



Sustainable Bioethanol Production from Carica (Carica pubescens) Peel Waste: Optimization of Acid Hydrolysis and Fermentation Time

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Abstract

The global energy crisis and continued reliance on fossil fuels have intensified the search for sustainable alternative energy sources, particularly biomass-derived biofuels. One promising yet underutilized resource is the peel waste of *Carica pubescens*, a papaya variety indigenous to the Dieng Plateau. This study investigates the potential of *Carica* peel waste as a bioethanol feedstock through sulfuric acid (H_2SO_4) hydrolysis and fermentation using *Saccharomyces cerevisiae*. To optimize sugar yield, the concentration of H_2SO_4 was varied between 0.1 M and 0.8 M, while fermentation durations were set at 96, 120, 144, and 168 hours. Results indicated that hydrolysis with 0.8 M H_2SO_4 produced the highest sugar concentration (6.8%). The most effective fermentation period was 120 hours, yielding 64% bioethanol with a density of 0.8679 g/mL, a calorific value of 4,831 kcal/kg, a flame height of 14.6 cm, and a combustion temperature of 438°C. These findings demonstrate the viability of *Carica* peel waste as a valuable raw material for bioethanol production. Its high efficiency and favorable fuel properties highlight its potential for integration into local renewable energy initiatives, contributing to sustainable energy development. Further studies on large-scale implementation and process optimization are recommended to maximize its industrial application.

Keywords: bioethanol; carica pubescens; fermentation; hydrolysis; biomass waste, optimization

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INTRODUCTION

The global demand for renewable energy has intensified due to concerns over fossil fuel depletion, environmental degradation, and climate change. In Indonesia, the demand for fuel oil in the last 5 years has always increased annually by 3%. These needs are met through domestic production and partly from imports. Domestic oil and gas production has decreased by 2% per year. This is due to the fact that oil and gas reserves in Indonesia have decreased a lot and the remaining old wells with a higher water content than the oil. To overcome this problem, it is necessary to diversify fuel into other fuels (Setyono & Kiono, 2021). The substitution of fossil energy with new and renewable energy (EBT) has a great opportunity because Indonesia has abundant natural resources. The use of EBT has increased every year with the use in 2014 amounting to 4.4% and increasing to 9.2% in 2019

(Siagian et al., 2023). The government in PP 79/2014 targets the role of EBT in 2025 at least 23% and in 2050 at least 31% (Peraturan Pemerintah Republik Indonesia No.79 Tahun 2014 Tentang Kebijakan Energi Nasional, 2014).

Among the various alternative energy sources, bioethanol has emerged as a viable solution due to its sustainable production potential and lower carbon footprint compared to conventional fossil fuels. Biomass-derived bioethanol, particularly from agricultural waste, offers a promising pathway for reducing dependency on petroleum-based fuels while addressing waste management issues. In this context, exploring underutilized biomass sources is essential for advancing sustainable energy solutions. One type of biomass that can be used as an alternative to bioethanol is food crop and plantation residues or waste (Setyono & Kiono, 2021).

Food crops and plantations produce large amounts of waste that can be converted into biofuels. Waste-to-energy conversion can be done through direct combustion, thermochemical conversion and biochemical conversion. Biochemical conversion is conversion through biochemical processes such as hydrolysis, fermentation, and anaerobic digestion. The process of making ethanol from biomass belongs to biochemical conversion (Figure 1) (Parinduri & Parinduri, 2020). Bioethanol is one of the most promising fuels to replace fossil fuels. In its production bioethanol requires 68% less energy than high-octane gasoline. Bioethanol production from waste is highly dependent on the composition of the waste. Besides affecting the amount of ethanol produced, the composition also affects the process (Bender et al., 2022).

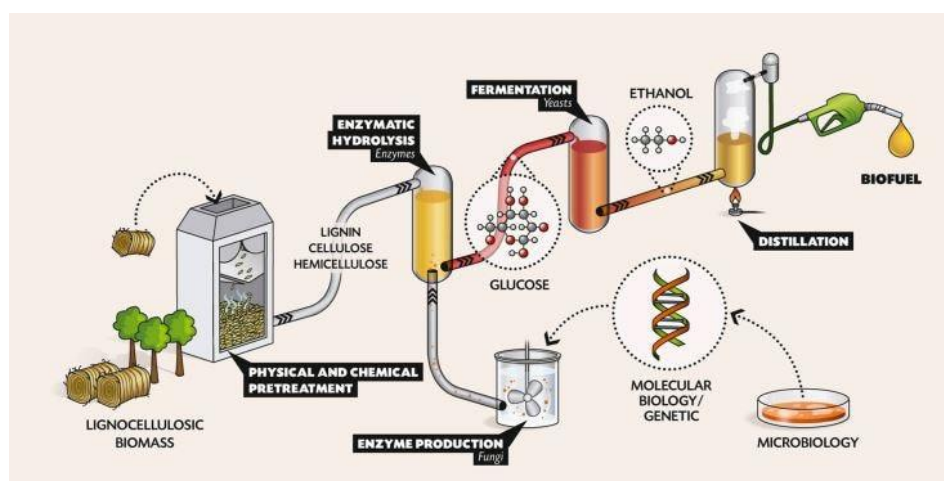


Figure 1. The bioethanol production process involves a series of complex stages, starting from the collection of raw materials to the production of bioethanol that is ready for use.

Papaya waste has great potential as a substrate for bioethanol production. Carica (*Carica pubescens*) is one of papaya variant native to the Dieng Plateau, generates significant peel waste during fruit processing, yet its potential as a bioethanol feedstock remains largely unexplored. Fruit peels are rich in carbohydrates, particularly cellulose and hemicellulose, which can be converted into fermentable sugars through hydrolysis. However, efficient hydrolysis and fermentation optimization are critical to maximizing sugar yield and ethanol production. Understanding the effects of acid hydrolysis concentration and fermentation duration is essential to developing an efficient bioconversion process that enhances bioethanol yield while maintaining economic and environmental viability (Tan & Oh, 2023).

In the process of producing bioethanol, sulfuric acid (H_2SO_4) hydrolysis has been widely utilized for lignocellulosic biomass pretreatment due to its ability to break down complex polysaccharides into fermentable sugars. However, determining the optimal acid concentration for hydrolysis without excessive degradation of fermentable sugars is a crucial step in enhancing bioethanol production efficiency. Similarly, fermentation conditions, including duration, microbial activity, and environmental factors, influence ethanol yield. Optimizing these parameters is necessary to develop a practical and scalable bioethanol production process (Amanullah & Kapilan, 2021).

In addition, pH and fermentation temperature strongly influences the concentration of ethanol produced from papaya waste. The optimum pH for fermentation is in the range of 3.0-4.8. The effect of temperature is more dominant than pH. Ethanol production increases with increasing temperature up to 45°C (Tan & Oh, 2023). Through optimization of fermentation conditions, bioethanol yield significantly increased to 3.7% (v/v), which is 6.2 times higher than the initial conditions (Amanullah & Kapilan, 2021). The use of *S. cerevisiae* immobilized in PVA-alginate increases the fermentation efficiency and allows cell reuse. The optimum fermentation conditions produced 0.514 g/L bioethanol (Abdulla et al., 2018).

Although various studies have been conducted on papaya waste, the focus on local varieties such as *Carica pubescens* (*Carica Dieng*) is still limited. *Carica Dieng*, which grows in the highlands of Dieng, Central Java, has unique characteristics that set it apart from regular papaya, including different sugar and fiber content. The potential of *Carica Dieng* peel waste as bioethanol raw material has not been widely explored, thus opening up further research opportunities. Several studies related to bioethanol from papaya waste have been conducted, but have not specifically examined *Carica Dieng* skin. *Carica* skin, which has only been a waste, has not received attention in research as an alternative energy source. Therefore, this research focuses on making bioethanol from carica peel waste (*carica pubescens*) through yeast fermentation process.

The findings from this study are expected to contribute to the development of sustainable energy initiatives while promoting the utilisation of agricultural waste. Ultimately, the integration of *Carica* peel waste into bioethanol production offers opportunities to address various sustainability challenges, including waste reduction, energy security, and environmental conservation.

METHOD

The methodology employed in this study involved several key stages to optimize bioethanol production from *Carica pubescens* peel waste. Initially, *Carica* peels were collected, thoroughly washed, dried at 70°C for 24 hours, and ground into fine powder for processing (Abdulla et al., 2018). Hydrolysis was conducted by mixing the peel powder with distilled water at a 10% (w/v) ratio, followed by preheating at 121°C for 15 minutes. The cooled mixture was treated with varying sulfuric acid (H_2SO_4) concentrations (0.1 M – 0.8 M) to maximize sugar extraction, with pH subsequently adjusted to 5 (Putri et al., 2024). The hydrolyzed solution with the highest sugar content was selected for fermentation using *Saccharomyces cerevisiae*, with additional nutrients—NPK (3% w/v) and urea (1% w/v)—to enhance microbial activity (Mulyadi et al., 2023).

Fermentation times were varied at 96, 120, 144, and 168 hours to determine optimal ethanol yield. After fermentation, manual redistillation was performed until ethanol concentration stabilized, and the final ethanol concentration was measured using an alcohol refractometer (Hargono et al., 2024). Bioethanol characterization involved calorific value assessment using a Bomb Calorimeter (IKA C200), density measurement via a DMA 4100 density meter (ASTM D4052-22 method), and flame tests to evaluate combustion properties, including flame height, burning duration, and combustion temperature. This comprehensive methodological approach allowed for the determination of optimal hydrolysis and fermentation conditions, ensuring efficient bioethanol production from *Carica pubescens* peel waste as a sustainable energy source. The flowchart for this study can be seen in **Figure 2**.

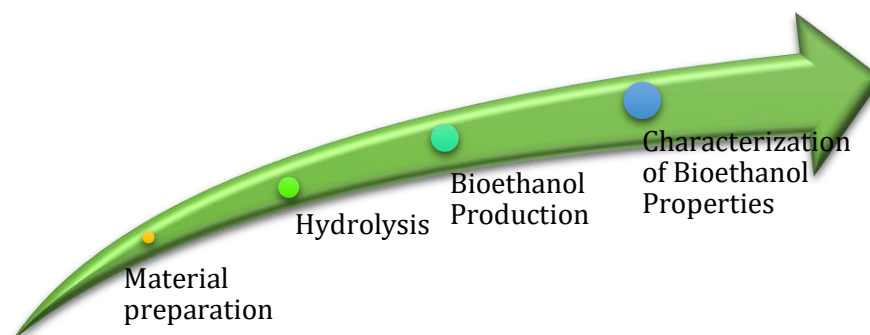


Figure 2. The process of producing bioethanol from carica waste to measuring its properties

RESULTS AND DISCUSSION

Effect of H₂SO₄ concentration on sugar content

From the hydrolysis process of carica peel with H₂SO₄ concentrations of 0.1 M, 0.2 M, 0.3 M, 0.4 M, 0.6 M and 0.8 M produced different sugar content as in **Table 1**. The highest sugar content was obtained at a concentration of 0.8 M. An increase in the concentration of H₂SO₄ used as a catalyst led to higher sugar yields (Kiswanto & Rubianto, 2023; Julian et al., 2024; Aksari, 2024). The increase in sugar content is caused by the breakdown of cellulose in Carica peel into glucose. However, excessive use of acid catalyst causes sugars such as glucose to be broken down into HMF (hydroxy methyl furfural) and furfural compounds which reduce the glucose content produced (P. A. Wulandari et al., 2023).

Table 1. Sugar content of hydrolysis results

Concentration (M)	Sugar content (%)
0.1	1.4
0.2	4.6
0.3	4
0.4	6
0.6	6.4
0.8	6.8

Effect of fermentation duration on bioethanol

Fermentation duration does not always have a positive effect on bioethanol yield. Initially, extending the fermentation time increases bioethanol concentration, but beyond a certain point, the yield begins to decline. In this study, fermentation time increased bioethanol content up to 120 hours, after which the ethanol level declined. The increase in bioethanol concentration in the early phase of fermentation is attributed to the active metabolic activity of yeast during its exponential growth phase. During this phase, the number of yeast cells increases rapidly, and their enzymatic activity significantly intensifies. Yeast actively produces enzymes that play a key role in converting glucose into ethanol, resulting in the highest bioethanol yield (Rizaldi et al., 2022).

Tabel 2. Bioethanol analysis results

Fermentation Time (Hour)	Bioethanol content (%)
96	60
120	64
144	62
168	60

Beyond 120 hours of fermentation, a decrease in ethanol concentration was observed, which is attributed to the slowing of yeast growth due to the depletion of essential nutrients, particularly glucose (**Table 2**) (Yumas & Rosniati, 2014). After surpassing the optimal fermentation period, yeast cells enter the death phase, leading to the production of organic acids such as lactic acid, acetic acid, and esters. These organic acids act as impurities, thereby reducing the final ethanol content (Putra & Sanjaya, 2020).

Bioethanol density analysis

The density measurements presented in **Table 3** indicate that fermentation for 120 hours resulted in the lowest density, 0.8679 g/mL. Lower density is an indicator of increased ethanol purity, as ethanol has a lower density compared to water and other impurities. Compared to findings from other studies (**Table 4**), the bioethanol density observed in this study (ranging from 0.8679–0.8775 g/mL) falls within an acceptable range and tends to approach optimal values. Density can serve as an indirect parameter to evaluate ethanol concentration and purity. The closer the density is to pure ethanol (0.789 g/mL at 20°C), the higher the ethanol concentration. This trend aligns with the bioethanol content data in **Table 2**, which shows that higher ethanol content corresponds to lower density. From **Tables 2** and **Table 3**, it is evident that ethanol content trends inversely with density

(Figure 3). Thus, optimizing fermentation time is crucial to producing bioethanol with optimal density, which reflects high product quality.

Table 3. Bioethanol density

Fermentation Time (Hour)	Density (g/ml)
96	0.8775
120	0.8679
144	0.8714
168	0.8751

Table 4. Bioethanol density from several studies

No	Raw Material	Bioethanol Density (g/mL)	Source
1	Sago Waste	0.82	(Numberi, 2022)
2	Tobacco Stalks	0.99569	(P. F. Wulandari et al., 2023)
3	Empty Palm Fruit Bunches	0.8757	(Khairiah & Ridwan, 2021)
4	Fruit Waste	0.924–0.9832	(Amarasinghe et al., 2024)

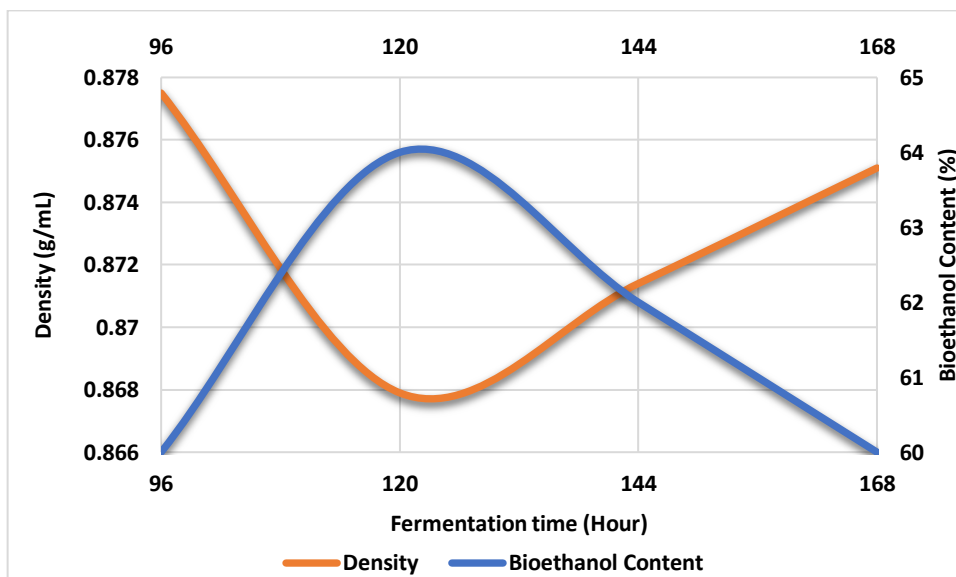


Figure 3. Comparison of bioethanol density and ethanol content

Bioethanol calorific value analysis

The calorific value of the produced bioethanol increased from 96 to 120 hours, reaching a peak at 4,831 kcal/kg. This increase is directly associated with the elevated ethanol concentration in the mixture. Ethanol, as the principal component of bioethanol, has a high calorific value, approximately 7,097 kcal/kg (29.7 MJ/kg) in its pure form (Hakkarainen et al., 2017). After 120 hours, the calorific value decreased at 144 hours and further declined at 168 hours. This drop is consistent with the reduction in ethanol concentration (Tables 2 and Table 5). Hence, the higher the ethanol content, the greater the energy produced during combustion.

Table 5. Calorific value of bioethanol

No	Fermentation Time (Hours)	Calorific Value (kcal/kg)
1	96	4,629
2	120	4,831
3	144	4,775
4	168	4,657

Flame test analysis

The results indicate that the burning duration of bioethanol derived from Carica peel varies with fermentation time. The sample fermented for 120 hours exhibited the longest combustion time at 218 seconds. Although this is slightly lower than the 230 seconds reported by [Sindunatha & Muhaji \(2019\)](#) for tomato-based bioethanol, the discrepancy may be attributed to differences in raw material characteristics and ethanol concentration. The flash point of a fuel influences its combustion time. The higher the flash point, the more stable and prolonged the combustion, due to slower vaporization and efficient burning.

Table 6. Flame Test Results

No	Fermentation Time (Hours)	Burning Time (s)	Flame Height (cm)	Flame Temperature (°C)
1	96	197	11.8	427
2	120	218	14.6	438
3	144	213	14.4	434
4	168	203	12.2	430

The flame temperature also increased with fermentation time, peaking at 438°C at 120 hours. This temperature is close to the 452.3°C reported for tomato-based ethanol ([Sindunatha & Muhaji, 2019](#)). The increase in flame temperature correlates with the ethanol concentration in the bioethanol. The higher the ethanol content, the greater the heat released during combustion. This highlights that optimal fermentation improves combustion performance by increasing energy yield and efficiency.

Flame height also fluctuated with fermentation time. The highest flame, 14.6 cm, occurred at 120 hours of fermentation. Flame height is influenced by the chemical composition of the fuel, particularly its carbon and hydrogen content, as well as fuel density. According to [Sindunatha & Muhaji \(2019\)](#), flame height is inversely related to fuel density. Higher density leads to lower fluid pressure, resulting in shorter flame heights. Therefore, the quality of bioethanol is determined not only by ethanol concentration but also by other physicochemical properties that affect combustion behavior.

CONCLUSION

This study demonstrates that Carica pubescens peel waste has significant potential as a raw material for bioethanol production through acid hydrolysis and fermentation using *Saccharomyces cerevisiae*. The optimal H₂SO₄ concentration for hydrolysis was 0.8 M, yielding the highest sugar content of 6.8%. While increasing the H₂SO₄ concentration enhances sugar yield, excessive levels pose the risk of forming inhibitory compounds such as HMF, which can reduce the efficiency of glucose conversion into bioethanol. The optimal fermentation duration for bioethanol production was 120 hours, resulting in the highest bioethanol concentration of 64%, the lowest density (0.8679 g/mL), and the highest calorific value (4,831 kcal/kg). Beyond this duration, ethanol content declined due to nutrient depletion and yeast cell death. Physical characterization revealed that bioethanol obtained from the 120-hour fermentation exhibited superior quality, with the highest flame height (14.6 cm), the longest burning time (218 seconds), and the highest flame temperature (438°C), indicating optimal combustion efficiency. In conclusion, fermentation for 120 hours produces high-quality bioethanol with maximum ethanol content and physicochemical properties that enhance combustion efficiency. Furthermore, H₂SO₄ usage in hydrolysis must be optimized to maximize sugar yield while minimizing the formation of inhibitory compounds. This study confirms that Carica pubescens peel is a promising raw material for bioethanol production, with optimal parameters that can enhance efficiency and product quality.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest concerning the publication of this article. The authors also confirm that the data and the article are free of plagiarism.

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