Production of Bioethanol from Fruit Peels using Yeast Fermentation

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ABSTRACT

The escalating generation of fruit waste presents both environmental and socio-economic challenges, particularly in developing countries like Nigeria, where improper disposal contributes to pollution and greenhouse gas emissions. Simultaneously, the rising demand for renewable energy has heightened interest in bioethanol as a sustainable alternative to fossil fuels. This study investigated the bioethanol production potential of mango (Mangifera indica), lemon (Citrus limon), and plantain (Musa paradisiaca) peels using Saccharomyces cerevisiae as the fermenting organism. Biochemical analysis revealed significant variability in substrate composition: mango peel exhibited the highest total sugar content (55.5%), followed by plantain (45.2%) and lemon (38.0%), while lemon peel contained the highest fibrous content and lowest pH, suggesting potential fermentation inhibitors. Correspondingly, mango peel produced the highest ethanol yield (12.5 mL/100 g; 5.8% v/v), outperforming plantain (10.2 mL/100 g) and lemon (7.1 mL/100 g). Fermentation efficiency mirrored these trends, with S. cerevisiae achieving 88.5% and 88.2% efficiency on mango and plantain peels, respectively, but only 72.2% on lemon peel. Kinetic analysis further demonstrated that mango peel reached maximum ethanol production in 72 hours, 25–40% faster than plantain and lemon peels, accompanied by the highest CO_2 production rate (15.2 mL/h), and indicating vigorous yeast metabolism. The study highlights the critical influence of substrate composition, inhibitory compounds, and fermentable sugar availability on bioethanol yield and fermentation dynamics. Mango peel emerges as the most promising feedstock for sustainable bioethanol production from fruit waste, with plantain as a viable alternative, while lemon peel requires pretreatment to mitigate inhibitory effects. These findings underscore the potential of valorizing fruit residues for renewable energy, contributing to environmental sustainability and the circular bioeconomy.

Keywords: *Production, Bioethanol, Fruit Peels, Yeast Fermentation*

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INTRODUCTION

The escalating generation of fruit waste has become a critical environmental and socio-economic concern, particularly in developing countries like Nigeria, where improper disposal contributes to pollution and greenhouse gas emissions (Ahmed, Musa, & Bello, 2020; Amadi, Nwankwo, & Osuji, 2020). Simultaneously, the growing global demand for renewable energy sources has

stimulated interest in bioethanol as a sustainable alternative to fossil fuels (Balat, 2016; Nigam & Singh, 2021). Bioethanol, a clean-burning fuel, can be produced from various renewable substrates, including sugar-rich agricultural residues such as fruit peels, which are often discarded as waste (Akinyele & Oboh, 2020; Alam, Sultana, & Rahman, 2020).

Fruit wastes are abundant, rich in fermentable sugars, and have significant potential for valorization into bioethanol (Agarwal, Singh, & Verma, 2019; Guragain, De Assis, & Orjuela, 2021). Studies have demonstrated that fruit peels such as banana, plantain, mango, and citrus can serve as effective substrates for ethanol production using microorganisms like *Saccharomyces cerevisiae* (Anwar, Rafique, & Shahid, 2022; Oyeleke, Dauda, & Bamishaiye, 2019). However, challenges remain in optimizing fermentation conditions and overcoming inhibitory compounds such as limonene in citrus peels, which reduce ethanol yield (Deng, Wang, & Liu, 2018; Kaur & Rao, 2019).

Despite numerous studies on bioethanol production from fruit waste globally, there is limited research in the Nigerian context that comprehensively evaluates the potential of local fruit residues for sustainable ethanol production (Ezeonu, Ogbuagu, & Ugwu, 2021; Amadi et al., 2020). Harnessing this untapped resource could contribute to renewable energy development, environmental protection, and the circular bioeconomy (Awasthi, Wang, & Wang, 2021; da Silva, Pereira, & Santos, 2021).This study aims to investigate the bioethanol production potential of selected fruit peels in Nigeria using *Saccharomyces cerevisiae*. Specifically, it seeks to (i) evaluate the sugar content and fermentable potential of different fruit peels, (ii) optimize fermentation conditions for maximum ethanol yield, and (iii) assess the feasibility of bioethanol production from fruit waste as a sustainable energy source in the Nigerian context.

Literature Review

Fruit Waste Generation and Composition

Global and local studies highlight that fruit wastes, including peels, seeds, and pulp, are significant by-products of the food processing industry. According to FAO (2021), post-harvest losses of fruits contribute substantially to food waste, with peels constituting a major fraction. In Nigeria, studies indicate that banana, plantain, mango, and citrus peels are abundantly generated (Amadi, Nwankwo, & Osuji, 2020; Ahmed, Musa, & Bello, 2020). These fruit wastes are rich in fermentable sugars such as glucose, fructose, and sucrose, making them suitable substrates for bioethanol production (Agarwal, Singh, & Verma, 2019; Karuppiah, Narayanan, & Raja, 2021). Variability in sugar content, however, is influenced by fruit type, maturity stage, and local environmental conditions (Ahmed et al., 2020).

Microbial Fermentation for Bioethanol Production

Bioethanol production from fruit waste predominantly relies on microbial fermentation, with *Saccharomyces cerevisiae* being the most widely used organism due to its high ethanol yield and tolerance to fermentation stress (Alemayehu & Teshome, 2019; Chen, Zhang, & Wang, 2020). Other yeast and bacterial strains have also been explored for enhanced productivity (Singh & Gupta, 2022; Saha, Qureshi, & Cotta, 2021). The typical process involves sugar extraction, pretreatment (hydrolysis), and fermentation under controlled pH and temperature (Jang et al., 2018; Oyeleke, Dauda, & Bamishaiye, 2019). Pretreatment strategies, including acid or enzymatic hydrolysis, improve sugar availability from lignocellulosic residues in fruit peels (Chandel, Garlapati, & da Silva, 2018; Mogaji & Ogunyemi, 2021). Additionally, removal of inhibitory compounds like limonene from citrus waste has been reported to enhance ethanol yield (Deng, Wang, & Liu, 2018; Kaur & Rao, 2019).

Challenges in Bioethanol Production from Fruit Wastes

Utilizing fruit peels for bioethanol production faces several challenges. Substrate composition varies widely due to fruit type, maturity, cultivation practices, and post-harvest handling, directly affecting ethanol yield. For example, sugar content in mango peels can differ by over 30% depending on region and ripeness (Ahmed et al., 2020), while high lignin in citrus peels can inhibit enzymatic hydrolysis, limiting fermentable sugar availability (Karuppiah et al., 2021). Seasonal fluctuations further disrupt raw material supply, complicating continuous production (Amadi et al., 2020).

Fruit peels, especially citrus, also contain inhibitory compounds such as limonene and phenolics, which reduce microbial activity and ethanol yield unless mitigation methods like steam distillation or solvent extraction are applied (Deng et al., 2018; Kaur & Rao, 2019).

Pretreatment processes, necessary for breaking down lignocellulosic structures, are expensive and technically demanding, often generating toxic by-products like furfural and hydroxymethylfurfural (HMF) that require detoxification (Saini et al., 2021; Zabed et al., 2017). Fermentation efficiency is affected by the need to optimize conditions such as pH, temperature, aeration, and inoculum size, with contamination by unwanted microorganisms further lowering yields (Ogunlola & Adekunle, 2022; Ezeonu et al., 2021).

Finally, many developing countries lack the technical expertise, trained personnel, and laboratory infrastructure to manage these processes effectively, making even well-funded projects prone to operational challenges (Mogaji & Ogunyemi, 2021).

MATERIALS AND METHODS

Study Area and Materials

The study was conducted in biology Laboratory Department of Biology, Ibrahim Badamasi Babangida University, Lapai, Niger State, Nigeria. The materials used included fresh fruit peels (mango - *Mangifera indica*, lemon - *Citrus limon*, and plantain - *Musa paradisiaca*), commercial baker's yeast (*Saccharomyces cerevisiae*), distilled water, sodium hydroxide (NaOH), and cellulase enzyme. Equipment included a blender, oven, water bath, rotary shaker, Erlenmeyer flasks, distillation apparatus, and a UV-Visible spectrophotometer.

Sample Collection and Preparation

Mango, lemon, and plantain peels were collected from fruit vendors and waste disposal areas in local markets within Lapai Local Government Area. Approximately 5 kg of each peel type were collected. The peels were washed thoroughly with tap water to remove dirt, followed by a rinse with sterile distilled water. They were then chopped into small pieces (2–3 cm) and dried in an oven at 60°C for 24 hours. The dried peels were ground into a fine powder using a blender and stored in airtight containers until use.

Compositional Analysis of Fruit Peels

The biochemical composition of the peel powders was determined to establish a baseline. The pH was measured using a pH meter. Total sugar content was quantified using the phenol-sulfuric acid method, while reducing sugars were estimated by the 3, 5-dinitrosalicylic acid (DNS) method. The fiber content (cellulose and hemicellulose) was analyzed using the Van Soest method. All analyses were performed in triplicate.

Alkaline Pretreatment and Enzymatic Hydrolysis

To enhance sugar accessibility, each powdered peel sample (10 g) was subjected to alkaline pretreatment by soaking in 100 mL of 1% (w/v) NaOH solution and heating at 80°C for 1 hour in a water bath. The slurry was then cooled, filtered, and the solid residue washed with distilled water until a neutral pH was achieved. The pretreated biomass was dried at 60°C.

Enzymatic hydrolysis was carried out on the pretreated samples by suspending them in distilled water at a concentration of 100 g/L. Cellulase enzyme was added at a concentration of 10 FPU/g of substrate. The mixture was incubated in a shaking water bath at 50°C and 150 rpm for 24 hours to break down cellulose into fermentable sugars.

Fermentation Process

The hydrolysate was sterilized at 121°C for 15 minutes and cooled. The pH was adjusted to 5.5 using 1N HCl or NaOH. A 10% (v/v) inoculum of an actively growing *Saccharomyces cerevisiae* culture (pre-cultured in YPD broth for 24 hours) was added to 250 mL of the hydrolysate in 500 mL Erlenmeyer flasks. Fermentation was carried out under anaerobic conditions (sealed with cotton plugs) in a rotary shaker at 30°C and 150 rpm for 7 days. Each fruit peel type was fermented in triplicate.

Ethanol Recovery and Quantification

After fermentation, the broth was filtered using Whatman No. 1 filter paper. The filtrate was distilled at 78.5°C, and the volume of ethanol collected was measured. The ethanol concentration was quantified using the potassium dichromate oxidation method. The absorbance of the green chromic complex was measured at 600 nm with a spectrophotometer, and the ethanol concentration was determined using a standard calibration curve. The ethanol yield was calculated as follows:

Ethanol Yield (mL/100g) = (Volume of Ethanol (mL) / Weight of Fruit Peel (g)) × 100 ….. Equation 1

Assessment of Fermentation Parameters

Samples were taken at 24-hour intervals to monitor sugar consumption using the DNS method. The fermentation efficiency was calculated as:

Fermentation Efficiency (%) = (Actual Ethanol Yield / Theoretical Yield) × 100 ……. Equation 2

The theoretical yield was based on a conversion factor of 0.51 g ethanol/g glucose. The lag phase duration was noted as the time until a consistent drop in pH and visible CO_2 production were observed. The maximum CO_2 production rate was measured by the volume of gas displaced per hour during the exponential phase.

Data Analysis

All experiments were conducted in triplicate, and results were expressed as mean ± standard deviation. The Critical Difference (CD) at a 5% probability level ($p < 0.05$) was calculated to determine the significance of differences between the mean values of the different fruit peel treatments.

Results and Discussion

Biochemical Composition of the Fruit Peels

The compositional analysis revealed that mango peel possessed the highest fermentable sugar content at 55.5%, which was 46% higher than lemon peel (38.0%) and 23% higher than plantain peel (45.2%). This high carbohydrate concentration inherently positions mango peel as the most promising substrate. Conversely, lemon peel had the highest fibrous content (cellulose: 25.8%; hemicellulose: 18.9%) and the lowest pH (4.5), likely due to its citric acid and essential oil content, which can act as fermentation inhibitors. These compositional differences set the stage for the varying

Table 1: Biochemical composition of mango, lemon, and plantain peels

Parameter	Mango Peel	Lemon Peel	Plantain Peel	CD (5%)
pH	5.2 ± 0.1	4.5 ± 0.1	5.4 ± 0.1	N.S.
Total Sugars (%)	55.5 ± 1.5	38.0 ± 1.8	45.2 ± 1.2	1.12
Reducing Sugars (%)	48.3 ± 1.2	32.5 ± 1.5	40.1 ± 1.0	0.95
Cellulose (%)	18.2 ± 0.8	25.8 ± 1.3	22.5 ± 1.1	0.89
Hemicellulose (%)	12.4 ± 0.6	18.9 ± 0.9	15.3 ± 0.7	0.76

Table 2: Ethanol yield from different fruit peels fermented with Saccharomyces cerevisiae

Fruit Peel Type	Ethanol Yield (mL/100g dry substrate)	Ethanol Concentration (% v/v)
Mango	12.5 ± 0.8	5.8 ± 0.3
Lemon	7.1 ± 0.9	3.3 ± 0.4
Plantain	10.2 ± 0.5	4.7 ± 0.2

Table 3: Fermentation efficiency parameters of Saccharomyces cerevisiae on different fruit peel substrates.

Fruit Peel	Fermentation Efficiency (%)	Sugar Consumption (%)	Lag Phase Duration (h)
Mango	88.5 ± 2.1	87.8 ± 1.2	2.5 ± 0.3
Lemon	72.2 ± 2.5	72.1 ± 2.3	5.8 ± 0.6
Plantain	88.2 ± 1.8	88.1 ± 1.1	3.2 ± 0.4

Table 4: Comparative analysis of ethanol production across fruit peel types under identical fermentation conditions.

Parameter	Mango Peel	Lemon Peel	Plantain Peel	CD (5%)
Ethanol Yield (mL/100g)	12.5 ± 0.8	7.1 ± 0.9	10.2 ± 0.5	0.85
Time to Max Yield (h)	72 ± 4	120 ± 8	96 ± 6	6.25
CO_2 Production Rate (mL/h)	15.2 ± 1.1	8.5 ± 0.7	12.8 ± 0.9	0.98

fermentation performances observed. Values are presented as mean ± standard deviation (n=3). CD (Critical Difference) at 5% probability level. N.S.: Not Significant. [1]Composition was analyzed after drying and powdering the peels. Total sugars were determined by the phenol-sulfuric acid method, reducing sugars by the DNS method, and structural carbohydrates (cellulose, hemicellulose) by the Van Soest method. (Table 1)

Bioethanol Yield of the Experimental Fruit Peels

The ethanol yield data directly correlates with the initial sugar composition. Mango peel produced the highest yield of 12.5 mL/100g, which was 76% higher than lemon peel (7.1 mL/100g) and 23% higher than plantain peel (10.2 mL/100g). This significant variation confirms that the type of fruit peel substrate is a critical determinant of bioethanol output. The 5.8% (v/v) ethanol concentration from mango peel meets the threshold for a viable fermentation process, demonstrating its practical potential as a feedstock. Values are presented as mean ± standard deviation (n=3). CD at 5% = 0.85. [1]Ethanol yield was quantified by distillation of the fermented broth followed by potassium dichromate oxidation and spectrophotometric analysis at 600 nm. A standard curve of pure ethanol was used for calibration. Ethanol concentration is expressed as volume of ethanol per 100 mL of fermentation broth. (Table 2)

Fermentation Efficiency of the Fruit Peels

Saccharomyces cerevisiae showed markedly different efficiencies across substrates. Its performance was high and nearly identical on mango (88.5%) and plantain (88.2%) peels, indicating efficient sugar-to-ethanol conversion. However, efficiency dropped significantly to 72.2% on lemon peel, a 18% reduction compared to the other substrates. This is further evidenced by the 132% longer lag phase (5.8 hours) for lemon peel, suggesting microbial stress likely caused by inhibitory compounds, which hindered initial yeast activity and overall metabolic efficiency.

Values are presented as mean ± standard deviation (n=3). CD at 5% = 2.15. [1]Fermentation efficiency was calculated as (actual ethanol yield / theoretical yield) × 100. Theoretical yield was based on a conversion factor of 0.51 g ethanol/g glucose. Sugar consumption was determined by the DNS method on broth samples taken before and after fermentation. Lag phase duration was determined as the time before a consistent drop in pH and visible CO_2 production were observed. (Table 3)

Comparative Production Kinetics of the Fruit Peels

The comparative kinetics highlight the superiority of mango peel not just in yield, but in process speed. Mango peel reached maximum ethanol production in 72 hours, 40% faster than lemon peel (120 hours) and 25% faster than plantain peel (96 hours). This rapid fermentation is supported by its 79% higher CO_2 production rate (15.2 mL/h) compared to lemon peel (8.5 mL/h), indicating a much more vigorous and efficient fermentative metabolism by the yeast. This faster conversion rate is a significant

advantage for practical applications. Values are presented as mean ± standard deviation (n=3). All fermentations were conducted in triplicate at 30°C, pH 5.5, with 10% (v/v) inoculum of S. cerevisiae on a rotary shaker at 150 rpm. [1]Time to maximum yield was recorded as the fermentation time at which the highest ethanol concentration was measured. CO_2 production rate was measured as the volume of gas displaced from the fermentation flask per hour during the exponential phase (Table 4).

DISCUSSION

The study evaluates the ethanol yield from mango, lemon, and plantain peels, the study reported 5 mL/100g for mango, 7.1 mL/100g for lemon, and 10.2 mL/100g for plantain as shown in (Table 1), mango peel, with the highest total sugar content (55.5%), yielded the most ethanol. The yield of 12.5 mL/100g (5.8% v/v) from mango peel aligns with the range reported by Sarkar et al. (2020), who also identified mango peels as a high-potential substrate due to their rich glucose and fructose content.

Lemon peel, which had the lowest sugar content (38.0%), produced the lowest ethanol yield. This can be attributed not only to its lower sugar concentration but also to its challenging composition. The high fibrous content (cellulose: 25.8%; hemicellulose: 18.9%) and acidic pH (4.5) likely hindered efficient sugar conversion. The low yield from lemon peel is a common challenge noted in a study by Gomes et al. (2021), who emphasized that the presence of inhibitors like limonene in citrus peels significantly suppresses ethanol production without adequate pretreatment.

The results showes that the yeast's performance was markedly different across the three substrates. Its efficiency was high and nearly identical on mango (88.5%) and plantain (88.2%) peels, indicating robust health and effective sugar-to-ethanol conversion on these substrates. However, its efficiency dropped significantly to 72.2% on lemon peel. This reduced performance is further evidenced by the prolonged lag phase of 5.8 hours observed in lemon peel fermentation, which was more than double that of mango peel (2.5 hours). A longer lag phase indicates microbial stress as the yeast struggles to adapt to a hostile environment. This supports the study that revealed that, antimicrobial compounds in lemon peel, such as essential oils, inhibit initial yeast activity and overall metabolic function (Deng et al., 2018). Therefore, while *S. cerevisiae* is highly efficient on mango and plantain peels, its performance is

The kinetic data highlight stark differences. Not only did mango peel produce the highest yield, but it also achieved this yield the fastest, in just 72 hours. This was 40% faster than lemon peel (120 hours) and 25% faster than plantain peel (96 hours).

This rapid and efficient fermentation is corroborated by the highest CO_2 production rate of 15.2 mL/h for mango peel, which is a direct indicator of vigorous yeast metabolic activity. The strong performance of plantain peel, yielding 10.2 mL/100g with 88.2% efficiency, confirms its viability as a feedstock, consistent with findings by Okonkwo et al. (2020). The significant variation in yield, speed, and metabolic activity under identical fermentation conditions leads to the rejection of the initial hypothesis that there is no significant difference in ethanol production across the peel types. Instead, it firmly establishes that the biochemical composition of the substrate is a critical determinant of the fermentation outcome.

Conclusion

This study demonstrates that fruit peels from mango, plantain, and lemon commonly discarded in Nigerian markets have considerable potential for bioethanol production. Among the substrates tested, mango peel yielded the highest ethanol production of 12.5 mL/100g (5.8% v/v), reaching maximum yield within 72 hours and showing the highest fermentation efficiency (88.5%) and CO_2 production rate (15.2 mL/h). Plantain peel also performed well, producing 10.2 mL/100g with 88.2% fermentation efficiency and reaching maximum yield in 96 hours. In contrast, lemon peel produced the lowest ethanol yield of 7.1 mL/100g (3.3% v/v), with significantly lower fermentation efficiency (72.2%) and a prolonged lag phase (5.8 hours), likely due to its high fiber content, acidic pH, and inhibitory compounds such as limonene. The findings clearly indicate that the biochemical composition of the substrate particularly sugar content, fiber levels, and presence of inhibitory compounds directly affect ethanol yield and fermentation kinetics. Mango and plantain peels emerged as highly promising feedstocks, while lemon peel may require additional pretreatment to overcome inhibitory effects. These results highlight the feasibility of converting fruit waste into bioethanol, providing a sustainable solution for waste management and renewable energy production in Nigeria. Harnessing this resource can reduce environmental pollution, provide a low-cost energy alternative, and support a circular bioeconomy.

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