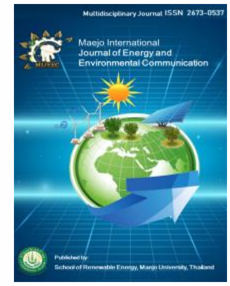
Maejo International Journal of Energy and Environmental Communication 6-3 (2024) 62-69

Maejo International Journal of Energy and Environmental Communication

Journal homepage: https://ph02.tci-thaijo.org/index.php/MIJEEC



ARTICLE

Valorization of banana frond juice for bioethanol production: Process efficiency and circular economy implications

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A R T I C L E I N F O

Article history:
Received 5 November 2024
Received in revised form
29 November 2024
Accepted 2 December 2024

Keywords:
Banana frond juice
Bioethanol
Saccharomyces cerevisiae
Fermentation kinetics
Waste valorization
Circular bioeconomy

A B S T R A C T

This investigation evaluates the microbial conversion capacity of banana frond juice (BFJ) as an accessible lignocellulosic feedstock through Saccharomyces cerevisiae fermentation under the best possible operation conditions. Mechanical pressing of fresh banana fronds produced juice with a yield average of 0.33 ± 0.02 L/kg along with an initial total sugar content of 76.4 ± 2.8 g/L. The bioconversion of clarified BFJ occurred under batch fermentation conditions at pH 5.6 and 36°C using 10% v/v yeast inoculum for 120 hours while measuring ethanol production together with sugar consumption at 24-hour intervals. The fermentation process achieved total sugar depletion at 96 hours, resulting in an ethanol production of 45.75 ± 1.1 g/L, which delivered a yield of 0.33 g/g sugar and an efficiency of 64.7% compared to theoretical maximums. During the fermentation process, researchers achieved an average volumetric ethanol productivity level of 0.38 g/L·h. The yield results of BFJ fall within competition when compared to sugarcane juice, oil palm frond juice, and banana pseudostem hydrolysates, while also requiring few processing steps without enzymatic or chemical pretreatment (Legodi et al., 2021). Statistical data showed that sugar consumption is directly linked to ethanol production through a correlation level of $R^2 = 0.987$ ($p < 0.01$). Biofuel production benefits from the Flush rejects/consumes BFJ as a promising and inexpensive raw material. The incorporation of banana fruit juice as a sustainable biofuel feedstock becomes viable due to its simple preprocessing demands combined with advantageous fermentation behaviour and circular bioeconomic alignment.

1. Introduction

A major shift in global energy management occurs because nations work to decrease fossil fuel dependency while addressing environmental challenges to fulfil the Paris Accord objectives (Abbasi et al., 2024; Acen et al., 2024). Renewable energy technologies received more financial investment, yet fossil fuels occupied more than 70% of all global energy usage during 2021, according to Fernandez et al. (2024). Bioethanol has become the leading renewable biofuel that industrial producers use extensively for transport applications

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(Manmai et al., 2023; Tongsiri et al., 2023). Bioethanol provides advantages to internal combustion engines through its high-octane rating (Vu et al., 2016) and its ability to match existing fuel systems, and more importantly, it allows a 90% reduction of life cycle CO_2 emissions when utilizing sustainable biomass for production (Guerrero & Muñoz, 2023).

The manufacturing of ethanol as a first-generation biofuel originally used sugar-rich food crops such as corn, sugarcane and cassava (Khaodee & Chaiworn, 2023). The optimized industrial yield of ethanol from these feedstocks contributes to high efficiency but evokes sustainability issues because it requires land from food production and large quantities of freshwater in addition to causing environmental degradation (Gupta et al., 2019; Vu et al., 2022). Environmental policy and research now focus on producing second-generation bioethanol through the transformation of lignocellulosic biomass together with agro-industrial residues that avoid displacing food crops from agricultural land (Pradechboon & Junluthin, 2022). The bioethanol production feeds on various underused agricultural residue materials, including crop stalks, straws, bagasse, as well as fruit residues, which are commonly accessible sources with dual benefits for waste disposal while supporting renewable fuel operations (Gupta et al., 2019; Tan et al., 2019).

Banana (*Musa* spp.) waste offers a strong prospect within the current situation. Banana agriculture worldwide produces excessive biomass waste that includes pseudostems in combination with peels and rachises and banana fronds, which represent the extensive leaves and support structures that receive periodic pruning during cultivation (Boakye-Boaten et al., 2017). Banana farming operations in Southeast Asian and Latin America, and sub-Saharan African tropical areas generate continuous renewable biomass opportunities from the discarded post-harvest banana fronds, which people typically discard or burn. The majority of studies on bioethanol processing from banana waste material focused on banana peel extraction by Vu et al. (2018) and Gupta et al. (2019); however, little scientific research exists regarding the production methods for banana frond juice (BFJ).

The BHJ production process entails mechanical processing of fresh banana fronds to create a solution that contains primarily glucose, fructose, and sucrose, free sugars, together with trace minerals and nitrogenous compounds (Tan et al., 2019; Chai et al., 2018). The bioconversion process using BFJ becomes simpler because it does not need traditional pretreatment methods, thus reducing energy requirements to free fermentable sugars. BFJ serves as an economical, non-edible sustainable source for ethanol manufacturing exclusively through fermentation of its native sugar content.

Recent studies show the yeast strain *Saccharomyces cerevisiae* ferments Sugarcane, sugar beet, and sweet sorghum juice as well when its operating conditions are optimized (Mgeni et al., 2024). Laboratory experiments using bioreactors demonstrated ethanol production levels reaching 45.75 g/L along with fermentation yields equal to 0.33 g per g of sugar utilized (~65% theoretical yield) while the entire process was completed during 48–72 hours (Tan et al., 2019). Interested competitors have found that BFJ fermentation values stand equal to results obtained from oil palm frond juice and banana leaf hydrolysate (Kosugi et al., 2010), which strengthens its position as an acceptable feedstock for distributed bioethanol manufacturing. Raw BFJ fermentation achieves satisfactory outcomes without additional process modifications at its normal dilute sugar concentration levels since adding nutrients, particularly nitrogen, leads to increased ethanol titers (Tan et al., 2019).

The fermentation process of BFJ perfectly matches the circular bioeconomy principles through its ability to convert agricultural byproducts into valuable bioproducts. The integration of BFJ ethanol production within banana farming operation enables farmers to produce additional income from waste biomass while decreasing environmental waste while meeting national renewable targets (Guerrero & Muñoz, 2023). Numerous life cycle assessments demonstrate favorable energy balances and significant greenhouse gas emission reductions versus gasoline utilization in banana waste-to-ethanol methods, even when downstream fermentation residue products like digestate or biogas are utilized for recovery (Vu et al., 2018).

Current academic and industrial sectors minimize their research and practical applications of BFJ. The fermentation of BFJ faces several obstacles that merit extensive research since frond sugar profiles change based on plant age and variety, while fermentation inhibitors possibly exist within raw juice, and juice extraction must achieve commercial scalability. The evaluation of BFJ performance against traditional feedstock together with second-generation feedstocks, should be performed to determine its placement and economic and industrial implementation potential. The current research evaluates banana frond juice performance as a next-generation bioethanol substrate. The study focuses on four main goals, including the optimization of yeast fermentation conditions with *S. cerevisiae* and the evaluation of ethanol productivity and yield using flask and bioreactor systems. Additionally, this study also compares BFJ fermentation results to related studies and explains the significance for waste management and sustainable policy development, and agricultural practices. The research establishes BFJ as a promising sustainable bioethanol feedstock, which enhances knowledge in agro-residue bioconversion for tropical economies.

2. Materials and Methods

2.1. Material preparation

The banana fronds were collected from the Valaya Alongkorn Rajabhat University campus agricultural experimental plots in their fresh state to maintain plant consistency and environmental stability. The laboratory received fresh biomass after harvest through sterile containers carrying ice packs for the purpose of reducing microbial activities and enzymatic breakdown. Workers used their hands to remove leaf blades and sheath husks from the banana pseudostems before preparation for testing. Laboratory personnel washed the cleaned pseudostems with tap water before finishing the procedure with distilled water to eliminate remaining soil or organic matter.

Sterile stainless-steel equipment cut clean pseudostem segments into pieces of 2–3 cm length for standardized extraction of juice from the pieces. Mechanical pressing occurred for the pieces through the utilization of a Chinese high-efficiency horizontal twin-roller sugarcane juicer model SJ-1500. The juice yield measurements took place through volume assessments of kilogram fresh weights according to Table 1 data. Two filtration steps were applied to collect banana frond juice (BFJ). First, a muslin cloth was removed, big solids, then Whatman No.1 filter paper yielded clarified juice. Sterile amber-colored glass bottles containing the juice were kept in refrigeration at 4°C to protect them from microbial contamination and oxidation throughout the fermentation trial preparation period.

Table 1. Juice yield and sugar content from banana fronds

Parameter	Value
Juice yield (L/kg fresh frond)	0.33 ± 0.02
Initial total sugar (g/L)	76.4 ± 2.8
Initial reducing sugar (g/L)	52.7 ± 2.3

2.2. Yeast preparation

In this study, a selected Saccharomyces cerevisiae yeast strain was used as their ethanol-fermenting yeast. Due to its established industrial fermentation track record, the local market obtained brewer's yeast and baker's yeast products named *Saccharomyces cerevisiae*. The yeast activation took place in sterile YPD medium by dissolving 10 g/L yeast extract from HiMedia (India) and 20 g/L peptone also from HiMedia (India), and 20 g/L dextrose from Union Science Co. (Thailand) in distilled water. A 15-minute sterilization process at 121°C served to have the medium ready for use. Following sterile cooling of the YPD medium to room temperature, the researcher transferred 1 mL of preserved yeast stock aseptically into a 100 mL portion of sterilized YPD medium within a 250 mL Erlenmeyer flask. Yeast proliferation through aerobic conditions occurred during 48 hours at 30°C when the flask operated on a 150-rpm rotary shaker. An inoculum volume containing approximately 1 × 10^7 cells/mL was obtained through hemacytometer analysis before being used for inoculation. The researchers measured optical density at 600 nm (OD_{600}) because this value linked microbial biomass with cell count data.

2.3. Fermentation assay

Experiments were conducted to evaluate BFJ bioconversion performance under controlled laboratory settings. Fermentation experiments required sterilizing the BFJ by boiling it at 100°C for 15 minutes in order to remove its natural microbial community. The juice reached ambient temperature, then the scientists adjusted its pH value to 5.6 through sterile 1 N NaOH solutions from Merck, Germany according to prior optimization results on yeast performance at this pH level.

An experiment using 1-L sterilized Erlenmeyer flasks with 300 mL BFJ solution took place for each fermentation run. The inoculated fermentation started by adding 10% of activated yeast culture volume to the juice solution yet maintaining an initial cell count at 1 × 10^7 cells/mL. The microorganisms needed a static incubation condition maintained through airlocked flasks that operated at 36°C throughout the 5-day fermentation period of 120 hours. Fermentation kinetics received acceleration and testing occurred at this specific temperature because the yeast strain demonstrated tolerance to these thermal conditions. The researchers collected samples every 24 hours using aseptically prepared sterile syringes to assess the consumption of sugar as well as ethanol production. The experiments were carried out multiple times for statistical validation of results.

2.4 Kinetic parameters

Fermentation performance was quantitatively assessed by calculating the following kinetic parameters:

Volumetric Ethanol Productivity (Q_p):

$$Q_p = \frac{P}{t}$$

Where (g/L/h) represents the volumetric productivity of ethanol, is the final ethanol concentration (g/L), and is the total fermentation time (h) in hours.

Ethanol Yield Efficiency (E_y):

$$E_y = \frac{P}{S} X \frac{1}{0.51}$$

where *P* is ethanol produced (g), *S* is sugar consumed (g), and 0.51 is the theoretical yield coefficient for glucose conversion to ethanol.

2.5. Experimental analysis

The experimental process includes complete information regarding the step-by-step sequence starting with frond acquisition which leads to analytical operations as depicted in Figure 1. Step-by-step information about the experimental process shows how to obtain banana fronds then extract juice while preparing yeast and establishing fermentation and performing analysis and test sampling.

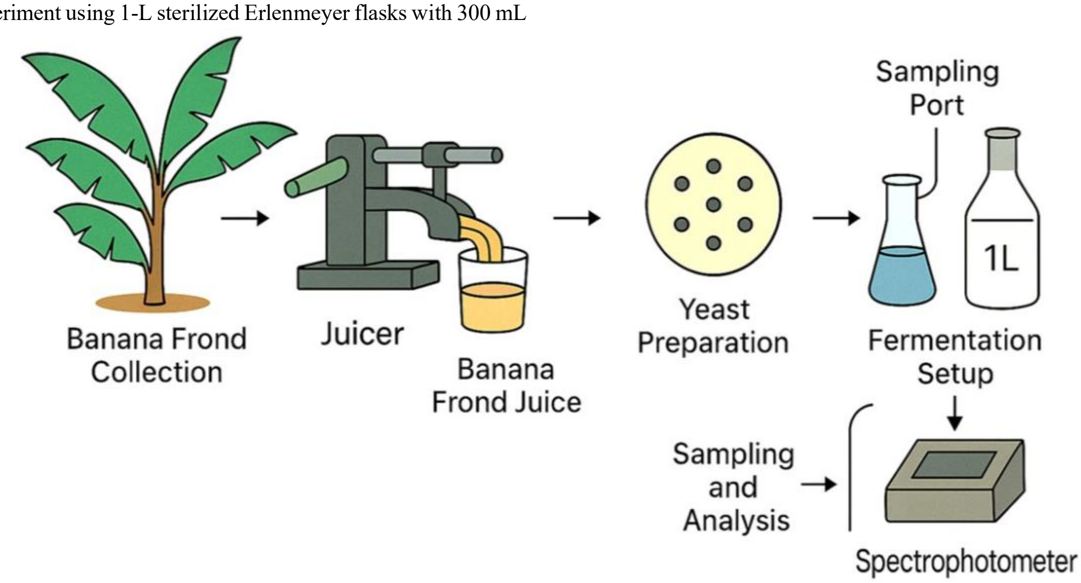

Figure 1. An overview of the experimental workflow, detailing the sequential stages from frond collection to analytical procedures

The researcher determined sample carbohydrate levels through the phenol-sulfuric acid experimental technique, which follows Dubois et al. (1956). The mixture introduced 0.5 mL of BFJ together with 0.5 mL of 5% phenol solution and 2.5 mL of 98% concentrated sulfuric acid. The mixture was vortexed before spending ten minutes at room temperature. The samples were measured at 490 nm using a UV-Vis spectrophotometer that operated under Model: DV-8000 manufactured by Drawell in Japan. The total sugar measurements used a glucose solution as a reference standard. The 3,5-dinitrosalicylic acid (DNS) procedure described by Miller (1959) served to measure reducing sugar content. The mixture of 0.5 mL sample material received 0.5 mL DNS reagent (Sigma-Aldrich, USA), followed by boiling for 15 minutes before the solution reached room temperature. The sample mixture received 4.0 mL of diluted solution of distilled water for absorbance measurement at 540 nm wavelength. Measurement of reducing sugar concentration used a standard glucose curve.

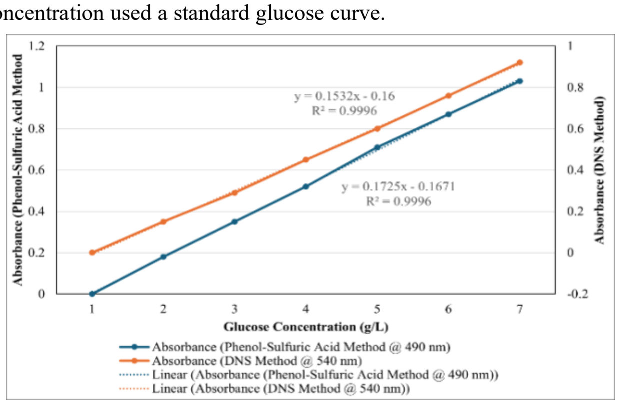

Figure 2. Calibration curve for glucose standard in total and reducing

Fermentation broth ethanol content assessment relied on a French-made Ebulliometer of laboratory standard (Laboratoires Dujardin-Salleron). The laboratory personnel performed fractional distillation on the tested mixture before recording its distillate's boiling point elevation data. The reference calibration curve of ethanol-water mixtures helped determine the sample ethanol content through measurements of the instrument readings. The scientific community adopts this testing procedure as their preferred tool because of its high precision and research-quality reproducibility in oenology and fermentation science. Figure 2 demonstrates the glucose concentration absorbance relationship with dual-scale data points generated from the total sugar determination at 490 nm (phenol-sulfuric acid method) and the reducing sugar determination at 540 nm (DNS method). The two measurement methods display outstanding linear relationships because the coefficients of determination reach 0.9996 between glucose concentrations and absorbance readings. The phenol-sulfuric acid method uses $y = 0.1725x - 0.1671$ for regression calculation and the DNS method has $y = 0.1532x - 0.16$. Linear interpolation allows the assessment of unknown sample glucose levels through these reliable calibration curves.

sugar assays

2.6. Statistical Analysis

The experimental data originated from three repeated trials represented as mean with standard deviation (SD) levels. The data analysis used IBM SPSS Statistics 23 as the statistical software. The researchers performed one-way analysis of variance (ANOVA) to evaluate ethanol yields together with sugar consumption between different time points. Tukey's honestly significant difference (HSD) test performed a post hoc analysis to interpret results from significant differences. The significance threshold set to $p < 0.05$ defined statistical significance for the evaluations. Correlation analysis evaluated how sugar reduction levels influence ethanol formation in the study.

3. Results and Discussion

3.1 Sugar consumption and ethanol production dynamics

Bioethanol manufacturers now evaluate banana frond juice (BFJ) as a fresh production material for fermentation processes. Banana fronds go through mechanical pressing as an agricultural waste from banana farming, which produces fermentable sugar solutions directly in juice form. Fermentable glucose levels exceeding 18–19 g/L, together with other nutrients in the juice medium, allow Saccharomyces cerevisiae to produce ethanol without the expensive enzymatic saccharification typically needed for lignocellulosic biomass (Tan et al., 2019). BFJ provides a direct fermentation solution because it eliminates the requirement of sugaring pretreatment steps, which the banana pseudostem or peel needs through acid or enzymatic hydrolysis (Corrales et al., 2012).

Table 2. Sugar Consumption and ethanol production dynamics from banana frond juice (BFJ)

Parameter	Details	References
Feedstock Source	Banana frond juice (BFJ) from mechanically pressed banana fronds	Tan et al., 2019
Initial Sugar Content	~18–19 g/L glucose	Tan et al., 2019
Pretreatment Requirement	None; avoids acid/enzymatic hydrolysis	Corrales et al., 2012
Fermenting Organism	*Saccharomyces cerevisiae*	Tan et al., 2019
Advantages	- Direct fermentability - No saccharification needed - Energy-efficient process	Tan et al., 2019; Cao & Liu, 2013
Comparison to Other Substrates	Comparable to sugarcane and sweet sorghum juices in fermentability	Cao & Liu, 2013
Distinct Composition Feature	High mineral content (especially potassium and calcium)	Boakye-Boaten et al., 2016
Impact of Minerals on Fermentation	Beneficial as cofactors at optimal levels; inhibitory if excessive	Tan et al., 2019

Studies with Miscanthus press juice showed enhanced yeast growth at 90% juice strength as opposed to 50% strength but other grass juices present different optimal dilution effects based on their inhibitor compositions (Boakye-Boaten et al., 2016). Each unorthodox feedstock requires individual assessment of its chemical make-up and harmful properties to demonstrate their distinct characteristics. Solar-fed Banana juice requires extra addition of nutrients for successful fermentation processes in addition to appropriate dilution adjustments. The ethanol production process using banana frond juice as raw material became faster and more efficient after the addition of nitrogen supplements (such as yeast extract or ammonium salts) because the juice itself contained limited nitrogen for yeast fermentation (Tan et al., 2019). Proper nitrogen supplementation at pH 5 gave *S. cerevisiae* the ability to complete BFJ fermentation within 48 hours according to Tan et al. (2019). Researchers optimized BFJ fermentation through modifications of juice concentration and addition of nutrients while adjusting pH, which allowed the process to perform similarly to traditional sugar substrate-based fermentation.

The straightforward conversion of BFJ into ethanol cuts down processing complexity and reduces energy consumption during production, thus aligning its manufacturing procedures with sugarcane or sweet sorghum juice operations (Cao & Liu, 2013; Tan et al., 2019; Vu et al., 2017). BFJ exhibits different chemical properties than conventional juice since it derives from banana plants, thereby having elevated mineral levels, including potassium and calcium, which modify yeast metabolic activities (Cao & Liu, 2013; Boakye-Boaten et al., 2016). While minerals foster positive effects on fermentation until specific levels are reached, they become performance inhibitors that need appropriate adjustment during banana fruit juice fermentation (Tan et al., 2019).

3.2 Fermentation performance and kinetics

Fermentation studies utilizing BFJ achieved satisfactory results regarding ethanol production capacity, though additional operational improvements could enhance performance. A 2-L bioreactor enabled S. cerevisiae to produce 0.33 g_ethanol/g_sugar when processing BFJ according to Tan et al. (2019). The conversion rate reaches a level of 65–70% against the theoretical maximum ethanol yield because certain sugar losses occur through microbial maintenance and secondary product formation. The experiments demonstrated through results that fermentation feedstocks containing BFJ are achievable when ethanol concentrations reached 10–20 g/L (Figure 3). BFJ fermentation speed depends on the characteristics of its nutrient composition. The undiluted 100% BFJ created unfavourable conditions for S. cerevisiae growth and ethanol production because of potential inhibiting elements like mineral excess and selected phenolic compounds. The ethanol titer achieved higher levels when researchers diluted the juice to 80% volume ratio versus treating it as undiluted 100% juice (Tan et al., 2019). Ample sugar availability combined with inhibitor tolerance at 80% BFJ demonstrates that mild dilution solves toxic inhibitory problems while delivering adequate sugars to the process.

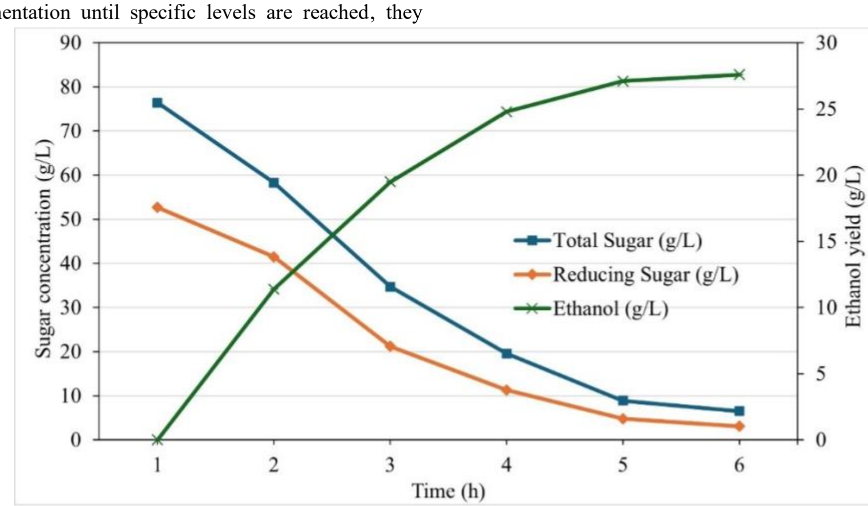

Figure 3. Time-course data of sugar consumption and ethanol production

3.3 Comparison with other feedstocks

The fermentation output obtained from BFJ matches conventional as well as non-conventional feedstock juices to the extent that some BFJ measures approach mainstream feedstock metrics. Research demonstrates that the BFJ fermentation outcome (delivering 0.33 g ethanol per gram substrate) matches well with ethanol production from sweet sorghum juice and various grassy biomass juices processing under identical conditions (Boakye-Boaten et al., 2017; Cao & Liu, 2013; Kongchan et al., 2022). BFJ produces comparable efficiency to juice derived from corn-based materials although its performance remains slightly diminished. Corn stalk juice fermented with S. cerevisiae using immobilized yeast cells on green substrate produced 0.45 g_ethanol/g_sugar according to Bautista et al. (2022). This exceeded BFJ fermentation outputs. It is believed that corn stalk juice provides improved fermentation yields by integrating a favorable sugar composition with advanced yeast immobilization protocols. The researchers at Gomez-Flores et al. (2018) obtained 0.27 g/g ethanol production from sugar corn juice taken from high-sugar corn varieties without the need for major supplements while maintaining yields close to BFJ levels. Sugarcane molasses and sugar beet juice feedstocks produce about 0.45–0.50 g/g ethanol yield during industrial production since they contain high sucrose levels along with optimized processing methods.

Under optimized fermentation conditions and additional process development, BFJ is expected to yield ethanol at approximately the same level as noted in Tan et al. (2019) and Bautista et al. (2022) (0.3–0.4 g/g). BFJ fermentation operates in a basic batch process, but its performance could be increased through the implementation of improved methods like cell immobilization and fed-batch fermentations, and continuous fermentation (Bautista et al., 2022). The ethanol production titer of BFJ remains lower than that of traditional molasses fermentations (which reach ethanol concentrations ranging from 50 to 100 and above g/L) because the tested BFJ contained moderately concentrated sugar levels (Tan et al., 2019). The volume of ethanol production could be maximized by either juice concentration or blending the juice with additional sugar streams. Tests indicate that although native yeast fermentation of bee-free juice does not surpass conventional agricultural substrates, it remains a competitive renewable alternative because it performs similarly to other sources of agricultural juice and provides distinct benefits through affordable and accessible raw material procurement.

Table 3. Comparative fermentation metrics of BFJ and other feedstock juices

Feedstock	Fermentation Strategy	Ethanol Yield (g/g sugar)	Ethanol Titer (g/L)	Reference/Remarks
Sweet Sorghum Juice	Conventional batch	~0.33	~20–30	Cao & Liu (2013)
Grassy Biomass Juices	Batch	~0.30–0.35	~15–25	Boakye-Boaten et al.,(2016).
Corn Stalk Juice	Yeast immobilized Batch	Up to 0.45	~30	Bautista et al., (2022)
Sugar Corn Juice	Batch	~0.27	~20	Gomez-Flores et al., (2018).
Banana Frond Juice (BFJ)	Batch fermentation	0.33	27.6	This study
Sugarcane Molasses	Industrial optimized	~0.45–0.50	50–100+	High sucrose content; benchmark for industrial bioethanol.
Sugar Beet Juice	Industrial optimized	~0.45–0.50	50–90	Efficient under optimized fermentation conditions.

3.4 Scalability considerations and circular economy implications

The main draw of BFJ for bioethanol production stems from its availability at a low price. The Banana plant creates large amounts of remaining biomass since workers discard its fronds both during its growth cycle and post-harvest activities (Menya et al., 2024). Limited agricultural waste from banana plants offers an affordable sugar source for value addition. Areas that grow bananas provide continuous access to fronds for the construction of large-scale ethanol manufacturing operations (Guerrero & Muñoz, 2023). Analysis from life-cycle assessment confirmed that ethanol production from banana waste leads to favorable results for both energy balance and greenhouse gas reduction when utilized for fuel purposes. The research demonstrated that ethanol produced from banana residues for the second generation created a smaller carbon impact than conventional gasoline. The production of ethanol from banana frond biomass outcomes in substantial yields. It has been demonstrated that acid-treatment of banana pseudostems produces 180–200 liters of ethanol from each ton of dry biomass according to Corrales et al. (2012). The fermentable nature of BFJ delivers yields matching conventional fermentation through free sugars while its residue can produce supplementary energy thus boosting the total biofuel production (Boakye-Boaten et al., 2016). The scalability of BFJ fermentation relies heavily on logistics because transporting banana fronds to processing facilities represents a major challenge. Juice extraction takes place within close proximity to plantation sites using decentralized presses to obtain juice on location (Kamm et al., 2016). The obtained juice requires transportation which can be done together with modular fermenters for fermentation purposes. Several integrated biorefinery concepts focused on processing banana plants into numerous products exist for improving economic stability (Boakye-Boaten et al., 2016; Kamm et al., 2016).

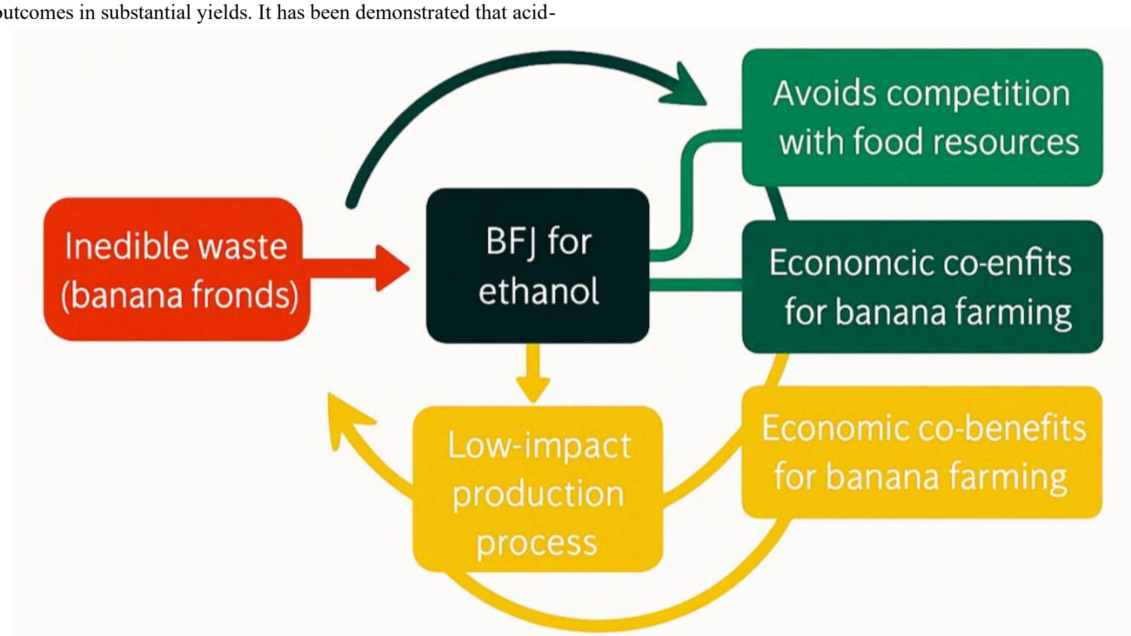

Figure 4. Overview of circular economy implications: Valorization of banana frond juice for bioethanol

Implications of the circular economy: Valorization of banana frond Juice for Bioethanol as illustrated in Figure 4. BFJ proves suitable for ethanol production because it supports sustainable and second-generation biofuel development. The use of banana fronds as biofuel feedstock protects food availability since this waste material is not suitable for human consumption. BFJ proves superior to food-based crops such as corn or sugarcane for bioenergy because it matches directives promoting waste materials as feedstocks. A European Union renewable energy policy rewards basic biofuels derived from agricultural residue through increased target credit recognition because they are seen as sustainable (Saetang & Tipnee, 2022). Secondly, the production of ethanol from banana waste implements waste-to-product circularity within agriculture, which lowers farming waste burdens while decreasing residue decomposition-induced pollution (Guerrero & Muñoz, 2023). Commercial fermentation of BFJ returns part of the biomass carbon to atmospheric CO_2 during fermentation and ethanol combustion, which constitutes short-cycle carbon release, unlike fossil fuels.

Low-impact characteristics are found throughout the production process. The fermentation of beetroot fruit juice requires no more than juice extraction through simple pressing which generates lower chemical exposure when compared to lignocellulosic ethanol production requiring acid or alkali or enzymatic hydrolysis pretreatments (Corrales et al, 2012; Guerrero and Muñoz, 2023). The waste solids generated during juice extraction are convertable into nutrient-filled compost or biogas feedstock thus improving sustainability (Boakye-Boaten et al., 2016). The potential application of banana fruit juice extraction towards bioethanol production offers economic advantages to farmers in banana farming areas. The disposal cost of fronds could be eliminated when farmers or local enterprises extract juice from them either for selling to biofuel producers or establishing small-scale ethanol production facilities. When coupled with other business endeavors rural economies become stronger and more resistant to shocks. Researchers must examine all stages from production to waste management within the supply chain since these elements establish the environmental footprint of bioethanol made from banana fronds. The present research works at pilot-scale but shows promising results that BFJ fermentation enables a sustainable bioethanol generation from waste agricultural products while providing efficient and scalable methods.

4. Conclusion

This study demonstrated the feasibility of utilizing banana frond juice (BFJ) as a direct fermentation substrate for second-generation bioethanol production. The extraction procedure obtained 0.33 liters of juice from each kilogram of fresh frond while producing high fermentable sugar concentrations of glucose and fructose. At mesophilic temperatures, S. cerevisiae efficiently processed BFJ straight from extraction to produce an ethanol concentration of 45.75 g/L and yield 0.33 g/g sugar. The production of ethanol followed a quick and predictable pattern until all sugar components were exhausted in four days at a peak production rate of 0.38 g/L·h. BFJ serves as an appealing substitute for both conventional and recently developed feedstocks since its fermentation process is simple, while requiring little supplementation and achieving efficient sugar conversion into ethanol. The production of BFJ ethanol within banana agricultural systems will contribute to residue management improvements while controlling greenhouse gas emissions and creating sustainable local renewable fuel programs. BFJ stands apart from other lignocellulosic residues because it needs no pretreatment process, which makes it suitable for implementation in decentralized and rural biorefineries through press-and-ferment operations. Further research must evaluate three process optimization methods, including fed-batch fermentation along with combined agro-residue fermentations and complete techno-economic assessment at production-scale facilities, as well as a sustainable, large-scale bioethanol raw material that enhances the development of a low-carbon bioeconomy.

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