Biological Production of Glucose Syrup from Dominico-Hartón Banana Peel (Musa paradisiaca spp.): Effect of Ripening Stage and Electromagnetic Field Pretreatment

Producción biológica de jarabe de glucosa a partir de cáscara de plátano Dominico-Hartón (Musa paradisiaca spp.): Efecto de la etapa de maduración y el pretratamiento con campo electromagnético

Produção biológica de xarope de glicose a partir da casca da banana Dominico-Hartón (Musa paradisiaca spp.): efeito do estágio de maturação e do pré-tratamento com campo eletromagnético

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Abstract

The valorization of agro-industrial residues represents a sustainable alternative to producing high value-added bioproducts. This study evaluated the effect of the maturity stage of Dominico-Hartón plantain peel (green, ripe, and overripe), substrate concentration (10, 20, and 30%), and the application of low-intensity electromagnetic fields on the production of glucose syrup obtained through biological hydrolysis using Trichoderma viride. The experiment was conducted under a completely randomized 3 × 3 × 2 factorial designs comprising a total of 54 experimental units. The peels were subjected to drying, grinding, and electromagnetic treatment prior to fermentation. Bromatological parameters, pH, glucose content, and refractometric behavior were determined as indicators of the conversion process. The results revealed differences associated with both the maturity stage and the electromagnetic treatment. Ripe and overripe peels exhibited greater availability of fermentable sugars and improved performance during hydrolysis. The application of the electromagnetic field enhanced the conversion of starch into glucose, increasing viscosity and facilitating the hydrolytic activity of the microorganism. Furthermore, an increasing trend in glucose content was observed after 72 h of fermentation, particularly in treatments with higher substrate concentrations. The findings suggest that plantain peel is a promising feedstock for the sustainable production of glucose syrup and that the incorporation of electromagnetic fields constitutes a technological strategy capable of improving process efficiency. These results contribute to the integrated utilization of agro-industrial residues and support the development of bioeconomy and circular economy models.

Keywords: circular economy; agro-industrial residues; biological hydrolysis; glucose; Trichoderma viride.

Resumen

La valorización de residuos agroindustriales constituye una alternativa sostenible para la generación de bioproductos de alto valor agregado. En este estudio se evaluó el efecto del estado de madurez de la cáscara de plátano Dominico-Hartón (verde, madura y sobremadura), la concentración del sustrato (10, 20 y 30%) y la aplicación de campos electromagnéticos de baja intensidad sobre la producción de jarabe de glucosa obtenido mediante hidrólisis biológica con Trichoderma viride. La investigación se desarrolló bajo un diseño factorial completamente aleatorizado 3×3×2 con un total de 54 unidades experimentales. Las cáscaras fueron sometidas a secado, molienda y tratamiento electromagnético previo a la fermentación. Se determinaron parámetros bromatológicos, pH, contenido de glucosa y comportamiento refractométrico como indicadores del proceso de conversión. Los resultados evidenciaron diferencias asociadas al estado de madurez y al tratamiento electromagnético. Las cáscaras maduras y sobremaduras presentaron mayor disponibilidad de azúcares fermentables y mejor comportamiento durante la hidrólisis. La aplicación del campo electromagnético favoreció la conversión del almidón a glucosa, incrementando la viscosidad y facilitando la acción hidrolítica del microorganismo. Asimismo, se observó una tendencia de incremento en los contenidos de glucosa después de 72 h de fermentación, particularmente en los tratamientos con mayores concentraciones de sustrato. Los hallazgos sugieren que la cáscara de plátano constituye una materia prima promisoria para la obtención sostenible de jarabe glucosado y que la incorporación de campos electromagnéticos representa una estrategia tecnológica capaz de mejorar la eficiencia del proceso. Estos resultados contribuyen al aprovechamiento integral de residuos agroindustriales y fortalecen el desarrollo de modelos de bioeconomía y economía circular.

Palabras clave: economía circular, residuos agroindustriales, hidrólisis biológica, glucosa, Trichoderma viride.

Resumo

A valorização de resíduos agroindustriais constitui uma alternativa sustentável para a geração de bioprodutos de alto valor agregado. Este estudo avaliou o efeito do estádio de maturação da casca da banana Dominico-Hartón (verde, madura e supermadura), da concentração do substrato (10, 20 e 30%) e da aplicação de campos eletromagnéticos de baixa intensidade na produção de xarope de glicose obtido por hidrólise biológica com Trichoderma viride. A pesquisa foi conduzida utilizando um delineamento fatorial inteiramente casualizado 3×3×2 com um total de 54 unidades experimentais. As cascas foram submetidas à secagem, moagem e tratamento eletromagnético antes da fermentação. Parâmetros bromatológicos, pH, teor de glicose e comportamento refratométrico foram determinados como indicadores do processo de conversão. Os resultados mostraram diferenças associadas ao estádio de maturação e ao tratamento eletromagnético. Cascas maduras e supermaduras apresentaram maior disponibilidade de açúcares fermentáveis e melhor desempenho durante a hidrólise. A aplicação de um campo eletromagnético promoveu a conversão do amido em glicose, aumentando a viscosidade e facilitando a ação hidrolítica do microrganismo. Além disso, observou-se uma tendência crescente no teor de glicose após 72 horas de fermentação, particularmente nos tratamentos com maiores concentrações de substrato. Esses resultados sugerem que a casca de banana é uma matéria-prima promissora para a produção sustentável de xarope de glicose e que a incorporação de campos eletromagnéticos representa uma estratégia tecnológica capaz de melhorar a eficiência do processo. Esses resultados contribuem para a utilização integral de resíduos agroindustriais e fortalecem o desenvolvimento de modelos de bioeconomia e economia circular.

Palavras-chave: economia circular, resíduos agroindustriais, hidrólise biológica, glicose, Trichoderma viride.

Introduction

The transition toward sustainable production systems has driven the development of strategies aimed at the integrated utilization of agro-industrial residues in alignment with the principles of bioeconomy and circular economy. Globally, a significant proportion of the waste generated along agri-food value chains consists of biomass rich in lignocellulosic compounds, starches, and sugars that can potentially be converted into value-added bioproducts. In this context, the valorization of agricultural by-products not only contributes to reducing the environmental burdens associated with waste disposal but also promotes the generation of alternative feedstocks for the food, energy, and biotechnology industries (Acevedo et al., 2021; Silva et al., 2025). Several studies have demonstrated that fruit-processing residues constitute a promising source of functional compounds, bioenergy, and industrially relevant bioproducts (Bishnoi et al., 2023; Silva et al., 2025).

Among these residues, plantain peels have attracted increasing scientific interest due to their high availability and favorable chemical composition. Colombia ranks among the world's leading plantain-producing countries, generating millions of tons annually, which in turn results in substantial volumes of residual biomass during fruit commercialization and processing stages (Ministerio de Agricultura y Desarrollo Rural, 2013; Ministerio de Agricultura, 2018). Plantain peel is estimated to account for approximately 35% to 40% of the total fruit weight, making it an abundant yet underutilized biomass resource (Acevedo et al., 2021; Putra et al., 2022). From a compositional perspective, this residue contains considerable amounts of starch, dietary fiber, phenolic compounds, and other structural carbohydrates that are amenable to biotechnological conversion. These characteristics make plantain peel a promising feedstock to produce glucose syrups and other industrially valuable derivatives (Quiceno et al., 2014; Hikal et al., 2022).

Recent advances in biorefinery development have encouraged the utilization of fruit-processing residues as renewable feedstocks to produce bio-based chemicals, functional ingredients, bioenergy, and industrial bioproducts. Within this framework, banana-derived residues have received considerable attention because of their abundance, low cost, and high carbohydrate content. Current evidence suggests that banana peels can be integrated into circular production systems where waste streams are converted into marketable products, thereby reducing environmental impacts while generating additional economic value along the agri-food chain (Acevedo et al., 2021; Bishnoi et al., 2023). Such approaches are increasingly recognized as essential components of sustainable resource management and bioeconomy strategies.

The production of glucose syrup from unconventional feedstocks has gained increasing attention in recent years due to the need to diversify traditional sugar sources and reduce the costs associated with the use of cereals and tubers. Glucose syrups are widely used ingredients in the food industry because of their sweetening, functional, and technological properties (Quitiguiña & Santacruz, 2012). Previous studies have shown that starches present in plantain residues can be efficiently hydrolyzed through chemical, enzymatic, or biological treatments, enabling the release of glucose and other fermentable sugars (Aparicio-Saguilán et al., 2014; Wang &

Chen, 2019). However, the efficiency of the hydrolysis process is influenced by several factors, including fruit maturity stage, the availability of hydrolyzable starch, and the physicochemical conditions under which bioconversion takes place (Utrilla-Coello et al., 2014; Sabbadini et al., 2021).

Beyond their carbohydrate content, banana peels contain significant amounts of pectin, hemicellulose, phenolic compounds, minerals, and dietary fiber, all of which may influence hydrolytic conversion processes and the quality of derived products. Recent investigations have demonstrated that these components can be selectively recovered or transformed through environmentally friendly technologies, supporting the concept of whole-biomass utilization. Consequently, banana peel biomass is increasingly regarded as a multifunctional feedstock capable of supporting diversified biotechnological and food-processing applications (Putra et al., 2022; Khamsaw et al., 2024).

In parallel, the application of emerging technologies to optimize biomass conversion processes has attracted considerable interest within the scientific community. Among these technologies, low-intensity electromagnetic fields have demonstrated the ability to modify the physicochemical properties of water, cellular structures, and plant matrices, thereby enhancing phenomena related to mass transfer, nutrient availability, and microbial metabolic activity (Insua et al., 2009; López et al., 2019). Recent studies have reported that exposing carbohydrate-rich materials to electromagnetic fields can increase substrate availability for hydrolysis and fermentation processes, thereby improving the efficiency of producing biotechnologically relevant products (Suárez-Rivero et al., 2017; Sincak et al., 2024; Guzmán-Armenteros et al., 2024). Nevertheless, information regarding the combined effects of plantain peel maturity stage and electromagnetic field application on the production of glucose syrups through biological hydrolysis remains limited.

The growing interest in agro-industrial waste valorization has also been driven by the need to establish sustainable production models capable of reducing dependence on fossil-based resources. Recent studies have emphasized that agricultural residues should no longer be viewed as waste streams but rather as alternative raw materials for industrial biotechnology. This paradigm shift has encouraged the implementation of innovative technologies that maximize substrate conversion efficiency while minimizing energy consumption and environmental burdens associated with conventional processing systems (Awasthi et al., 2023; Silva et al., 2025).

Considering this knowledge gap, the present study aimed to evaluate the effects of the maturity stage of Dominico-Hartón plantain peel (Musa paradisiaca spp.), substrate concentration, and the application of low-intensity electromagnetic fields on glucose syrup production through biological hydrolysis using Trichoderma viride. It was hypothesized that the combination of plantain residues at advanced stages of maturity and electromagnetic stimulation would enhance the conversion of starch into reducing sugars, thereby contributing to the development of sustainable alternatives for agro-industrial waste valorization within bioeconomy and circular economy frameworks (Aparicio-Saguilán et al., 2014; Suárez-Rivero et al., 2017).

In parallel, recent advances in physical process intensification have highlighted the potential of electromagnetic technologies as environmentally friendly tools for enhancing microbial bioprocesses. Magnetic and electromagnetic fields have been associated with improvements in mass transfer, enzymatic activity, substrate availability, and microbial growth kinetics, resulting in increased productivity in several fermentation systems. Although the underlying mechanisms are not yet fully understood, growing evidence supports the incorporation of these technologies into biomass conversion processes as a means of improving process performance without the addition of chemical reagents (Guzmán-Armenteros et al., 2024; Yousfi et al., 2025; Sincak et al., 2024).

Materials and Methods

Experimental Design

A completely randomized factorial design (3 × 3 × 2) was established to evaluate the combined influence of three factors on glucose syrup production from Dominico-Hartón plantain (*Musa paradisiaca* spp.) peel. The factors evaluated were: (i) raw material maturity stage (green, ripe, and overripe), (ii) substrate concentration in the bioreactor (10, 20, and 30% w/v), and (iii) application of a low-intensity electromagnetic field (118 μT), assessed at two levels: with electromagnetic treatment and without electromagnetic treatment. The combination of these factors resulted in 18 experimental treatments, allowing the assessment of both the main effects of each variable and their potential interactions on the efficiency of biological hydrolysis and reducing sugar production. The combination of maturity stage, substrate concentration, and electromagnetic field exposure generated 18 experimental treatments, as summarized in Table 1.

Each treatment was conducted under semi-controlled conditions and evaluated using three independent replicates, resulting in a total of 54 experimental units. In all treatments, a constant inoculum concentration of *Trichoderma viride* (0.4 g L^{-1}) was employed, and incubation was carried out at 28°C for 72 h. The response variables analyzed included pH, glucose concentration, reducing sugar content, and dextrose equivalent (DE) of the syrups produced. This methodological approach enabled the determination of the individual and combined contributions of peel maturity stage, substrate concentration, and electromagnetic field exposure to process performance, providing relevant information for the biotechnological valorization of agro-industrial residues and the optimization of glucose syrup production.

Table 1. Experimental Treatments Evaluated for Glucose Syrup Production from Dominico-Hartón Plantain Peel

Treatment	Maturity Stage	Substrate Concentration (% w/v)	Electromagnetic Field (118 μT)
T1	Green	10	No
T2	Green	10	Yes
T3	Green	20	No
T4	Green	20	Yes
T5	Green	30	No
T6	Green	30	Yes
T7	Ripe	10	No
T8	Ripe	10	Yes
T9	Ripe	20	No
T10	Ripe	20	Yes
T11	Ripe	30	No
T12	Ripe	30	Yes
T13	Overripe	10	No

Treatment	Maturity Stage	Substrate Concentration (% w/v)	Electromagnetic Field (118 µT)
T14	Overripe	10	Yes
T15	Overripe	20	No
T16	Overripe	20	Yes
T17	Overripe	30	No
T18	Overripe	30	Yes

Note: Each treatment was conducted with three independent replicates, resulting in a total of 54 experimental units. All experimental units were inoculated with Trichoderma viride at a concentration of 0.4 g L^{-1} and incubated at 28°C for 72 h.

Raw Material and Pretreatment

Dominico-Hartón plantain peels were obtained at three maturity stages. The samples were washed, disinfected, cut into fragments of approximately 1 cm², and dried at 40°C for 48 h. Subsequently, the dried material was ground to obtain a homogeneous flour. A portion of the samples was subjected to a low-intensity electromagnetic treatment (118 µT) for 24 h prior to fermentation.

Glucose Syrup Production

Dominico-Hartón plantain (*Musa paradisiaca* spp.) peels were used as the feedstock for glucose syrup production. The peels were obtained from fruits at three physiological maturity stages: green (commercial stage 2), ripe (stage 5), and overripe (stage 7). The selection of these maturity stages allowed the evaluation of biochemical changes associated with the progressive conversion of starch into simple sugars and their influence on glucose syrup production. Following collection, the peels were washed and disinfected to remove impurities and reduce the superficial microbial load. The material was then cut into portions of approximately 1 cm² to facilitate heat transfer during drying and ensure sample homogeneity.

The prepared samples were dried in a forced-air circulation oven at 40°C for 48 h until suitable storage and processing conditions were achieved. The dried material was subsequently milled using intermittent mechanical grinding to obtain a homogeneous plantain peel flour, which served as the substrate for biological hydrolysis. To evaluate the influence of electromagnetic fields on polysaccharide availability within the biomass, a fraction of each flour sample was exposed to a low-intensity electromagnetic field (118 µT) for 24 continuous hours, whereas another fraction remained untreated and served as the control group. This procedure allowed the comparative evaluation of treated and untreated samples during glucose syrup production.

The selection of plantain peel as a substrate for glucose syrup production is supported by recent advances in biomass valorization and biorefinery concepts. Banana processing residues contain substantial amounts of starch, cellulose, hemicellulose, pectin, and other carbohydrate-rich fractions that can be transformed into high-value products through biological and enzymatic routes. Recent studies have highlighted that banana peel biomass may serve as a strategic feedstock to produce biofuels, biochemicals, functional ingredients, and fermentable sugars, contributing to waste reduction and resource circularity within agro-industrial systems (Acevedo et al., 2021; Bishnoi et al., 2023; Krungkaew et al., 2023). The utilization of these residues aligns with current circular bioeconomy approaches aimed at maximizing material recovery while reducing the environmental burdens associated with organic waste disposal.

Experimental Variables and Analytical Methods

The study evaluated the effects of three independent variables on glucose syrup production from Dominico-Hartón plantain peel (*Musa paradisiaca* spp.): (i) raw material maturity stage (green, ripe, and overripe), (ii) substrate concentration in the bioreactor (10, 20, and 30% w/v), and (iii) application of a low-intensity electromagnetic field (118 μT; treated and untreated samples). The dependent variables included fermentation medium pH, glucose concentration, reducing sugar content, dextrose equivalent (DE), and physicochemical characteristics of the raw material associated with the hydrolysis process, such as moisture content, ash content, dietary fiber, and colorimetric attributes. These variables were selected because of their direct influence on the availability of fermentable carbohydrates and the efficiency of starch bioconversion into simple sugars (Quiceno et al., 2014; Wang & Chen, 2019).

The inclusion of physicochemical characterization prior to hydrolysis is particularly relevant because biomass composition strongly influences microbial accessibility to structural carbohydrates and overall conversion efficiency. Recent investigations have demonstrated that variations in moisture content, mineral composition, fiber fractions, and carbohydrate availability significantly affect hydrolytic performance and subsequent sugar release during biological processing. Moreover, colorimetric evaluation has emerged as a rapid, non-destructive approach for monitoring biochemical transformations associated with fruit ripening and biomass quality assessment in industrial applications (Putra et al., 2022; Khamsaw et al., 2024).

Prior to hydrolysis assays, plantain peel flours were characterized using standardized physicochemical analyses. Moisture content was determined by gravimetric drying following AOAC Method 934.01, while ash content was quantified by controlled incineration according to AOAC Method 962.02. Total dietary fiber was determined using the enzymatic-gravimetric method described by Prosky et al., which is widely employed for quantifying structural components in plant-based matrices. Additionally, color properties were measured by instrumental colorimetry, recording the CIELAB parameters (L*, a*, and b*), which provide an effective means of monitoring biochemical changes associated with fruit ripening and pigment transformation during raw material processing (Pathare et al., 2013; Hikal et al., 2022).

The efficiency of the biological hydrolysis process was monitored through periodic measurements of pH and glucose concentration. pH was determined using a digital multiparameter meter equipped with a combined electrode, as this parameter is a key indicator of microbial metabolic activity and fermentation process stability (Lehninger, 2014). Glucose concentration was quantified using the 3,5-dinitrosalicylic acid (DNS) spectrophotometric method, which is based on the reduction of the DNS reagent by reducing sugars followed by absorbance measurement at 540 nm. This methodology has been extensively validated for the quantification of reducing carbohydrates generated during biomass hydrolysis processes (Miller, 1959; López et al., 2020).

Finally, the technological quality of the syrups obtained was assessed by determining reducing sugar content and dextrose equivalent (DE). Reducing sugars were quantified using the Eynon-Lane volumetric method, a widely recognized reference procedure for products derived from starch hydrolysis. Based on these results, the DE value was calculated as an indicator of the degree of hydrolysis achieved and the sweetening capacity of the resulting syrup. This approach made it possible to establish relationships among raw material characteristics, treatment conditions, and the overall performance of the glucose production process from plantain residues (Quitiguiña & Santacruz, 2012; Aparicio-Saguilán et al., 2014).

Statistical Analysis

Prior to inferential analysis, the experimental data were organized, screened, and verified for consistency. Descriptive statistics, including measures of central tendency and dispersion, were calculated to characterize the behavior of the evaluated variables. To determine the effects of the experimental factors and their potential interactions on the response variables, an analysis of variance (ANOVA) corresponding to a completely randomized factorial design was performed. When significant differences among treatments were detected ($p < 0.05$), means were separated using Duncan's multiple range test, allowing the identification of treatments exhibiting superior performance in glucose production.

Additionally, correlation analyses were conducted between the physicochemical properties of the raw material and the response variables of the process to identify associations that could explain the behavior of biological hydrolysis. Statistical analyses and graphical representations were performed using Origin 5.0 and Statgraphics Plus software packages.

Results and Discussion

Bromatological and Colorimetric Characterization of the Raw Material

The bromatological characterization of the plantain peel samples (Table 2) revealed substantial differences between green and ripe peels, primarily associated with the physiological changes occurring during fruit ripening. Green peel exhibited a moisture content of 44.99 ± 0.90%, whereas a slight reduction was observed in ripe peel (42.72 ± 0.85%). Concurrently, ash content increased from 5.01 ± 1.10% in green peel to 7.28 ± 1.15% in ripe peel, suggesting a greater relative concentration of mineral constituents because of moisture loss. Likewise, dietary fiber content increased from 0.12 ± 0.01% to 0.27 ± 0.02%, which may be attributed to structural modifications occurring within the cell wall during the ripening process. A similar trend was observed for protein content, which increased from 6.82 ± 0.34% in green peel to 7.45 ± 0.37% in ripe peel. In contrast, lipid content decreased from 3.11 ± 0.16% to 2.48 ± 0.12%, whereas total carbohydrates increased from 34.95 ± 1.75% to 38.62 ± 1.93%. This behavior reflects the metabolic transformations characteristic of fruit ripening, particularly the progressive degradation of starch reserves and the accumulation of soluble sugars. These findings indicate that ripe plantain peel possesses greater potential as a feedstock for hydrolysis processes aimed at glucose production due to its higher availability of carbon-rich compounds.

Table 2. Bromatological and colorimetric characterization of the raw material used for glucose syrup production from Dominico-Hartón plantain peel.

Parameter	Green Peel (Mean ± SD)	Ripe Peel (Mean ± SD)
Moisture (%)	44.99 ± 0.90	42.72 ± 0.85
Ash (%)	5.01 ± 1.10	7.28 ± 1.15
Dietary fiber (%)	0.12 ± 0.01	0.27 ± 0.02
Protein (%)	6.82 ± 0.34	7.45 ± 0.37
Lipids (%)	3.11 ± 0.16	2.48 ± 0.12
Carbohydrates (%)	34.95 ± 1.75	38.62 ± 1.93
L* (Lightness)	62.21 ± 1.24	64.45 ± 1.29
a* (Green-Red Axis)	−11.46 ± 0.57	0.65 ± 0.03
b* (Blue-Yellow Axis)	34.99 ± 1.75	47.49 ± 2.37
C* (Chroma)	36.83 ± 1.84	47.50 ± 2.38
h° (Hue Angle)	−1.26 ± 0.06	0.51 ± 0.03

The compositional differences observed between green and ripe peels are consistent with current knowledge regarding physiological ripening in Musaceae fruits. During ripening, enzymatic activities associated with starch catabolism, cell wall remodeling, and sugar accumulation induce substantial modifications in the nutritional and structural composition of the peel. These transformations not only affect the physicochemical properties of the biomass but also enhance their suitability for biotechnological applications, particularly those involving microbial conversion and hydrolysis-based processes. Recent reviews have emphasized that mature banana peels represent a more favorable substrate due to their increased concentration of metabolically available carbohydrates and soluble compounds (Bishnoi et al., 2023; Khamsaw et al., 2024).

From a colorimetric perspective, fruit ripening induced marked changes in all evaluated parameters. Lightness (L*) increased from 62.21 ± 1.24 in green peel to 64.45 ± 1.29 in ripe peel, indicating a visually brighter surface. The a* parameter shifted from negative values (−11.46 ± 0.57) to positive values (0.65 ± 0.03), reflecting the transition from predominantly green hues toward coloration associated with chlorophyll degradation and the emergence of yellow and orange pigments. This trend was further supported by the increase in b* values from 34.99 ± 1.75 to 47.49 ± 2.37, demonstrating a greater intensity of yellow coloration. Similarly, chroma (C*) increased from 36.83 ± 1.84 to 47.50 ± 2.38, indicating more saturated and visually intense colors in ripe peel samples. Finally, the hue angle (h°) exhibited changes consistent with the chromatic evolution of the fruit during ripening, confirming the physiological modifications associated with this process.

Collectively, these results suggest that colorimetric parameters can serve as reliable indicators of maturity stage and the availability of compounds susceptible to transformation during biotechnological processing.

Comparison of the present findings with scientific literature demonstrates strong agreement with previously reported compositional and chromatic changes occurring during the ripening of Musaceae fruits. Moreno et al. (2021) reported that the ripening process in plantain and banana cultivars is characterized by a progressive reduction in starch content accompanied by an increase in soluble solids resulting from the hydrolysis of storage polysaccharides. This phenomenon provides a plausible explanation for the higher carbohydrate levels observed in ripe peel samples. Similarly, Mohd Zaini et al. (2022) identified plantain and banana peels as important sources of dietary fiber, structural carbohydrates, and bioactive compounds, whose concentrations vary according to the physiological stage of the fruit. Likewise, Hikal et al. (2022) reported significant ripening-induced changes in peel chemical composition, favoring the accumulation of simple sugars and altering physicochemical properties relevant to industrial applications.

Regarding color development, the results obtained herein are consistent with the observations of Moreno et al. (2021), who reported significant variations in the L*, a*, and b* parameters during the ripening of Dominico-Hartón plantains, primarily associated with chlorophyll degradation and carotenoid accumulation. Taken together, these findings support the use of ripe plantain peels as a promising feedstock for glucose syrup production through biological hydrolysis processes, given their enhanced carbohydrate availability and physicochemical characteristics favorable for bioconversion.

In addition to their relevance as indicators of maturity, the colorimetric changes observed in the present study may also reflect modifications in phenolic composition and antioxidant compounds. Previous investigations have reported that the transition from green to ripe peel is accompanied by degradation of chlorophyll pigments and increased expression of yellow-orange compounds, including carotenoids and phenolic metabolites. Such transformations may influence microbial interactions during fermentation and contribute indirectly to the efficiency of biomass conversion processes (Avram et al., 2022; Putra et al., 2022).

Effect of Hydrolysis Conditions and Electromagnetic Field Application on Glucose Syrup Production

The experimental conditions employed during biological hydrolysis demonstrated that substrate concentration, peel maturity stage, and electromagnetic field application were key factors influencing the conversion of structural carbohydrates into fermentable sugars. Under incubation conditions of 28°C for 72 h and using *Trichoderma viride* as the hydrolytic agent, flours produced from ripe plantain peels exhibited a more favorable performance than those obtained from green peels. This behavior can be attributed to the physiological transformations that occur during fruit ripening, during which a substantial proportion of starch reserves is degraded and converted into lower-molecular-weight sugars, thereby increasing the availability of readily hydrolyzable substrates. Consequently, samples derived from ripe peels showed higher glucose release and a more efficient fermentative response, suggesting a greater technological suitability of this feedstock for glucose syrup production.

The positive effect associated with electromagnetic field exposure may be explained by changes occurring at both physicochemical and microbiological levels. Recent evidence suggests that magnetic and electromagnetic fields can alter membrane permeability, enzyme conformation, ion transport mechanisms, and substrate diffusion phenomena in biological systems. These alterations may increase microbial metabolic activity and improve the accessibility of polysaccharides to enzymatic attack, thereby enhancing the release of fermentable sugars from lignocellulosic and starch-rich matrices (Sincak et al., 2024; Guzmán-Armenteros et al., 2024).

In contrast, green peel samples displayed a different response due to their high content of physiologically untransformed starch. Although this material exhibited considerable potential as a carbohydrate source, the more compact structure of starch granules and the lower initial availability of soluble sugars partially limited hydrolysis efficiency. Nevertheless, the application of a low-intensity electromagnetic field enhanced the conversion of these compounds, resulting in increased availability of sugars that could be metabolized by the microorganism. This effect was reflected in higher medium viscosity and in a consistent increase in glucose concentration throughout the 72-h incubation period.

Additionally, samples exposed to the electromagnetic field exhibited changes in pH values compared with untreated controls, particularly at higher substrate concentrations, where the largest decreases were recorded. This pH reduction may be interpreted as an indirect indicator of enhanced microbial metabolic activity associated with the degradation of organic compounds and the formation of metabolites during the biological hydrolysis process.

Table 3. Response variables as influenced by peel maturity stage and electromagnetic field application.

Maturity Stage	**Electromagnetic Field**	**pH Trend**	**Relative Glucose Production**	**Maturity Stage**
Green	Without EMF	Higher pH	Low	Low
Green	With EMF	Decreasing pH	Moderate	Moderate
Ripe	Without EMF	Intermediate	High	High
Ripe	With EMF	Lower pH	Very high	Very high

From a technological perspective, the observed interaction between substrate maturity and electromagnetic pretreatment reinforces the growing interest in combining biological and physical processing strategies for biomass valorization. Emerging non-thermal technologies have been reported to improve hydrolysis kinetics, microbial growth dynamics, and metabolite production while maintaining low energy requirements. Such approaches are increasingly considered viable alternatives for developing sustainable industrial processes consistent with the principles of circular economy and resource efficiency (Yousfi et al., 2025; Sincak et al., 2024).

The results obtained are consistent with findings reported in recent scientific literature. Moreno et al. (2021) demonstrated that ripening in Dominico-Hartón plantains is characterized by a significant reduction in starch content accompanied by an increase in soluble solids and simple sugars, conditions that favor subsequent biotechnological conversion processes. Similarly, Hikal et al. (2022) reported that ripe plantain peels possess greater availability of fermentable carbohydrates and bioactive compounds suitable for industrial valorization.

Furthermore, several studies have shown that electromagnetic fields can alter the physicochemical properties of water and biological materials, thereby enhance mass-transfer phenomena and increase the accessibility of polysaccharides to enzymatic action (López et al., 2019; Suárez-Rivero et al., 2017). In this context, the higher efficiency observed in electromagnetically treated ripe peel samples suggests a positive interaction between the physiological state of the raw material and the physical pretreatment applied. Such synergy appears to improve the potential yield of glucose syrup production from agro-industrial residues, supporting the development of more efficient and sustainable biomass valorization strategies within bioeconomy and circular economy frameworks.

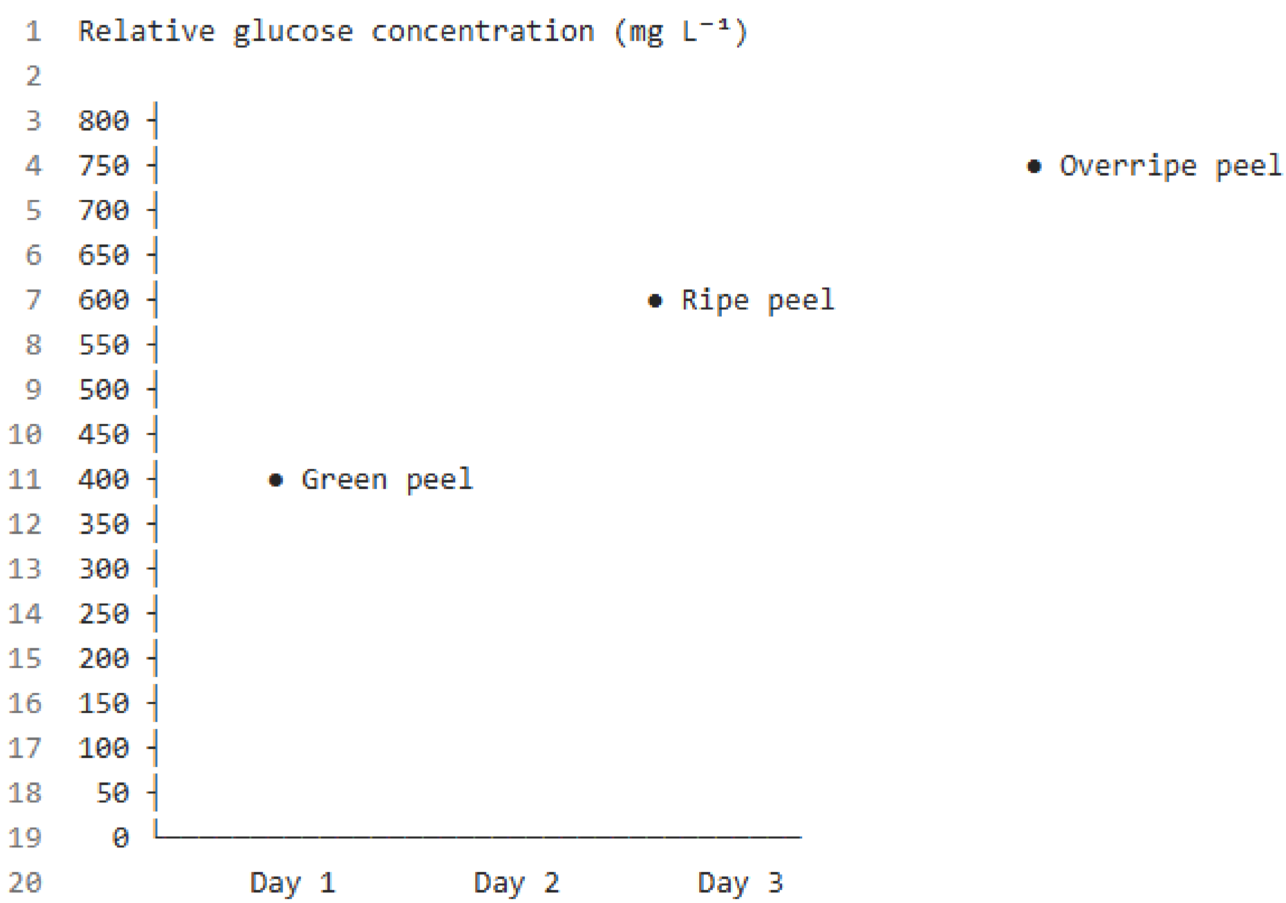
Glucose and Reducing Sugar Production

Glucose production during the biological hydrolysis process was markedly influenced by the maturity stage of the plantain peel, which affected both the availability and transformation of structural carbohydrates. As illustrated in Figure 1, green peels exhibited the lowest relative glucose concentration, reaching values close to 400 mg L^{-1} throughout the evaluation period. This behavior can be attributed to the high proportion of native starch present in immature tissues, where carbohydrates are predominantly stored as reserve polysaccharides. Under these conditions, the hydrolytic activity of *Trichoderma viride* depends on the progressive degradation of these structures to release simple sugars, thereby limiting initial glucose availability compared with more advanced maturity stages. Furthermore, the lower concentration of reducing sugars observed in this treatment suggests that a substantial fraction of carbon remained associated with complex compounds that had not yet been transformed during the experimental period.

In contrast, ripe peels exhibited a relative glucose concentration of approximately 600 mg L^{-1}, substantially exceeding the values recorded for green peels. This increase reflects the biochemical modifications associated with fruit ripening, during which natural starch hydrolysis occurs alongside a progressive accumulation of low-molecular-weight sugars.

The greater availability of fermentable substrates enhanced the metabolic activity of *T. viride*, resulting in a more efficient conversion of biomass into glucose and reducing sugars. Consequently, glucose production was approximately 50% higher than that observed in green peel samples. These findings confirm that ripening not only alters the chemical composition of biomass but also improves its biological accessibility and technological suitability for agro-industrial valorization processes aimed at producing natural sweeteners.

Figure 1. Evolution of relative glucose concentration during the biological hydrolysis of plantain peels at different maturity stages.



The progressive increase in glucose concentration observed across the maturity stages highlights the importance of substrate composition in determining hydrolysis efficiency. Similar trends have been reported in studies focused on banana waste valorization, where advanced maturity stages were associated with enhanced sugar availability and higher conversion yields. The reduction of starch reserves coupled with the accumulation of soluble carbohydrates facilitates microbial utilization and enzymatic hydrolysis, ultimately improving glucose recovery. These findings further support the use of mature and overripe banana residues as economically attractive feedstock for bioconversion processes (Acevedo et al., 2021; Bishnoi et al., 2023).

The most favorable trend was observed in overripe peels, which reached relative glucose concentrations of nearly 750 mg L^{-1}. This result suggests that the advancement of the ripening process promotes greater accumulation of soluble sugars and a significant reduction of the starch fraction, thereby facilitating hydrolysis and fermentation phenomena. These findings are consistent with those reported by Moreno et al. (2021), who demonstrated that ripening in Dominico-Hartón plantain cultivars is characterized by a significant reduction in starch content accompanied by an increase in soluble solids and simple carbohydrates. Likewise, Hikal et al. (2022) reported that ripe and overripe peels contain higher concentrations of fermentable compounds and exhibit greater potential for biotechnological and food industry applications. Similarly, Mohd Zaini et al. (2022) highlighted that plantain peel residues constitute an important source of utilizable carbohydrates and functional compounds, whose biotechnological value increases as physiological ripening progresses. Collectively, these studies support the results obtained in the present investigation and confirm that raw material maturity is one of the principal factors governing glucose and reducing sugar yields during biological hydrolysis.

The results obtained are also in agreement with recent evidence concerning the valorization of Musaceae residues. Moreno et al. (2021) reported that the ripening of Dominico-Hartón plantains involves a progressive decline in starch content coupled with an increase in soluble solids and simple sugars, conditions that favor the production of value-added derivatives through hydrolytic processes. Similarly, Hikal et al. (2022) described ripe plantain peel as a substrate with enhanced availability of fermentable carbohydrates and bioactive compounds suitable for industrial exploitation. Furthermore, Mohd Zaini et al. (2022) concluded that plantain peels possess considerable potential as a source of functional ingredients owing to their high content of structural carbohydrates and bioactive compounds, which can be effectively transformed through biotechnological processes. Taken together, these findings reinforce the results observed in the present study and confirm that fruit maturity is a critical determinant of glucose and reducing sugar production efficiency from plantain-derived agro-industrial residues.

Beyond the observed increase in glucose production, the results obtained in this study also have implications for sustainable waste management and agro-industrial diversification. Recent research has emphasized that the transformation of banana-processing residues into value-added products constitutes an important strategy for reducing environmental impacts while generating new economic opportunities within agricultural supply chains. The integration of biological hydrolysis technologies with residue recovery systems may therefore contribute to the development of decentralized biorefineries and circular bioeconomy models, particularly in tropical regions where banana production is highly concentrated (Krungkaew et al., 2023; Silva et al., 2025).

Conclusions

Dominico-Hartón plantain peel proved to be a viable feedstock for glucose syrup production through biological hydrolysis, owing to its high carbohydrate content and the compositional changes associated with the ripening process. Ripe peel exhibited a carbohydrate content of 38.62 ± 1.93%, higher than that observed in green peel (34.95 ± 1.75%), together with increases in protein (7.45 ± 0.37%) and dietary fiber (0.27 ± 0.02%). These characteristics enhanced the availability of fermentable substrates for the hydrolytic activity of Trichoderma viride.

The maturity stage of the raw material was one of the most influential factors affecting hydrolysis performance. Relative glucose concentration increased progressively from approximately 400 mg L^{-1} in green peels to 600 mg L^{-1} in ripe peels and nearly 750 mg L^{-1} in overripe peels, demonstrating that advancing ripening promotes the conversion of starch into simple sugars and improves glucose production efficiency. The difference observed between green and ripe peels represented an increase of approximately 50% in glucose availability.

The application of a low-intensity electromagnetic field (118 μT) positively influenced the biological hydrolysis process by increasing the availability of fermentable sugars and reducing pH values relative to the control treatments, particularly in systems containing higher substrate concentrations. The combination of ripe raw material and electromagnetic pretreatment exhibited the best technological performance, reaching very high levels of glucose production and greater hydrolysis efficiency compared with treatments without electromagnetic stimulation. These findings confirm the potential of this strategy as an effective approach for optimizing the biotechnological valorization of agro-industrial residues and advancing sustainable production systems within bioeconomy and circular economy frameworks. distintas formulaciones de alimentos para porcinos. Se puede destacar de cada materia prima que cada una aporta algo nutricionalmente importante para la elaboración de nuestro producto, la hoja tiene mayor humedad y grasa, con un 15,06 % y 13,70 % respectivamente, la cascarilla contiene 16,02 % de cenizas, la broza aporta 18,61 % de fibra y el tallo, al igual que la hoja, aporta un valor significante de humedad con un 14 %. Por otra parte, de acuerdo con los resultados de los análisis fisicoquímicos y mecánicos realizados en las cuatro formulaciones, se obtuvo que la ración más adecuada, teniendo en cuenta los requerimientos del animal, en este caso cerdos en fase de engorde, es la formulación #3, ya que los valores obtenidos de humedad, grasa y fibra son 8,73 %, 1,51 % y 33,34 % respectivamente, valores que cumplen nutricionalmente el desarrollo de dietas para cerdos. Estos resultados son de gran utilidad para el diseño de alimentos para animales, a partir de subproductos de la quinua. Para futuras investigaciones sería interesante evaluar la aceptación, digestión y palatabilidad del producto en cerdos, mediante pruebas *in vivo*.

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