also provide a crucial basis for quantitatively evaluating cellulose conversion efficiency.

3.3. Hydrolysis Reaction Conversion

Table 3. Conversion of Hydrolysis Reaction

Hydrolysis Temperature (°C)	**Conversion of Hydrolysis Reaction**				
	20 min	**40 min**	**60 min**	**80 Min**	**100 min**
70	0.8454	0.8517	0.8588	0.8698	0.8797
80	0.8523	0.8660	0.8686	0.8736	0.8923
90	0.8676	0.8693	0.8751	0.8910	0.8992
100	0.8732	0.8745	0.8804	0.8979	0.9198
110	0.8762	0.8814	0.8871	0.9097	0.9329

The data in **Table 3** above show that the higher the temperature and the longer the reaction time, the greater the conversion, although the increase in conversion is not always constant at each interval. This indicates that the reaction conditions have not reached saturation or product degradation, so the hydrolysis process is still proceeding efficiently. The increase in conversion is caused by the acceleration of the hydrolysis reaction due to higher temperature, which increases the molecular motion and increases the collision energy between cellulose and water. In addition, the longer the reaction time, the longer the interaction between water and the glucose substrate, leading to more complete hydrolysis[13]. At the highest hydrolysis conditions (110°C for 100 minutes), the conversion reached 93.29%.

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3.4. *Optimizations of Hydrolysis Conditions Using Response Surface Methodology (RSM)*

To determine the optimal conditions for cellulose hydrolysis to glucose, a response surface methodology (RSM) approach was employed using Design-Expert 13 software. The influence of temperature (70–110°C) and reaction time (20–100 minutes) on glucose conversion was analyzed. Experimental results were visualized through 3D surface and contour plots.

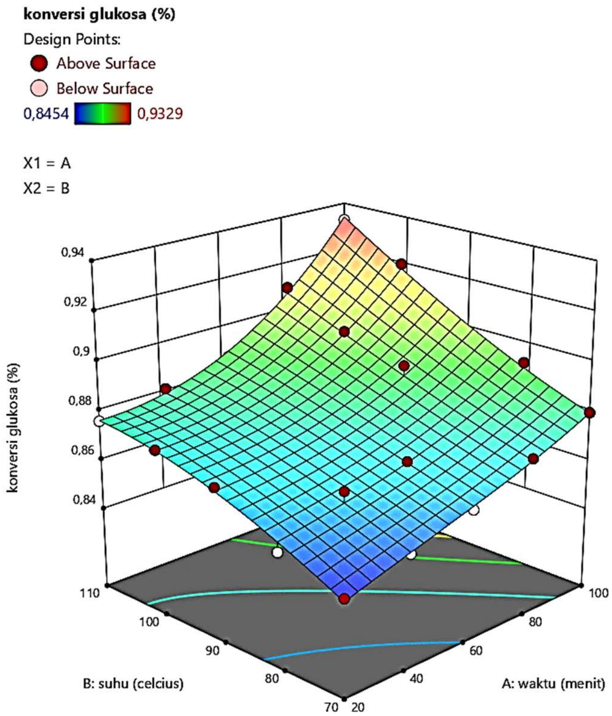

Figure. 2. Response Surface Relationship between Temperature and Hydrolysis Time on the Conversion of Hydrolysis Reaction of Petiole and Midrib of Kepok Banana Tree

Based on the 3D surface plot in Figure 2, increasing reaction time (from 20 to 100 minutes) consistently increased the percentage of glucose conversion across all temperature ranges tested for the hydrolysis of petioles and midribs of Kepok banana trees. The contour plot in the figure shows that the area with the highest glucose conversion, 0.9329 (93.29%), is concentrated in the upper-right corner of the plot. This area represents the combination of a longer time (100 minutes) and a higher temperature (110°C). The curvature of the contour lines indicates that the interaction between time and temperature affects glucose conversion. The 3D surface plot shows a slope upward toward the upper right corner, confirming that increasing these two factors results in a more optimal glucose yield.

Based on response surface analysis of data from the hydrolysis of banana tree petioles and midribs, it was found that temperature and time influence glucose conversion. Conversion increases with increasing temperature and time until it reaches a certain point. Optimization results based on the response surface for the hydrolysis of the petiole and midrib of kepok banana trees indicate that 110°C and 100 minutes are the conditions that yield the best conversion. According to [14], in heterogeneous reaction processes such as biomass hydrolysis, optimization of process parameters must account for kinetic and mass-transport limitations. This ensures that the optimum temperature and time conditions, as determined by the RSM model, not only reflect mathematical relationships but also strike a balance between chemical reactivity and product stability. The obtained model can provide a scientific basis for process design on a larger scale or in further research.

4. CONCLUSION

This research has successfully optimized the hydrolysis of cellulose from petioles and mibris of the kepok banana tree into glucose using diluted sulfuric acid as a catalyst. The optimization, conducted using Response Surface Methodology (RSM), revealed that the most effective hydrolysis condition was at 110°C and 100 minutes. Under this condition, the highest glucose conversion was (93.29%). The surface plots showed a strong interaction between temperature and time, confirming their significant effect on glucose yield. These results demonstrate that the petioles and midribs of banana waste, which are commonly discarded, have great potential as a renewable raw material for glucose production, supporting efforts to develop sustainable, locally sourced bio-based industries.

Based on the findings, it is recommended that future research focus on scaling up the optimized hydrolysis process to a pilot or industrial scale, including a techno-economic assessment to evaluate its feasibility. Additionally, integrating this hydrolysis process with downstream applications such as fermentation to bioethanol or hydrogenation to sorbitol can enhance the value chain and economic viability. Further exploration of pretreatment methods, accounting for the kinetics of the reaction process, alternative acid catalysts, or enzyme-assisted hydrolysis could also be considered to improve conversion efficiency while minimizing environmental impact. Utilization of other local agricultural residues with high cellulose content should be explored to support regional bioeconomy development.

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