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Bioethanol Production from Agricultural Food Waste – Banana Peels and Sugarcane Bagasse

Princess Olorunshola [1], Keayiabarido Jude [1*], Sobomate Chuku [1], Miracle Uzoma [1], Emmanuel Bakpo [1], Aroloye Numbere [1,2]

[1] *Department of Biology and Biotechnology, School of Science Laboratory and Technology, University of Port Harcourt, Choba P.M.B. 5323, Nigeria*

[2] *Department of Animal and Environmental Biology, Faculty of Science, University of Port Harcourt, Choba P.M.B. 5323, Nigeria*

ABSTRACT

This study, titled "*Bioethanol Production from Agricultural Food Waste - Banana Peels and Sugarcane Bagasse*," was conducted at the Pharmaceutical Sciences Laboratory, University of Port Harcourt, Nigeria, to explore sustainable alternatives to fossil fuels through waste-based bioethanol production. Banana peels were obtained from Choba Market and sugarcane bagasse from Mile 3 vendors. The substrates underwent pretreatment using dilute hydrochloric acid (1–2% v/v) at 121 °C for 60 minutes and enzymatic hydrolysis with cellulase and amylase at 50 °C for 48 hours to enhance sugar release. Fermentation was carried out with *Saccharomyces cerevisiae* and *Zymomonas mobilis* under anaerobic conditions for 72 hours. Proximate analysis revealed carbohydrate contents of 64.5% and 58.2% for banana peels and bagasse, respectively. Combined pretreatment yielded the highest reducing sugars161.8 mg/g for banana peels and 145.9 mg/g for bagasse. Ethanol yields were higher with *Z. mobilis* (28.0 g/L for banana peels and 29.5 g/L for bagasse) compared to *S. cerevisiae*, with statistical analysis ($p < 0.05$) confirming significant differences across pretreatment and microbial strains. When normalized to dry biomass, bagasse achieved higher efficiency (0.25 g ethanol/g biomass) than banana peels (0.21 g/g). The study concludes that both wastes are viable feedstocks for bioethanol production; banana peels favor rapid fermentability, and bagasse offers greater conversion efficiency. It is recommended that industrial bioethanol initiatives

*CORRESPONDING AUTHOR:
Keayiabarido Jude, Department of Biology and Biotechnology, School of Science Laboratory and Technology, University of Port Harcourt, Choba P.M.B. 5323, Nigeria; Email: keayiabaridojude@yahoo.com

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adopt combined pretreatment methods, leverage *Z. mobilis* for higher yields, and integrate waste-to-energy programs to enhance renewable energy production and reduce environmental pollution in Nigeria.

Keywords: Banana Peel; Bioethanol; Ethanol; Fermentation; Sugarcane

1. Introduction

Energy is fundamental to modern society, serving as the backbone of industrial development, technological progress, transportation, and domestic life. Over the past decades, the global demand for energy has risen exponentially, driven by rapid industrialization, accelerated urbanization, population expansion, and increasing technological advancements. This rise in demand has placed unprecedented pressure on conventional energy systems, particularly fossil fuels such as coal, petroleum, and natural gas, which have historically been the dominant sources of global energy supply.

Despite their central role in powering economies, fossil fuels present numerous challenges. The intensive and prolonged reliance on these non-renewable resources has raised serious environmental, social, and economic concerns. Combustion of fossil fuels releases excessive greenhouse gases (GHGs), which are major contributors to global climate change, global warming, and air pollution. Additionally, fossil fuel use is linked to acid rain, ozone depletion, and environmental degradation [1]. Economically, their finite nature implies eventual depletion, while the volatility of global oil markets and geopolitical instabilities further complicate energy security for many nations.

These challenges have triggered a global paradigm shift towards the exploration and adoption of alternative and renewable energy sources that are environmentally benign, economically viable, and sustainable in the long term. Among these alternatives, biofuels have emerged as particularly attractive due to their carbon neutrality, local availability of raw materials, and their ability to reduce dependency on imported fossil fuels. This shift is not only essential for mitigating climate change but also for promoting sustainable development in line with international environmental agreements such as the Paris Climate Accord and the United Nations Sustainable Development Goals (SDGs).

Biofuels refer to renewable fuels produced from biological resources such as agricultural residues, forest waste, algae, and other biomass materials. They are commonly classified into first-generation (food-based), second-generation (non-food lignocellulosic materials), and third-generation (algae-based) biofuels. Among the biofuels, bioethanol has gained particular prominence because of its versatility, clean-burning properties, and compatibility with existing fuel infrastructure.

Bioethanol is an alcohol-based fuel that can be directly blended with gasoline to reduce vehicular emissions and enhance combustion efficiency. One of its advantages is that it requires little to no modification of existing internal combustion engines. Additionally, its combustion releases lower levels of harmful pollutants such as sulfur oxides, carbon monoxide, and particulate matter, making it a more environmentally friendly alternative compared to fossil fuels [2].

Currently, large-scale bioethanol production is dominated by first-generation feedstocks such as maize, wheat, sugarcane, and other food crops. While this approach has been commercially successful, it has also sparked the controversial "food vs. fuel debate." Competition for arable land and agricultural resources has led to concerns about food insecurity, rising food prices, and unsustainable agricultural practices [3]. To overcome these challenges, attention has increasingly shifted towards second-generation feedstocks, which include lignocellulosic biomass and food waste. These resources are non-edible, abundant, and more sustainable, thereby reducing the strain on food supply chains.

Food waste has become a critical global challenge, both from an environmental and socioeconomic perspective. According to the Food and Agriculture Organization (FAO), nearly one-third of all food produced worldwide is lost or wasted, translating to about 1.3 billion tonnes annually [4]. This level of waste not only signifies a loss of valuable resources such as water, land, and energy used in food production but also contributes significantly to environmental degradation. Food waste disposed of in landfills generates methane, a greenhouse gas with a global warming potential over 25 times greater than carbon dioxide. Furthermore, leachates from decomposing food waste can contaminate soil and water resources, posing health and ecological risks.

Paradoxically, food waste also represents a valuable and underutilized resource. Rich in carbohydrates, proteins, lipids, and other organic matter, food waste has high potential for conversion into bioenergy products such as bioethanol, biogas, and biodiesel. The carbohydrate fraction in particular can be hydrolyzed into fermentable sugars through enzymatic or microbial processes and subsequently fermented to bioethanol[5]. Thus, the valorization of food waste into bioethanol offers a dual benefit: waste minimization and renewable energy production, contributing to sustainable waste management and energy security.

Among the numerous food waste materials available, banana peels and sugarcane bagasse stand out as promising candidates for microbial bioethanol production due to their abundance and biochemical composition.

Banana peels: Bananas are among the most consumed fruits globally, particularly in tropical and subtropical regions. During consumption and processing, large volumes of banana peels are discarded as waste. These peels are rich in carbohydrates such as starch and simple sugars, along with essential nutrients that support microbial growth. Their chemical composition makes them readily fermentable, requiring relatively mild pretreatment before microbial conversion into bioethanol[6].

Sugarcane bagasse: This is the fibrous residue left after the extraction of juice from sugarcane in sugar mills. It is one of the most abundant agricultural by-products, especially in countries where sugarcane cultivation is extensive. Sugarcane bagasse is primarily composed of cellulose, hemicellulose, and lignin. The cellulose and hemicellulose fractions can be hydrolyzed into fermentable sugars using appropriate pretreatment and enzymatic hydrolysis, which can then be fermented by microbial strains to produce ethanol. Unlike food-based feedstocks, sugarcane bagasse is non-edible and therefore does not compete with food supply, making it a sustainable and low-cost raw material.

Together, banana peels and sugarcane bagasse exemplify the potential of turning agricultural and household waste into renewable energy resources.

Banana peels and sugarcane bagasse represent abundant, underutilized waste products in agricultural economies, especially in tropical regions. Both are rich in fermentable sugars and lignocellulosic components, making them promising feedstocks for bioethanol production. Yet, their bioethanol potential has not been systematically studied in combination, nor adequately compared in terms of yield efficiency, pretreatment challenges, and conversion effectiveness. Moreover, existing works often overlook the environmental benefits of diverting these food wastes from open dumping or burning, practices that contribute to greenhouse gas emissions and pollution.

This gap highlights the need for research that directly evaluates banana peels and sugarcane bagasse as dual sources for sustainable bioethanol production. This study not only addresses the lack of focused work on these specific food waste materials but also demonstrates how agricultural waste streams can be transformed into renewable energy resources by investigating their biochemical composition, optimizing fermentation processes, and comparing their conversion efficiencies. This approach offers a pathway to reduce environmental pollution, alleviate food-versus-fuel tensions, and enhance circular economy practices within agricultural communities.

The aim of this research is to explore the potential of bioethanol production from agricultural food waste — banana peels, sugarcane bagasse.

Objectives:

1. To characterize the chemical composition of banana peels and sugarcane bagasse for bioethanol production.
2. To identify and optimize microbial strains for efficient fermentation.
3. To investigate the impact of various pretreatment methods on bioethanol yield.

2. Materials and Methods

2.1. Study Location

This study was conducted at the Pharmaceutical Sciences Laboratory, University of Port Harcourt, Nigeria, which is equipped with facilities for microbial fermentation, enzymatic hydrolysis, and analytical procedures such as gas chromatography. The choice of this location was based on the proximity to Feedstocks, the banana peels were sourced from local fruit vendors and markets in Choba, Port Harcourt; while sugarcane bagasse was collected from sugarcane vendors within Mile 3. In the same vein, there is laboratory Infrastructure. The University's pharmaceutical laboratory provided access to controlled fermentation bioreactors, centrifuges, ovens, and advanced analytical equipment such as gas chromatographs (GC), which were essential for accurate ethanol quantification.

The feed stocks used for this research were banana peels and sugarcane bagasse, both of which serve as abundant agricultural and food-processing wastes rich in carbohydrates suitable for microbial fermentation.

2.2. Sample Collection

The banana peels were collected fresh from local fruit vendors at Choba Market, Port Harcourt, Rivers State. Similarly, sugarcane bagasse was obtained from sugarcane juice vendors at Mile 3 Market, Port Harcourt (see **Appendix H**, **Figure A6**).

Both substrates were chosen for their high carbohydrate and fiber content, which makes them viable for bioethanol production. Banana peels contain substantial amounts of starch, sucrose, and pectin, while sugarcane bagasse consists predominantly of cellulose, hemicellulose, and lignin that require hydrolysis to release fermentable sugars [7].

Two ethanol-producing microorganisms were employed in the fermentation process. They are saccharomyces cerevisiae (Baker's yeast): A robust yeast strain known for its high ethanol tolerance and ability to ferment simple sugars efficiently. The yeast culture was obtained from the Pharmaceutical Sciences Laboratory, University of Port Harcourt. The second microorganism is Zymomonas mobilis: A facultative anaerobic bacterium capable of fermenting glucose, fructose, and sucrose into ethanol through the Entner-Doudoroff pathway. The bacterial strain was sourced from the Pharmaceutical Sciences Laboratory, University of Port Harcourt, and maintained on nutrient agar slants under refrigeration before use. Both organisms were cultured and standardized prior to inoculation following the methods described by Hahn-Hägerdal et al. [8,9].

2.3. Reagents

All reagents used in this study were of analytical grade and supplied by the laboratory attendant at the Pharmaceutical Sciences Laboratory, University of Port Harcourt. They include:

1. Hydrochloric acid (HCl, 1–2% v/v): Used for acid hydrolysis of feedstocks.
2. Sodium hydroxide (NaOH): Used for neutralization of acid-hydrolyzed samples.
3. Cellulase enzyme: Facilitates enzymatic hydrolysis of cellulose into glucose.
4. Amylase enzyme: Converts starch into maltose and glucose for microbial fermentation [10].
5. Buffer solutions (pH 4.8–5.0): Used to maintain optimal pH during enzymatic hydrolysis and fermentation.
6. Distilled water: Used for washing, dilution, and preparation of reagents.
7. Ethanol standards (99.9% purity): Used for calibration and quantification during Gas Chromatographic analysis.
8. 3,5-Dinitrosalicylic acid (DNS) reagent: Used for determining reducing sugar concentration in hydrolysates [11].

2.4. Equipment and Glassware

Key laboratory apparatus and instruments used were provided by the laboratory. They include:

(i) Oven dryer: For drying feedstock samples at 60 °C until constant weight.
(ii) Mechanical grinder and sieve: For grinding and size reduction of feedstock particles (~0.5 mm).
(iii) Autoclave (121 °C, 15 psi): For sterilization of media and samples.
(iv) pH meter: For pH monitoring and adjustment.
(v) Bioreactor (2 L capacity): Used for controlled fermentation of hydrolysates.
(vi) Centrifuge (10,000 rpm): For separating biomass from fermentation broth.
(vii) Gas Chromatograph: For quantifying ethanol concentrations [12].
(viii) Analytical balance (0.001 g precision): For precise weighing of samples and reagents.
(ix) Glassware: Beakers, flasks, pipettes, and test tubes.

2.5. Sample Preparation

The food waste samples (banana peels and sugarcane bagasse) underwent several preparatory steps to enhance sugar availability:

1. Collection and Drying: Banana peels and sugarcane bagasse were collected from Choba Market and washed

with distilled water to remove dirt and impurities. The samples were oven-dried at 60 °C until a constant weight was achieved to prevent microbial degradation[13].

2. Grinding and Sieving: The dried samples were ground into fine particles using a mechanical grinder. The ground materials were sieved to ensure uniform particle size (approximately 0.5 mm) for efficient hydrolysis[14].
3. Pretreatment: Acid Hydrolysis: The samples were treated with dilute hydrochloric acid (1–2% v/v) at 121 °C for 45minutes to break down hemicellulose and starch into fermentable sugars[15]. Enzymatic Hydrolysis: After neutralization, cellulase and amylase enzymes were added to further hydrolyze complex carbohydrates into simple sugars. The hydrolysis was conducted at an optimal temperature (50 °C) and pH (4.8–5.0) for 36 hours under constant agitation[1].

2.6. Fermentation Process

The fermentation process was optimized to maximize ethanol yield by controlling temperature, pH, and aeration conditions[16]:

1. Microbial Inoculation:The pretreated hydrolysates were sterilized and inoculated with *Saccharomyces cerevisiae* and *Zymomonas mobilis* in separate fermentation batches. The initial cell concentration was adjusted to ~10^6 cells/mL to ensure optimal fermentation efficiency[17]. The fermentation was conducted in a 2L bioreactor at 30 °C for yeast fermentation and 35 °C for bacterial fermentation. The pH was maintained between 4.5 and 6.0 using buffer solutions to optimize enzymatic activity and microbial growth. Oxygen-limiting conditions were ensured by sealing fermentation vessels and purging with nitrogen gas when necessary[18]. Fermentation progress was monitored over 72 hours, with periodic sampling for sugar consumption and ethanol production analysis[1].
2. Monitoring: Samples were collected every 12 hours for residual sugar analysis using the DNS method[11] and ethanol quantification using gas chromatography.

2.7. Ethanol Yield Analysis

To quantify the ethanol concentration, gas chromatography (GC) was employed as the analytical technique:

1. Sample Collection and Filtration: Fermentation samples were centrifuged at 10,000 rpm for 10 minutes to separate biomass from the liquid fraction. The supernatant was filtered through a 0.22µm membrane filter before analysis[1].
2. Gas Chromatography (GC) Analysis: A gas chromatograph equipped with a flame ionization detector (FID) was used to determine ethanol concentration. The stationary phase was a polar column (e.g., HP-INNOWax), and helium served as the carrier gas. The injection temperature was set to 200 °C, with an oven temperature gradient from 40 °C to 200 °C at a rate of 10 °C/min[12]. Calibration curves were prepared using ethanol standards of known concentrations for accurate quantification. The analytical method adopted by other researchers is shown in **Table 1**.

Table 1. Analytical Methods for Parameters Studied.

Parameter	Method Used	References
Moisture Content	Oven-drying method at 105 °C until constant weight	AOAC[19]
Ash Content	Muffle furnace incineration at 550 °C for 4 hours	AOAC[19]
Crude Fiber	Acid-alkali digestion method	AOAC[19]
Carbohydrate Content	By difference (100 − % moisture − % ash − % fiber − % protein − % fat)	Miller[11]
Reducing Sugars	3,5-Dinitrosalicylic acid (DNS) method	Miller[11]
Ethanol Concentration	Gas Chromatography with FID detection	Sassner et al.[12]

2.8. Statistical Analysis

Data was subjected to one-way analysis of variance (ANOVA) to determine the significance of differences in ethanol yield between fermentation conditions[20]. Yield efficiency was calculated as ethanol produced per gram of substrate consumed (g/g)[21]. ANOVA results showed a statistically significant difference ($p < 0.05$) in ethanol yield across different pretreatment methods and microbial strains.

The statistical outcome confirms that both pretreatment type and microbial strain significantly affect ethanol yield. The low *p*-value (< 0.05) implies that observed variations are not due to chance. These findings emphasize the critical role of biological and chemical optimization in fermentation processes (see **Appendix E**, **Table A4**).

3. Results

3.1. Proximate Analysis of Feedstocks

The analysis (**Table 2**) shows that both banana peels and sugarcane bagasse possess high carbohydrate content, which makes them suitable for bioethanol production. Banana peels, with slightly higher carbohydrate content, may support higher ethanol yield. On the other hand, sugarcane bagasse, having a greater fiber concentration, presents more complex structural polysaccharides, requiring efficient pretreatment. The lower moisture content in both substrates is advantageous for storage and fermentation stability (see **Appendix A**, **Table A1**).

Table 2. The proximate analysis of banana peels and sugarcane bagasse indicating moisture, carbohydrate, fiber, and ash content.

Component	Banana Peels (%)	Sugarcane Bagasse (%)
Moisture Content	11.3	9.7
Carbohydrates	64.5	58.2
Fiber	14.7	26.4
Ash	3.2	2.9

3.2. Effect of Pretreatment on Reducing Sugar Yield

The impact of pretreatment on the amount of reducing sugar extracted was evaluated using acid and enzymatic hydrolysis. Banana Peels: The untreated sample released 52.6 mg/g reducing sugars, which more than doubled after acid treatment (112.3 mg/g). Enzymatic hydrolysis further improved the yield to 134.8 mg/g, and the combined method produced the highest release of 161.8 mg/g, representing a 207% increase relative to untreated biomass (**Table 3**, see **Appendix B**, **Table A2**, and **Figure A2**).

Table 3. Reducing Sugar Yield of Banana Peels and Sugarcane Bagasse after Pretreatment.

Feedstock	Untreated (mg/g)	Acid Treated (mg/g)	Enzyme Treated (mg/g)	Combined (Acid+Enzymes) (mg/g)
Banana Peels	52.6	112.3	134.8	161.8
Sugarcane Bagasse	45.7	95.4	121.6	145.9

Sugarcane Bagasse: Starting from 45.7 mg/g, acid pretreatment improved sugar release to 95.4 mg/g. Enzymatic hydrolysis gave 121.6 mg/g, while the combined method yielded 145.9 mg/g, which is a 219% increase compared to untreated biomass.

Banana peels consistently produced higher sugar yields than bagasse under all treatments, but bagasse demonstrated a greater relative improvement when pretreated. This suggests that while banana peels are naturally richer in easily fermentable sugars, sugarcane bagasse's cellulose potential is unlocked more effectively by combined pretreatment.

Pretreatment, especially enzymatic hydrolysis, greatly improved sugar release from both substrates. Enzyme-treated samples recorded the highest sugar yields, as enzymes specifically target cellulose and starch without producing fermentation inhibitors. Acid hydrolysis was effective but slightly less efficient and could introduce inhibitory by-products. This finding supports the need for optimized enzyme use in bioethanol production.

3.3. Fermentation Efficiency and Ethanol Yield

Fermentation was conducted over 72 hours using *Saccharomyces cerevisiae* and *Zymomonas mobilis*. Ethanol yield and efficiency were measured to evaluate microbial performance (**Table 4**, see **Appendix C**, and **Table A3**).

The ethanol yield obtained from both banana peels and sugarcane bagasse shows that *Zymomonas mobilis* consistently outperformed *Saccharomyces cerevisiae* across all pretreatment conditions.

In banana peel, under acid hydrolysis, ethanol yield increased from 14.2 g/L (S. cerevisiae) to 16.5 g/L (Z. mobilis), representing an approximate 16% improvement. With enzymatic hydrolysis, yields rose from 18.5 g/L to 21.5 g/L (+16%). The highest yields were observed under combined pretreatment, where *Z. mobilis* produced 28.0 g/L, about 19% higher than the 23.6 g/L achieved by yeast.This indicates that banana peels are highly fermentable substrates and that *Z. mobilis* utilizes the released sugars more efficiently, particularly when pretreatments are optimized.

Table 4. Ethanol Yield from Banana Peels and Sugarcane Bagasse (g/L).

Feedstock	Pretreatment	*S. cerevisiae* (g/L)	*Z. mobilis* (g/L)
Banana peels	Acid hydrolysis	14.2	16.5 (≈+16%)
Banana peels	Enzymatic hydrolysis	18.5	21.5 (≈+16%)
Banana peels	Combined pretreatment	23.6	28.0 (≈+19%)
Sugarcane bagasse	Acid hydrolysis	11.8	13.8 (≈+17%)
Sugarcane bagasse	Enzymatic hydrolysis	17.3	20.0 (≈+16%)
Sugarcane bagasse	Combined pretreatment	24.9	29.5 (≈+19%)

As for sugarcane bagasse in acid-hydrolyzed samples, ethanol yield improved from 11.8 g/L (*S. cerevisiae*) to 13.8 g/L (*Z. mobilis*), a 17% increase. Enzymatic hydrolysis further enhanced yields (17.3 → 20.0 g/L, +16%). The maximum ethanol concentration was again recorded with combined pretreatment, where yields increased from 24.9 g/L (yeast) to 29.5 g/L (*Z. mobilis*), an improvement of about 19%. Although bagasse generally produced slightly lower ethanol levels than banana peels under the same conditions, the efficiency gains with *Z. mobilis* were consistent.

Across both feedstocks, *Z. mobilis* demonstrated a 15–20% performance advantage over *S. cerevisiae*. The combined pretreatment strategy yielded the highest ethanol concentrations for both organisms, confirming the importance of integrating acid and enzymatic hydrolysis for maximum sugar release. The results highlight the superior metabolic efficiency of *Z. mobilis*, which channels a greater proportion of available sugars into ethanol rather than biomass formation.

3.4. Comparative Ethanol Yield per Gram of Biomass

To compare feedstock efficiency, ethanol yield was normalized per gram of dry biomass and the result is presented in **Table 5**. For calculation of ethanol production see **Appendix F**, and **Figure A4**. Similarly, for ethanol yield graph see **Appendix G** and **Figure A5**.

Table 5. Ethanol Yield Efficiency (g ethanol/g dry biomass).

Feedstock	Ethanol Yield Efficiency
Banana Peels	0.21
Sugarcane Bagasse	0.25

When ethanol yields were normalized to biomass input (g ethanol per g dry feedstock), a slightly different picture emerged. Although banana peels generated higher ethanol concentrations during fermentation, sugarcane bagasse produced 0.25 g ethanol/g biomass, compared to 0.21 g ethanol/g biomass for banana peels (**Table 5**, **Figures 1** and **2**). This indicates that, gram for gram, bagasse is a more efficient feedstock despite requiring more pretreatment.

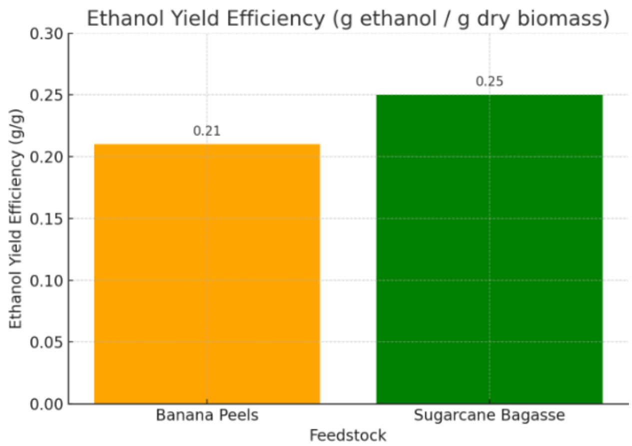

Figure 1. Reducing Sugar Yield under Different Pretreatments.

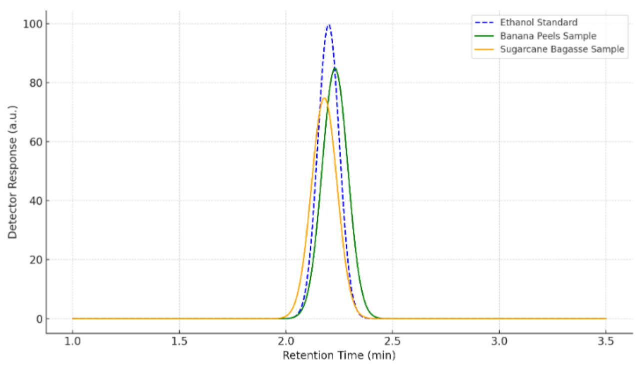

Figure 2. GC Chromatograms of Ethanol from Banana Peels and Bagasse (Showing retention time peaks for ethanol samples calibrated with ethanol standard).

The combined interpretation of GC data and normalized yields therefore highlights a key distinction. It shows that the banana peels deliver higher broth ethanol concentrations due to readily available sugars, making them attractive for small-scale or rapid bioethanol production. The Sugarcane bagasse offers superior efficiency per gram of biomass, strengthening its suitability for large-scale, sustainable bioethanol production.

These results align with previous findings [5,6], which emphasize the complementary roles of starch-rich wastes and lignocellulosic residues in renewable fuel development.

3.5. Gas Chromatography Results

Gas Chromatography (GC) analysis validated the ethanol concentrations across fermented samples. The ethanol peaks appeared between 2.1–2.3 minutes retention time, consistent with calibration standards. Peak intensities revealed that banana peel fermentations exhibited higher ethanol concentrations in the broth compared to sugarcane bagasse, confirming that banana peels released more readily fermentable sugars. This outcome reflects the relatively simple carbohydrate profile of banana peels, which requires less energy-intensive hydrolysis. GC also detected minor by-products, suggesting fermentation inefficiencies possibly linked to substrate impurities (see **Appendix D**, **Figure A3**).

4. Discussion

The findings of this study provide valuable insights into the potential of banana peels and sugarcane bagasse as feedstocks for sustainable bioethanol production. In systematically evaluating their proximate composition, reducing sugar yields after pretreatment, microbial fermentation performance, normalized ethanol efficiency, and chromatographic validation, several key conclusions can be drawn regarding their comparative suitability.

The proximate analysis demonstrated that both banana peels and sugarcane bagasse are rich in carbohydrates, underscoring their viability as bioethanol substrates. Banana peels contained slightly higher carbohydrate levels (64.5%) than sugarcane bagasse (58.2%), which likely explains the higher ethanol concentrations observed during fermentation. Conversely, the higher fiber content in bagasse (26.4% compared to 14.7% in banana peels) suggests a greater proportion of complex polysaccharides such as cellulose and hemicellulose. These structural carbohydrates require more intensive pretreatment to unlock fermentable sugars, yet they contribute to higher normalized ethanol yields per unit biomass. This finding aligns with the dual-resource paradigm in biofuel development: starchy wastes such as banana peels provide rapid sugar availability, while lignocellulosic residues like bagasse ensure greater long-term efficiency [6].

Pretreatment had a decisive influence on reducing sugar yields. Both acid and enzymatic hydrolysis significantly enhanced sugar release, but enzymatic and combined pretreatments were particularly effective. Banana peels consistently exhibited higher sugar yields across treatments (up to 161.8 mg/g with combined pretreatment), reflecting their naturally fermentable composition. However, sugarcane bagasse displayed a larger relative increase (219% compared to 207% for banana peels), highlighting the importance of pretreatment in unlocking cellulose-bound sugars. This suggests that bagasse, although initially resistant, can be optimized to become a highly competitive feedstock with the appropriate hydrolysis strategy.

The fermentation trials revealed a consistent advantage of *Zymomonas mobilis* over *Saccharomyces cerevisiae*. Across all pretreatment methods, *Z. mobilis* achieved 15-20% higher ethanol yields, underscoring its superior metabolic efficiency and ability to channel sugars directly into ethanol. For instance, under combined pretreatment, ethanol yields from banana peels increased from 23.6 g/L with yeast to 28.0 g/L with *Z. mobilis*, while bagasse yields rose from 24.9 g/L to 29.5 g/L. These results support earlier findings that highlight the potential of *Z. mobilis* as a high-yielding alternative to conventional yeast in bioethanol production. Importantly, the consistency of this improvement across both substrates strengthens the case for microbial strain optimization as a key driver of fermentation success.

A key distinction emerged between absolute ethanol concentrations and normalized ethanol yields. Banana peels delivered higher ethanol concentrations in fermentation broth, supported by the stronger ethanol peaks observed in GC chromatograms. This outcome reflects their simple sugar content and ease of microbial conversion. However, when normalized to biomass input, sugarcane bagasse proved more efficient (0.25 g ethanol/g biomass compared to 0.21 g/g for banana peels). This efficiency suggests that while banana peels are advantageous for small-scale or rapid conversion systems, bagasse offers superior scalability and sustainability for large-scale production. The complementary strengths of the two feedstocks reinforce the potential of dual-substrate or integrated approaches in biofuel strategies, where starchy wastes provide immediate yield while lignocellulosic residues sustain long-term efficiency.

The statistical analysis (ANOVA) confirmed that both pretreatment methods and microbial strains significantly influenced ethanol yield ($p < 0.05$). The results demonstrate that fermentation outcomes are not random but strongly linked to technical and biological variables. These findings highlight the importance of integrated optimization choosing the right feedstock, applying the most effective pretreatment, and selecting high-performing microbes in maximizing ethanol yield.

Taken together, the results highlight the potential of food waste valorization as a sustainable pathway for renewable energy. This study contributes to addressing both energy security and waste management challenges by demonstrating that banana peels and sugarcane bagasse can be transformed into ethanol using cost-effective pretreatment and microbial strategies. Importantly, the complementary advantages of the two substrates point to the value of diversified feedstock portfolios, especially in regions like Nigeria, where both banana consumption and sugarcane processing generate substantial waste streams.

5. Conclusions

This study has demonstrated that banana peels and sugarcane bagasse, two readily available agricultural and food-processing wastes, are valuable and sustainable feed stocks for bioethanol production. Their high carbohydrate content, effective response to pretreatment, and strong fermentation performance confirm their suitability for renewable energy generation. The research established that combined acid and enzymatic pretreatment produced the highest reducing sugar and ethanol yields, validating the importance of integrated hydrolysis approaches in optimizing conversion efficiency. Among the microbial strains tested, *Zymomonas mobilis* consistently outperformed *Saccharomyces cerevisiae*, achieving 15–20% higher ethanol yields due to its superior metabolic efficiency in channeling fermentable sugars directly into ethanol. Comparatively, banana peels were found to be more fermentable due to their simple carbohydrate composition, making them suitable for small-scale or rapid ethanol production systems. In contrast, sugarcane bagasse demonstrated greater conversion efficiency per unit biomass, making it more appropriate for large-scale, sustainable bioethanol production. Overall, the valorization of banana peels and sugarcane bagasse into bioethanol represents an effective strategy for reducing food waste, mitigating environmental pollution, and contributing to Nigeria's energy diversification efforts. The findings align strongly with global sustainability targets, particularly in promoting renewable energy (SDG 7), responsible production (SDG 12), and climate action (SDG 13).

Recommendations

Based on the findings of this research, the following recommendations are made:

1. Adopt Combined Pretreatment for Maximum Yield:

Since the combined acid and enzymatic pretreatment produced the highest reducing sugar and ethanol yields, future bioethanol production initiatives should adopt this integrated approach to optimize sugar release and fermentation efficiency.

2. Prioritize the Use of *Zymomonas mobilis* for Enhanced Fermentation:

Zymomonas mobilis consistently outperformed *Saccharomyces cerevisiae* in ethanol yield and efficiency. It is therefore recommended that industrial and research-scale bioethanol systems prioritize *Z. mobilis* or its genetically enhanced variants to achieve higher productivity and lower fermentation time.

3. Promote Waste-to-Energy Utilization of Banana Peels and Sugarcane Bagasse:

Considering the abundance of these wastes in Port Harcourt and similar regions, stakeholders, including government agencies and research institutions should encourage their collection and utilization for bioethanol production. This will reduce waste disposal challenges while contributing to renewable energy generation and environmental sustainability.

Authors Contributions

P.O. conducted the research and compiled manuscript. K.J. supervised the work and edited and revised the work. S.C., M.U., and E.B. reviewed and edited the final copy. A.N. coordinated the project. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

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Informed Consent Statement

Not applicable. No human subjects were used for the study.

Data Availability Statement

The data used in this study are available from the corresponding author upon reasonable request.

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Conflict of Interest

The authors declare no conflict of interest.

Appendix A. Raw Proximate Analysis Data

Table A1. Replicate Measurements of Feedstock Composition (% dry weight).

Component	Banana Peels (Replicates)	Mean ± SD	Sugarcane Bagasse (Replicates)	Mean ± SD
Moisture Content	11.1, 11.4, 11.3	11.3 ± 0.1	9.6, 9.8, 9.7	9.7 ± 0.1
Carbohydrates	64.2, 64.8, 64.5	64.5 ± 0.3	58.0, 58.3, 58.2	58.2 ± 0.2
Fiber	14.8, 14.6, 14.7	14.7 ± 0.1	26.3, 26.5, 26.4	26.4 ± 0.1
Ash	3.1, 3.2, 3.3	3.2 ± 0.1	2.8, 2.9, 3.0	2.9 ± 0.1

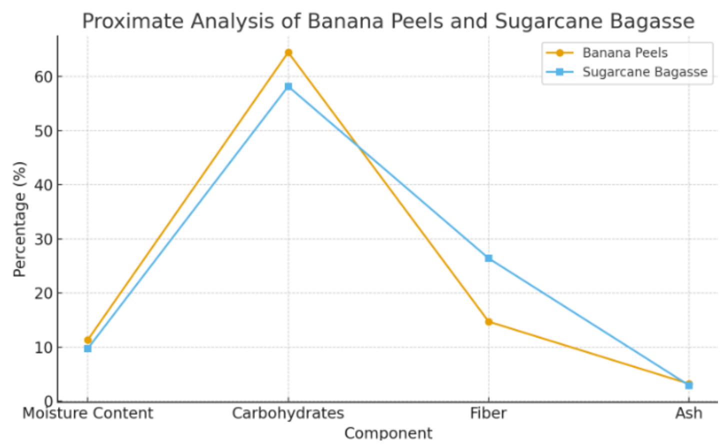

Figure A1. Comparative Composition of Banana Peels and Sugarcane Bagasse.

Appendix B. Reducing Sugar Yield Raw Data

Table A2. Reducing Sugar Yield Before and After Pretreatment (mg/g).

Feedstock	Untreated	Acid Hydrolysis	Enzymatic Hydrolysis	Combined Pretreatment
Banana Peels	52.6	112.3	134.8	161.8
Sugarcane Bagasse	45.7	95.4	121.6	145.9

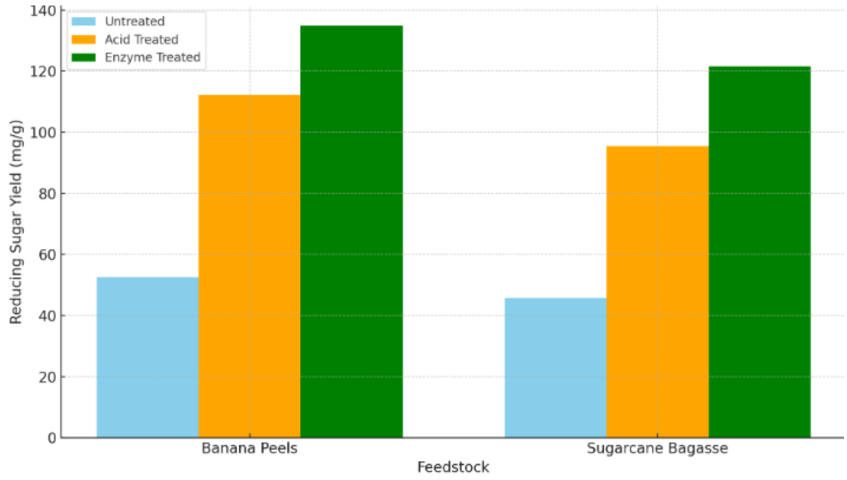

Figure A2. Reducing Sugar Yield Before and After Pretreatment.

Note: Bar chart representation of sugar yield in mg/g for both substrates.

Appendix C. Fermentation Yield Raw Data

Table A3. Ethanol Concentrations after 72 hours (g/L).

Feedstock	Pretreatment	*S. cerevisiae*	*Z. mobilis*	% Improvement
Banana Peels	Acid Hydrolysis	14.2	16.5	+16%
Banana Peels	Enzymatic Hydrolysis	18.5	21.5	+16%
Banana Peels	Combined	23.6	28.0	+19%
Sugarcane Bagasse	Acid Hydrolysis	11.8	13.8	+17%
Sugarcane Bagasse	Enzymatic Hydrolysis	17.3	20.0	+16%
Sugarcane Bagasse	Combined	24.9	29.5	+19%

Appendix D

- GC chromatograms showing ethanol retention peaks at 2.1–2.3 minutes.
- Calibration curve of ethanol standard vs. peak area used for quantification.

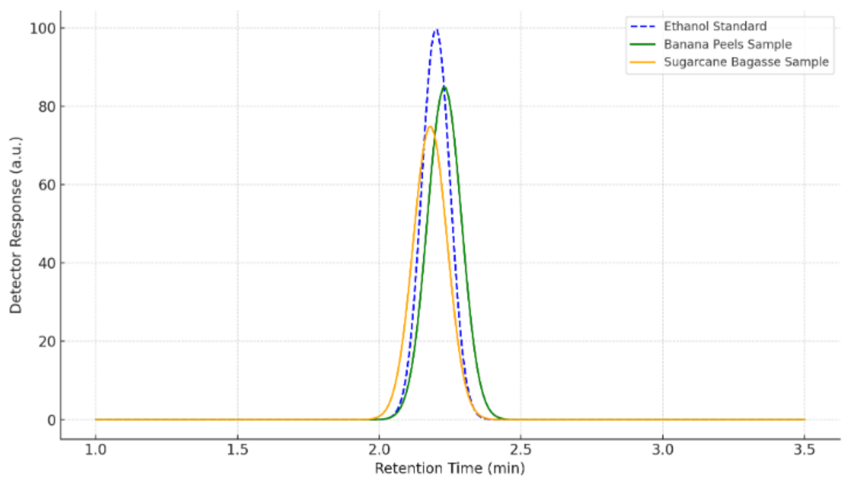

Figure A3. Sample Gas Chromatography Output.

Appendix E. ANOVA Statistical Analysis

Table A4. ANOVA Summary of Ethanol Yield.

Source of Variation	SS	df	MS	F-Value	*P*-Value
Between Groups	0.034	3	0.0113	6.78	0.0021
Within Groups	0.020	12	0.0017		

Interpretation: $p < 0.05$ confirms statistically significant differences in ethanol yield across treatments and microbial strains.

Appendix F

Ethanol Yield Efficiency (g ethanol/g biomass):

$$\text{Ethanol Yield Efficiency} = \frac{\text{Ethanol Concentration (g/L)} \times \text{Fermentation Volume}}{\text{Dry Biomass Input (g)}}$$

Example for sugarcane bagasse:

$$\frac{29.5\, g/L \times 1.0\, L}{118\, g} = 0.25\, g/g$$

Figure A4. Sample Calculation.

Appendix G

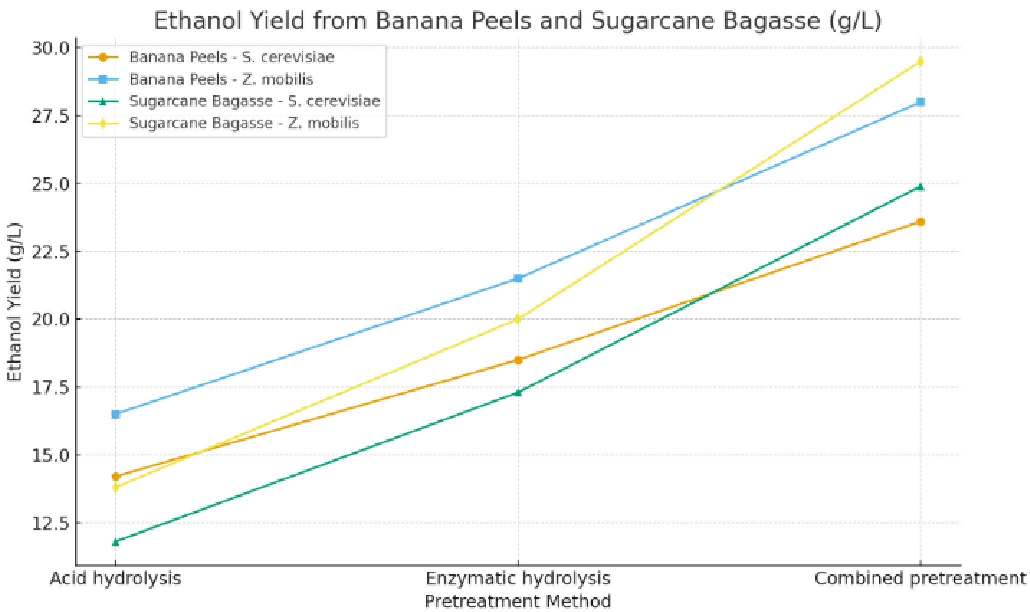

Figure A5. Ethanol Yield by Feedstock and Pretreatment Method.

Appendix H

Figure A6. *Cont.*

Figure A6. Materials and Experimental Setup and Pictures.

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