TOLEDO-VILLOSLADA, J. A.; CASSANA-HUAMÁN, I. A.; DA-FONSECA, M. V.; CARDOZO-SOAREZ, J.; PORTAL-CAHUANA, L. A. Bioethanol from *Musa paradisiaca* waste as a sustainable alternative in Amazonas, Peru. **Revista de Agricultura Neotropical**, Cassilândia-MS, v. 12, n. 1, e9041, Jan./Mar., 2025. ISSN 2358-6303. DOI: https://doi.org/10.32404/rean.v12i1.9041.

Bioethanol from *Musa paradisiaca* waste as a sustainable alternative in Amazonas, Peru

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Received: 12/08/2024; Accepted: 30/01/2025.

ABSTRACT

The production of bioethanol from organic waste is a promising option for sustainability. This study evaluated the quality of bioethanol obtained from bellaco plantain (*Musa paradisiaca*) waste in Amazonas, Peru. A total of 45 samples were used with different waste-to-water ratios: 0.5 kg per 5.5 liters, 1 kg per 5 liters, 1.5 kg per 4.5 liters, 2 kg per 4 liters, and 2.5 kg per 3.5 liters. Fermentation was conducted for 192, 196 and 200 hours. No significant differences were observed among the analyzed waste-to-water concentrations. However, fermentation time significantly affected the alcohol content. At 192 hours, the average alcohol content was 60.69%, while at 196 and 200 hours, it was 34.64% and 44.38%, respectively. Fermentation at 192 hours resulted in a significantly higher alcohol content compared to 196 and 200 hours. These findings suggest that a 192-hour fermentation period is the most efficient for obtaining high-quality bioethanol, with potential economic and quality benefits.

Keywords: Agricultural waste; Green ethanol; Renewable energy.

Bioetanol a partir de resíduos de *Musa paradisiaca* como uma alternativa sustentável no Amazonas, Peru

RESUMO

A produção de bioetanol a partir de resíduos orgânicos é uma opção promissora para a sustentabilidade. Este estudo avaliou a qualidade do bioetanol obtido a partir de resíduos de banana-da-terra (*Musa paradisiaca*) no Amazonas, Peru. Foram utilizadas 45 amostras com diferentes proporções de resíduo e água: 0,5 kg por 5,5 litros, 1 kg por 5 litros, 1,5 kg por 4,5 litros, 2 kg por 4 litros e 2,5 kg por 3,5 litros. A fermentação foi realizada em 192, 196 e 200 horas. Não houve diferença entre as concentrações de resíduo e água testadas. O tempo de fermentação afetou significativamente o teor de álcool. Após 192 horas, o teor médio de álcool foi de 60,69%, enquanto após 196 e 200 horas, foi de 34,64% e 44,38%, respectivamente. A fermentação por 192 horas produziu um teor de álcool significativamente mais alto do que em 196 e 200 horas. Esses resultados sugerem que a fermentação de 192 horas é a mais eficiente para obter bioetanol de alta qualidade, com possíveis benefícios econômicos e de qualidade.

Palavras-chave: Energia renovável; Etanol verde; Resíduos agrícolas.

1. Introduction

The urgent need for sustainable alternatives to fossil fuels has driven interest in bioethanol as a viable solution to mitigate the environmental impact of greenhouse gas emissions. Bioethanol, a biofuel produced from biomass, offers a renewable alternative to fossil fuels and can play a crucial role in the transition toward cleaner energy sources (Bušić et al., 2018). This compound, primarily obtained from sugar and starch-rich raw materials, has been shown to have a significantly lower environmental impact compared to traditional fuels (Sarkar et al., 2012). However, the efficient production of bioethanol faces technical challenges, such as the pretreatment of lignocellulosic biomass, which is essential for improving sugar conversion into ethanol (Cutzu & Bardi, 2017).

The use of agricultural waste, such as banana peels, represents a significant opportunity to enhance the sustainability of bioethanol production. Several studies have investigated the feasibility of using this waste as a raw material for bioethanol production. Bala et al. (2023) highlighted that banana waste can be effectively pretreated and fermented, yielding competitive bioethanol production compared to other substrates. Zulnazri et al. (2023) also emphasized the effectiveness of Kepok banana peels in bioethanol production, underscoring the importance of optimizing hydrolysis and fermentation conditions to achieve higher yields. Additionally, research by Rincón-Catalán et al. (2022) has demonstrated that banana waste, along with other agro-industrial residues, can be used to generate bioenergy through processes such as anaerobic digestion and microbial fuel cells.

Peru’s agricultural production has experienced significant growth and transformation in recent years, particularly in the export sector. The country has seen a rise in agricultural exports, with products such as blueberries rapidly becoming a key export commodity, generating substantial revenue and positioning Peru as one of the world's leading exporters (Bell et al., 2023). This expansion has contributed to a nearly tenfold increase in the value of agricultural exports, rising from approximately $200 million in 2001 to $1.95 billion in 2022 (Magallanes et al., 2023). Furthermore, Peru's agricultural sector has demonstrated high levels of competitiveness, with products such as grapes, blueberries, and avocados showing strong performance in international markets (Escalante et al., 2023).

The expansion of non-traditional agricultural exports, including blueberries, has been supported by large-scale agro-industrial investments, government initiatives and favorable geographic conditions in regions such as Áncash, La Libertad, Cajamarca, and Piura (Bell et al., 2023). This study aims to explore and optimize bioethanol production from bellaco plantain waste in the Amazonas region of Peru and contribute to understanding how different fermentation process variables influence the efficiency and quality of the bioethanol produced. The research focuses on improving the process efficiency by evaluating variables such as waste-to-water ratio, fermentation time and yeast type to assess their impact on bioethanol yield (Domínguez-Bocanegra et al., 2015; Shitophyta et al., 2023). This study is relevant not only for waste management in tropical regions but also for the development of sustainable bioethanol production strategies.

2. Material and Methods

The study was conducted in the locality of Valencia, a rural settlement in the district of Aramango, Bagua province, in the Amazonas region of Peru (Llique, 2011) (Figure 1). Geographically, this area is located in a transitional zone between the tropical dry forest and the premontane tropical humid forest (Romo et al., 2009), characterized by high biodiversity and a substantial biomass availability for bioethanol studies. The selection of this location was justified by the abundance of bellaco plantain (*Musa paradisiaca*) (INEI, 2022), whose waste is particularly suitable for bioethanol production due to its high fermentable sugar content.

Valencia serves as an ideal model for this study, as it reflects the typical conditions of tropical agricultural regions where crop residues are often underutilized (GORE Amazonas, IIAP, 2010). Additionally, this locality faces challenges in organic waste management, making this research an opportunity to address local environmental issues while contributing to the development of sustainable energy solutions. The proximity to cultivated areas and the availability of basic infrastructure for waste collection and processing ensure the project's feasibility and the relevance of its findings for similar communities in the Amazon region.

This study focuses on the production of bioethanol from *bellaco* plantain (*Musa paradisiaca*) waste in the district of Aramango, Bagua – Amazonas. The main objective is to assess the feasibility of utilizing this agricultural waste for bioethanol generation, thereby contributing to sustainable energy solutions and waste management in tropical regions. The *bellaco* plantain was selected due to its high production in the area and the significant amount of organic waste it generates, which is often not fully utilized (INEI, 2022). This species serves as an appropriate model for the study, as its processing into bioethanol has not only energy implications but also environmental and socioeconomic benefits, offering a practical approach for improving sustainability in similar agricultural communities.

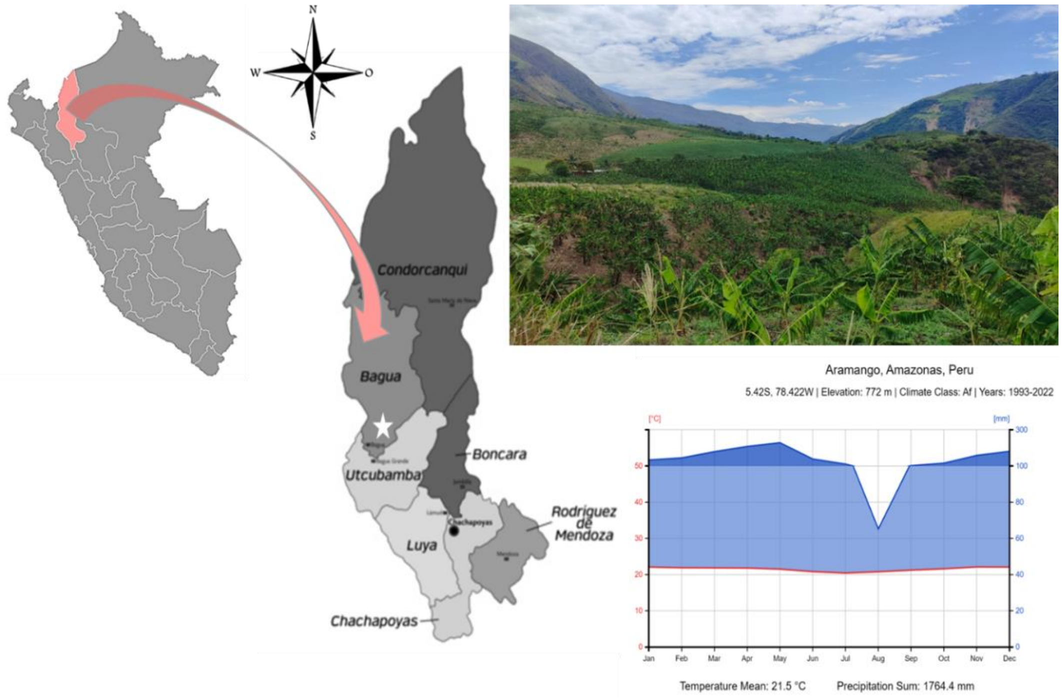

Figure 1. Location of the study area within the equatorial dry forest, Valencia (white star). Additionally, an image is provided to illustrate the site along with a climatic diagram of the Aramango district (Walter & Lieth, 1960).

A total of 67.5 kg of *bellaco* plantain peels and 67.5 liters of water were used for ethanol production. Forty-five plantain peel samples were prepared, weighing between 0.5 kg and 2.5 kg, along with 45 water samples ranging from 3.5 L to 5.5 L (Table 1). The pretreatment aimed to maximize sugar accessibility, minimize carbohydrate decomposition and by-product formation that could affect microbial fermentation efficiency, and ensure economic viability (Araneda et al., 2019).

To achieve optimal pretreatment efficiency, the best conditions among the available raw materials were selected.

A refining process was subsequently carried out to remove impurities and excess materials that could hinder ethanol production (García, 2021). The plantain peels were removed and cut into pieces of approximately 3 cm^2. A completely randomized design based on variance analysis was employed, allowing the determination of ethanol purity differences according to the varying concentrations of plantain samples, verifying their feasibility as a biofuel source.

Each sample was boiled at a constant temperature of 100 °C for 20 minutes, using different plantain-to-water ratios. The samples were categorized as follows:

Table 1. Proportions of plantain and water used in the treatments

Treatment	Plantain Quantity (kg)	Water Volume (L)
No. 1	2.5	3.5
No. 2	2.0	4.0
No. 3	1.5	4.5
No. 4	1.0	5.0
No. 5	0.5	5.5

The boiling process and concentrations were consistently applied across three fermentation series, each lasting 192 hours. The fermentation duration of 192 hours was selected based on studies reporting that this period achieves maximum ethanol yield. For example, *Lenzites betulinus* has been shown to reach its highest sugar-to-ethanol conversion efficiency after 192 hours, ensuring optimal process performance and minimizing residual sugars that could interfere with the bioethanol quality (Im et al., 2016).

After boiling, the samples were blended to release cellulose. *Saccharomyces cerevisiae* yeast was used for the fermentation process due to its high capacity to ferment sugars present in lignocellulosic residues and its wide commercial availability (García, 2021). A concentration of 0.5 g/L of active dry yeast was added to each blended sample. The yeast was pre-hydrated in warm water for 15 minutes to activate its metabolism before being incorporated into the fermentation medium. During fermentation, conditions were controlled to ensure an initial pH of 5.5, a constant temperature of 30 °C, and periodic agitation to maintain system homogeneity and prevent sedimentation. These conditions were selected to maximize the conversion efficiency of sugars into bioethanol.

Forty-five fermentation containers with appropriate sealing were used for sample fermentation. The blended samples were placed in airtight containers with a duct leading to a water-filled bottle to prevent oxygen exchange. Fermentation was monitored daily by observing CO_2 production and ethanol purity. Once the fermentation was completed, the samples were filtered using a fine mesh to separate the organic material from the liquid. The filtered liquid was distilled at a precise temperature of 78 °C, where it was evaporated and passed through a condenser to obtain ethanol.

The ethanol purity of each sample was measured using a refractometer (ATC alcohol 0–80% V/V). The sample with the highest purity underwent additional tests to assess its suitability for use, including chemical property analyses such as acidity, halogenation, dehydration, oxidation, chlorination and combustion.

To evaluate the influence of different factors on alcohol concentration, an analysis of variance (ANOVA) was conducted using the R statistical software (R Core Team, 2019).

The factors considered were "Fermentation Time," "Treatment" and "Replication." Three replicates were conducted for each treatment and fermentation time, ensuring a robust statistical analysis and determining significant differences between the evaluated conditions. A completely randomized design based on variance analysis was used to identify significant differences among different factor levels. Significance levels were indicated as follows: *** ($p < 0.001$), ** ($p < 0.01$), * ($p < 0.05$), and ($p < 0.1$).

A Tukey multiple comparison test was subsequently performed to identify significant differences between the different levels of the "Fermentation Time" factor. This analysis compared the mean alcohol concentrations produced at different fermentation times and determined which groups exhibited statistically significant differences.

To examine the dynamics of bioethanol production over fermentation time, a temporal trend analysis was performed. This analysis observed variations in alcohol concentration as a function of time and assessed fermentation efficiency at different stages.

A correlation analysis using Pearson's correlation coefficient was conducted to evaluate the relationship between fermentation time and ethanol concentration. This analysis helped to determine the direction and magnitude of the relationship between these two variables, providing deeper insights into the factors influencing bioethanol production.

3. Results and Discussion

The analysis of variance (ANOVA) was conducted for the factors "Fermentation Time", "Treatment" and "Replication", as well as for residuals. Asterisks (*) in the table indicate statistical significance levels, where *** represents a p-value < 0.001, ** a p-value < 0.01, * a p-value < 0.05 and a p-value < 0.1. According to the ANOVA results, the factor "Fermentation Time" showed statistical significance ($p < 0.05$), indicating significant differences in ethanol content based on the fermentation durations evaluated.

In the experiment, five treatments were evaluated, each with different raw material-to-water ratios: 2.5 kg of plantain per 3.5 L of water, 2 kg of plantain per 4 L of water, 1.5 kg of plantain per 4.5 L of water, 1 kg of plantain per 5 L of water, and 0.5 kg of plantain per 5.5 L of water. Each treatment was conducted in triplicate to ensure the robustness and reliability of the data obtained.

In contrast, the factors "Treatment" and "Replication" were not statistically significant, as their p-values were greater than 0.05. This indicates that variations in raw material-to-water proportions, as well as differences between replications, did not significantly affect the ethanol content. These results are detailed in Table 2.

Following the Tukey test (Figure 2), significant differences were found in ethanol content among the evaluated fermentation times. The results indicate that the 192-hour fermentation (group "a") exhibited a significantly higher ethanol content compared to the 196-hour and 200-hour fermentations, which correspond to groups "b" and "c," respectively. This suggests that fermentation duration has a significant impact on ethanol content obtained from *bellaco* plantain (*M. paradisiaca*) waste in the district of Aramango, Bagua – Amazonas.

Beyond the observed variations in fermentation time, the temporal trend analysis (Figure 3) also revealed significant differences among the treatments used. Treatments with a higher raw material-to-water ratio, specifically those with 2.5 kg of raw material per 3.5 L of water and 2 kg of raw material per 4 L of water, consistently showed higher ethanol content values compared to the other treatments. These findings suggest that raw material-to-water proportion may have a significant impact on bioethanol production efficiency. These differences should be considered when designing and optimizing the fermentation process to ensure optimal bioethanol production.

The correlation matrix analysis showed a moderate negative correlation between the variable "Fermentation Time" and "Ethanol Content", with a correlation coefficient of -0.29. This indicates that as fermentation time increases, ethanol content tends to decrease.

Table 2. Analysis of Variance (ANOVA)

Factor	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Fermentation Time	2	5181	2591	60.779	2.88e-12***
Treatment	4	17151	14288	100.599	<2e - 16
Replication	2	4	2	0.047	0.954
Residual	36	1534	43		

Significance levels: *** (p < 0.001), ** (p < 0.01), * (p < 0.05), (p < 0.1), ns (not significant).

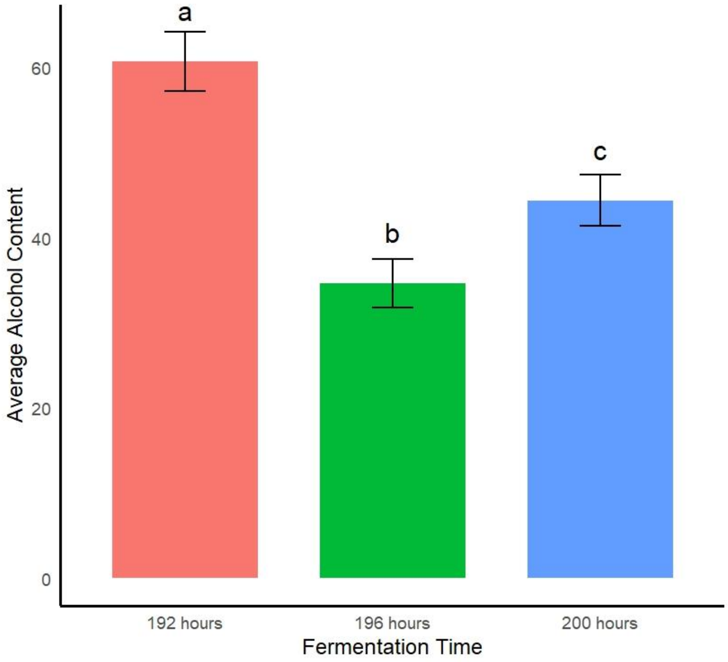

Figure 2. Ethanol Content by Fermentation Time and Group.

However, the magnitude of this correlation is not very strong, suggesting that other factors may also influence ethanol content beyond fermentation time (Figure 4). In detail, the results showed that rotten plantain was more efficient than rotten watermelon in bioethanol production, yielding 13.17% ethanol compared to 10.36%, respectively. This finding aligns with previous research demonstrating the feasibility of plantain peels as a raw material for bioethanol (Zulnazri et al., 2023; Shitophyta et al., 2023). The superior efficiency of rotten plantain may be attributed to its higher fermentable sugar content compared to watermelon, which is supported by literature indicating that plantain waste has a high concentration of starch and carbohydrates, facilitating higher ethanol yields (Sarkar et al., 2012; Budiastuti et al., 2023).

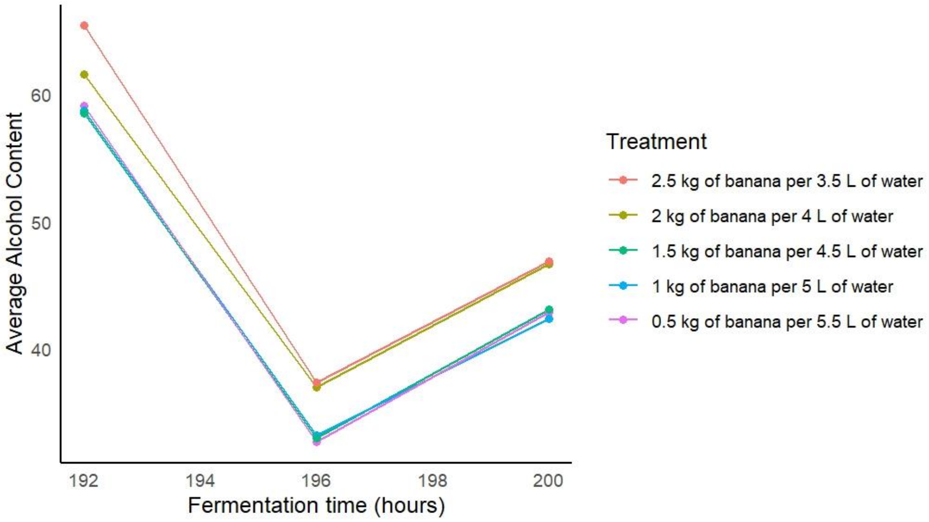

Figure 3. Temporal Trend Analysis of Ethanol Content.

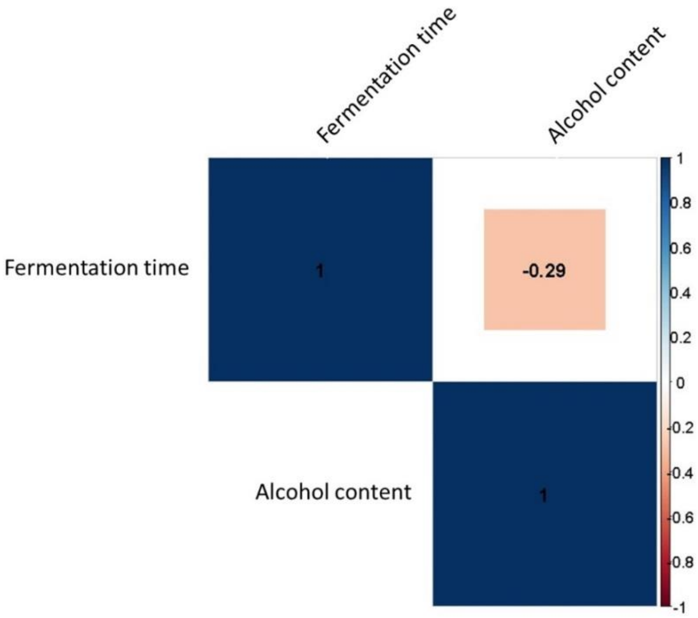

Figure 4. Correlation Matrix between "Fermentation Time" and "Ethanol Content".

Compared to the study by Kanthavelkumaran et al. (2023), which used pineapple and plantain peels with *Aspergillus niger* TISTR 3063, our study achieved a higher ethanol yield with rotten plantain, suggesting that substrate selection significantly impacts bioethanol production efficiency. Furthermore, our results align with the research by Shitophyta et al. (2023), which found that ethanol yield can vary significantly depending on the yeast strain used. The superiority of *Saccharomyces cerevisiae* over other yeasts in our study also supports these findings.

Conversely, studies by Budiastuti et al. (2023) and Domínguez-Bocanegra et al. (2015) showed that fermentation time and process conditions play a crucial role in bioethanol concentration, which was corroborated in our study, where variations in the fermentation process significantly impacted ethanol production. The results obtained with rotten plantain were superior to those using other substrates, suggesting that, in addition to substrate selection, fermentation time and conditions play a key role in optimizing bioethanol production.

Overall, our findings highlight the effectiveness of rotten plantain as a raw material for bioethanol production and underscore the need to continue exploring and optimizing the process to improve efficiency and reduce costs. Comparisons with previous studies indicate that, while using organic waste for bioethanol production is promising, there are still opportunities to enhance process efficiency through fermentation adjustments and condition optimization.

4. Conclusions

The ratio of plantain kilograms to liters of water does not significantly influence bioethanol production. However, fermentation time is a determining factor: at 192 hours, the highest ethanol content (60.69%) was obtained, surpassing 196 hours (34.64%) and 200 hours (44.38%). This confirms that 192-hour fermentation is the most efficient for producing high-quality bioethanol, offering economic benefits and potential for sustainable applications.

Authors' Contribution

Joel Abner Toledo-Villoslada: Contributed to the investigation, methodology, read and approved the final manuscript. Ingrid Aracelli Cassana-Huamán: Contributed to the software, formal análisis and read and approved the final manuscript. Mauro Vela Da-Fonseca: Contributed to the investigation, methodology, read and approved the final manuscript. Jorge Cardozo-Soarez: Contributed to writing and reviewing of the manuscript, read and approved the final manuscript. Leif Armando Portal-Cahuana: Contributed to the conception, experimental work and interpretation of the analyzed data, writing and reviewing of the manuscript, read and approved the final manuscript.

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