

Comparative Evaluation and Process Performance Analysis of Bioethanol Production from *Carica papaya* and *Citrullus lanatus* Peels

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Abstract

This paper comparatively assessed the potential of *Carica papaya* and *Citrullus lanatus* peels as inexpensive fruit-waste syrups for renewable energy production, evaluating their bioethanol production potential and process performance. A comparative experimental design was used, with peel samples collected in the Ozoro area of Delta State, Nigeria. The peels were dried, washed, powdered, and placed under dilute-acid hydrolysis with 250 mL of 1% H₂SO₄ /50g of dry substrate. The hydrolysates were adjusted to pH 5.0, 2g of *Saccharomyces cerevisiae* were inoculated, fermented for 7 days in darkness, and distilled at 78-82 °C to obtain ethanol. Comparative analysis was conducted on ethanol yield, ethanol volume, pH, density, sugar content, and ethanol mass, whilst advanced analysis used ratios of efficiency, density deviation, and composite feedstock performance. The findings revealed that watermelon peels were superior to pawpaw peels in total ethanol productivity, with ethanol yields of 26.0% and 9.0%, ethanol volumes of 13.0 mL and 4.5 mL, and ethanol masses of 11.7 g and 3.6 g, respectively. The pawpaw peels, however, contained more sugar (4.2% compared to 3.6%) and denser ethanol than the standard ethanol. The results suggest that high ethanol performance was determined by actual bioconversion efficiency rather than by sugar content alone. The research finds that *Citrullus lanatus* peels are more promising as a substrate for bioethanol production under the conditions tested. The consequence of this is that it adds value to waste, harnessing renewable energy and promoting environmental management for sustainability.

Keywords: Bioethanol production, *Carica papaya* peels, *Citrullus lanatus* peels, fruit-waste valorization, renewable energy, process performance.

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Introduction

The escalating environmental and economic issues associated with reliance on fossil fuels have made the search for renewable energy sources and their cleaner alternatives more serious. Bioethanol is now one of the most promising alternatives, as it is a clean-burning, biodegradable, and sustainable fuel derived from plant-based products (Kim *et al.*, 2013; Basic, 2018; Edeh, 2021). The added benefit of bioethanol over conventional fossil fuels is that it minimises greenhouse gas emissions while enhancing energy diversification and sustainability objectives. Nevertheless, there is concern that bioethanol production from edible crops is competing with the food supply, hence the growing interest in using non-food and waste-based biomass as alternative feedstocks (El Zawawy *et al.*, 2011; Singh *et al.*, 2020). The given framing aligns with the project's subject, which focuses on transforming fruit peel waste into ethanol through hydrolysis, fermentation, and distillation. There are such wastes as pawpaw (*Carica papaya*) and watermelon (*Citrullus lanatus*) peels, which are produced and dumped mindlessly in spite of the fact that they both contain fermentable sugars and other biodegradable elements that can be used in producing ethanol. The fact that they can be converted into bioethanol provides them with a twofold advantage as a renewable fuel and could also give agricultural waste greater value. Past researchers have highlighted the potential of fruit residues as an inexpensive feedstock for producing bioethanol, particularly in developing nations where biomass waste is plentiful and underutilised (Singh *et al.*, 2020; Kumar *et al.*, 2020; Balasubramanian *et al.*, 2022). In the current study, the two types of peels were evaluated as possible substrates for bioethanol production under similar pretreatment and fermentation conditions, thereby providing a basis for direct performance comparison. Despite numerous studies on ethanol production, very little information is available on the comparative performance of ethanol production from peels of *Carica papaya* and *Citrullus lanatus*. The present study was hence structured to compare the bioethanol production by the two fruit peels by applying the following key parameters that will be used to compare the production of the two peels in relation to ethanol yield, ethanol volume, pH, weight obtained, density and sugar contents. The research is important as it adds to the existing literature on the sustainable production of biofuels using fruit peels as a renewable energy source and gives feasible information on the relative viability of the fruit peels that are readily available in a region regarding their usage in renewable energy generation.

Materials and Methods

Study Design

In this study, the production and testing of bioethanol was carried out using a comparative experimental design on the use of two fruit-wastes, such as *Carica papaya* peels and *Citrullus lanatus* peels. The design was designed in a way to compare the performance of the two feedstock both with the same pretreatment, hydrolysis, fermentation, and distillation conditions to ensure that any differences in the ethanol yield and process features could be mainly due to substrate-dependent attributes and not differences in the way the operation of the process was varied. The study emphasis on the analysis was hence based on the comparative bioconversion efficiency, ethanol recovery and physicochemical performance indicators.

The core end result variables in the original work were ethanol yield, ethanol volume, pH, density, sugar content and ethanol weight.

Study Area and Sample Source

The peels of the fruits studied were collected from local fruit sellers in Ozoro, Delta State, Nigeria. The choice of Ozoro as the sample source was driven by the pragmatic purpose of processing the waste resources of fruit-processing enterprises, which are locally available, easily discarded, and used sparingly. The research, which obtained peels from open-market suppliers, provided a realistic waste stream that would otherwise be utilised as a low-cost feedstock base by small- or community-scale bioethanol production systems. The sampled substrates were paw paw (*Carica papaya*) and watermelon (*Citrullus lanatus*) peels.



Figure 1a. Fresh Samples of Watermelon Peels and Papaya Peels

Materials, Reagents, And Equipment

Materials and reagents used in the study included sulphuric acid (H_2SO_4), sodium hydroxide ($NaOH$), distilled water, dry baker's yeast (identified as *Saccharomyces cerevisiae*), and optional nutrient supplements containing nitrogen, phosphorus, and potassium. The equipment used was a weighing balance, measuring cylinders, beakers, conical flasks, a blender, a pressure cooker / autoclave-style heating device, fermentation bottles/tanks, *filter* paper, a pH metre / universal pH indicator, a thermometer, a water bath/incubator (as appropriate), simple distillation equipment, and airtight storage containers. Dehydration equipment, including molecular sieves, was also described in the original project, but the procedure provided and the products reported suggest that the final ethanol was recovered mainly by simple distillation rather than deep dehydration.

Collection, Cleaning, and Preparation of Sample

Pawpaw and fresh watermelon peels were all picked and sorted by hand to exclude those peels with visible spoilage, contamination, or other invalid or invalid materials. The peels were washed with clean water, and the soil particles attached were washed away to remove dust and any other contaminants that might have interfered with the hydrolysis and fermentation processes. The peels were washed, then cut into smaller pieces to expose as much surface area as possible, allowing uniform drying. The peels were cut into pieces, dried in the sun, and then dried in the oven at 80 °C to a moisture content deemed sufficient for grinding. Drying (as shown in Figure 1b) was required to reduce microbial degradation before use, reduce unwanted moisture, increase grinding power, and homogenise substrate quality before hydrolysis. The peels were then dried, ground to a fine powder (as in figure 1c) in a blender, weighed,

and stored in airtight containers for use. This preparation step was intended to enhance the uniformity and homogeneity of the substrates and to improve acid penetration during the hydrolysis process.



Figure 1b. Drying Samples of Watermelon Peels and Papaya Peels



Figure 1c. Blended Dried Samples of Watermelon Peels and Papaya Peels

The Feedstock Loading

Mass accuracy. Masses of (dried) powdered peel samples from each substrate were accurately weighed into separate reaction vessels (50g each). The comparative analysis was deliberately based on equal loading of the substrates to ensure the two types of peels were compared on an equal basis. This not only enabled a direct comparison of ethanol production results on a constant dry-feedstock basis, but also increased the understandability of the difference in conversion efficiency measured between the two materials.

Acid Hydrolysis Procedure

The pretreatment process involved dilute-acid hydrolysis to convert the complex carbohydrates in peels into simple fermentable sugars. It was measured, and 250 mL of 1% Sulphuric acid solution was added to each 50 g beaker of peel, respectively. The mixtures obtained were acidified, placed in a pressure cooker, and left to cool for 20 minutes. The hydrolyzed slurry was filtered on filter paper (as shown in Figure 1d) after cooling to separate the liquid hydrolysate from the insoluble residue. The soluble portion

was collected as a sugar-containing hydrolysate for later fermentation. The acid hydrolysis process was used to break down plant structural polymers, liberate fermentable sugars in the fruit peel matrix, and provide yeast with access to the substrate during fermentation.



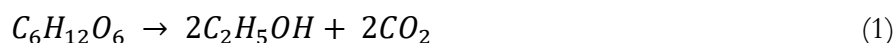
Figure 1d. Filtered Hydrolysates Liquid Containing Sugars

Adjustment of pH and Inoculation of Yeast

After hydrolysis and filtration, the pH of each hydrolysate was adjusted to 5.0 with 1 M sodium hydroxide. This had to be done because acidic hydrolysates produced by sulphuric-acid treatment would suppress yeast growth if they were maintained too acidic. A pH of 5.0 was chosen to provide optimal fermentation conditions for *Saccharomyces cerevisiae*. The fermenting organism was dry baker's yeast (*Saccharomyces cerevisiae*). Each hydrolysate was rehydrated in 15 minutes with 0.5 g of lukewarm water, then inoculated. Rehydrated yeast was then added to the adjusted hydrolysate to cause fermentation. The inoculum mass used on both substrates was the same, ensuring consistent microbial loading across treatments.

Fermentation Process

Inoculated hydrolysates were placed in sterilised fermentation vessels and barely covered with perforated or punched covers to ensure minimal gas escape while preventing direct contact with oxygen and contamination of the hydrolysates. The fermentation took place in a dark room for 7 days. The minimization of unwanted environmental interference and the desire for relatively stable fermentation conditions led to dark incubation. In the course of fermentation, the associated yeast converted the present fermentable sugars into ethanol and carbon dioxide via the general biochemical route:



When glucose is used as the model fermentable sugar, the product is ethanol, the desired biofuel, and the by-product is carbon dioxide. Despite the lack of controlled incubation temperature as indicated in the original project, fermentation time was kept at least 7 days across both feedstocks to provide a similar basis for comparison and contrast.

Distillation and Ethanol Recovery Process

The broth from all samples was filtered at the end of fermentation to remove any solids. Simple distillation was then done on the filtrate. The ethanol distillation system was warmed, and it was assumed that the fraction recovered between 78 °C and 82 °C was ethanol, as it fell within the boiling-point range

associated with ethanol-rich distillate. The distillates recovered from the pawpaw and watermelon fermentation runs were separately placed in airtight containers before physicochemical testing. The recovery step for ethanol in the original study involved simple distillation, and the resulting density values indicated that some water or impurities remained in the final product.

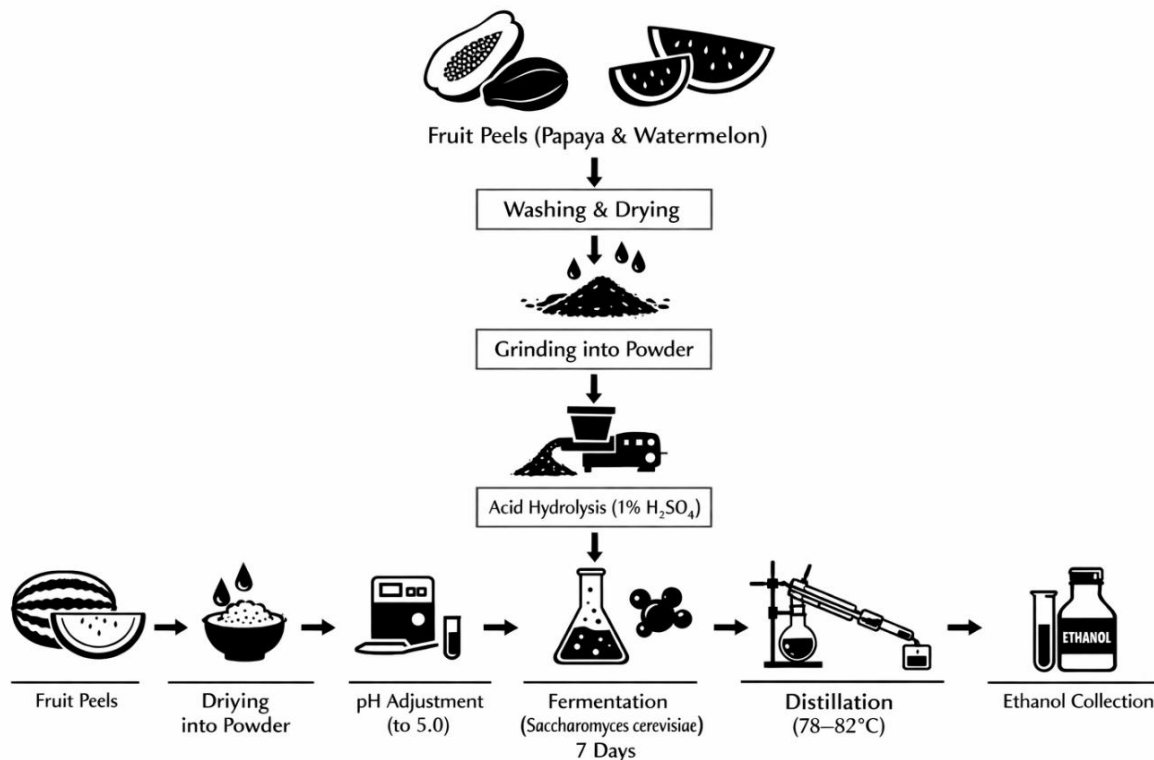


Figure 1e. Process Flow Diagram for Bioethanol Production from *Carica papaya* and *Citrullus lanatus* Peels

Determination of Ethanol Volume

Each substrate was distilled using an ethanol-containing mixture to obtain a total volume of ethanol-rich solution, and this was measured in milliliters (mL). One of the direct measures of process productivity was used, and in the future, ethanol volume was preferred for calculating ethanol yield and ethanol density. Recovery volumes of watermelon peels and pawpaw peels reached 13 mL and 4.5 mL, respectively, in the original study.

Ethanol Yield Determination

The post offered two similar expressions of ethanol yield. Ethanol yield was defined in the procedures section as the volume of ethanol produced/initial volume of hydrolysate x 100. Nevertheless, the yield actually obtained was calculated by dividing the quantity of ethanol by the weight of dried peels, then multiplying by 100. As the 26% watermelon and 9% pawpaw numbers were calculated on the basis of dried-peel mass, that is, the working formula to which the manuscript should remain constant.

Ethanol yield was then determined as:

$$\text{Ethanol Yield (\%)} = \frac{V_e}{W_s} \times 100 \quad (2)$$

Where V_e = volume of ethanol recovered (mL); W_s = weight of dried peel sample used (g)

Determination of Ethanol Density

The ratio of the mass of the recovered ethanol and the ethanol volume was used to determine the density of the recovered ethanol. The given project provided ethanol weight of 11.7g for watermelon and 3.6g as well as recovered volumes of 13 ml and 4.5 ml, accordingly. Density was then known by:

$$\text{Density } (\rho) = \frac{W_e}{V_e} \quad (3)$$

where ρ = density of ethanol (g/cm³); W_e = weight of ethanol recovered (g) and V_e = volume of ethanol recovered (mL)

Determination of Sugar Content

The sugar percentage, such as before or during fermentation-related analyses, was documented on the project using a volumetric relation based on Fehling. The original work reported the sugar content as the ratio of the volume of Fehling solution to the volume of the sample, times 100. Sugar content, therefore, was estimated as:

$$\text{Sugar Content } (\%) = \frac{V_f}{V_s} \times 100 \quad (4)$$

Where V_f = volume of Fehling solution used (mL) and V_s = volume of sample analyzed (mL)

Despite the simplified version of this term being employed in the project, the actual discussion involving the manuscript should approach sugar content information with caution as an operational correlator of reduced-sugar response, rather than a comprehensive sugar profile.

Measurement of pH

The pH of any fermentation broth or other process liquid was measured using a pH meter or a universal pH indicator, as specified in the project materials. The pH values were included in the comparative physicochemical evaluation, as it is well known that fermentation performance and yeast viability depend strongly on medium acidity. The obtained end results revealed a pH of 6.8 in pawpaw fermentation media and 6.8 in watermelon fermentation media.

As part of making the manuscript more descriptive and analytical, one can consider adding derived performance measures based on the underlying measurements. These indices are not substitutes of the mainstream experiment findings but rather enhance the interpretation of the substrate efficacy.

Relative advantage of watermelon versus pawpaw might be in the form of the same:

$$\text{Relative Yield Advantage } (\%) = \frac{Y_w - Y_p}{Y_p} \times 100 \quad (5)$$

where Y_w is the ethanol yield of watermelon peels, and Y_p is the ethanol yield of pawpaw peels.

Ethanol recovery ratio can be stated as:

$$\text{Ethanol Recovery ratio} = \frac{V_{e,w}}{V_{e,p}} \quad (6)$$

where $V_{e,w}$ and $V_{e,p}$ are the recovered ethanol volumes from watermelon and pawpaw peels, respectively.

Mass efficiency of the substrate can be expressed as:

$$\text{Mass Conversion Index} = \frac{W_e}{W_s} \quad (7)$$

which is the mass of ethanol recovered per gram of dry substrate.

To compare the measured ethanol density and the standard ethanol density, the purity deviation index is calculated as:

$$\text{Purity Deviation (\%)} = \frac{\rho_m - \rho_{std}}{\rho_{std}} \times 100 \quad (8)$$

where ρ_m is the measured ethanol density and ρ_{std} is the reference density of pure ethanol.

Statistical Analysis

The arithmetic mean was calculated as follows:

$$\bar{x} = \frac{\sum_{i=1}^n x_i}{n} \quad (9)$$

where $\bar{x}$ is the mean, x_i is each observation, and n is the number of observations.

The value of standard deviation was calculated as:

$$SD = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}} \quad (10)$$

The coefficient of variation was computed to assess relative dispersion:

$$CV(\%) = \frac{SD}{\bar{x}} \times 100 \quad (11)$$

Where comparisons between the two substrates are based on replicate measurements, the independent-samples t-test may be applied:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}} \quad (12)$$

where $\bar{x}_1$ and $\bar{x}_2$ are the sample means, S_1^2 and S_2^2 are the sample variances, and n_1 and n_2 are the sample sizes for watermelon and pawpaw groups, respectively.

One-way analysis of variance was employed in cases of additional treatment conditions and repeated levels of optimization:

$$F = \frac{MS_{between}}{MS_{within}} \quad (13)$$

In which $MS_{between}$ is the between-groups mean square and MS_{within} is the within-groups mean square.

Quality Check and Repeatability of Experiments

The similarity of the two substrates was ensured by using equal weights of the dry samples, equal volumes of yeast, equal fermentation time, equal hydrolysis time, equal pH adjustment goal, and equal mass of inoculated yeast in both treatments. The same conditions used in the process minimized procedural bias and enhanced the validity of observed substrate differences. However, the work was a laboratory-level study that was limited by easy distillation, single yeast strain use, and minimal process optimization, which must be considered in interpreting the final ethanol properties.

Ethical and Safety Considerations

Although no human or animal lives were affected during the experiment, the safety of the laboratories was a factor throughout the exercise, as it involved handling dilute sulphuric acid, sodium hydroxide, heated hydrolysates, yeast fermentation cultures, and flammable, volatile ethanol distillations. Normal laboratory safety was thus necessary, including proper handling of hazardous substances, the exclusive use of non-hot materials in hydrolysis and distillation, and the proper storage of reclaimed ethanol in airtight containers away from sources of heat. Hydrolysis and fermentation waste residues would be disposed of in compliance with good laboratory practise.

Results

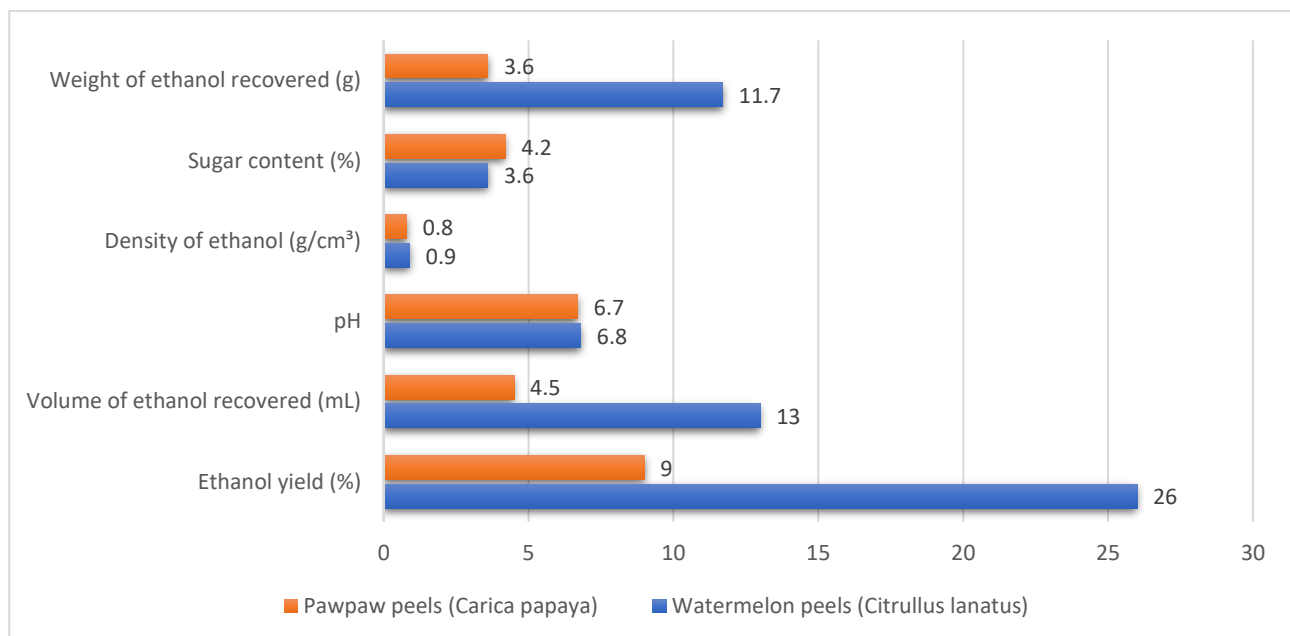


Figure 2. Comparative Production and Physicochemical Characteristics of Bioethanol from *Citrullus lanatus* and *Carica papaya* Peels

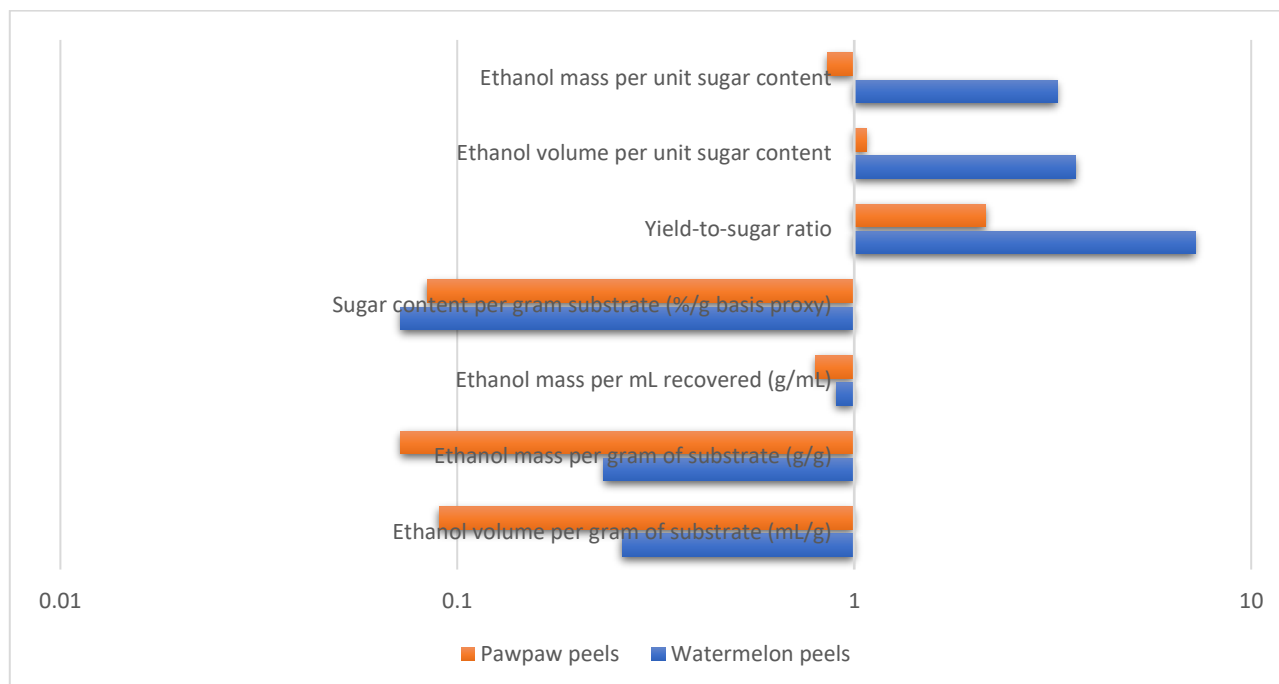


Table 3: Comparative efficiency analysis of bioethanol production from *Citrullus lanatus* and *Carica papaya* peels

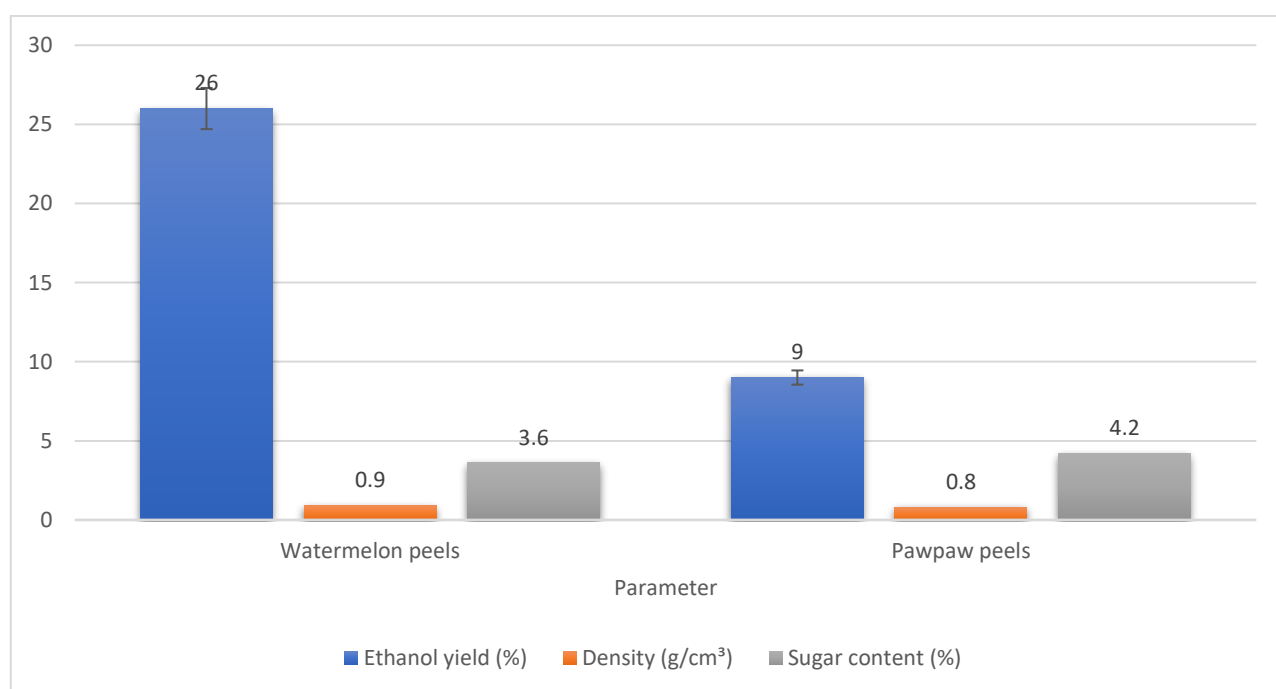


Figure 4. Comparative Ethanol Yield and Sugar Content of Bioethanol Produced from Watermelon and Pawpaw Peels

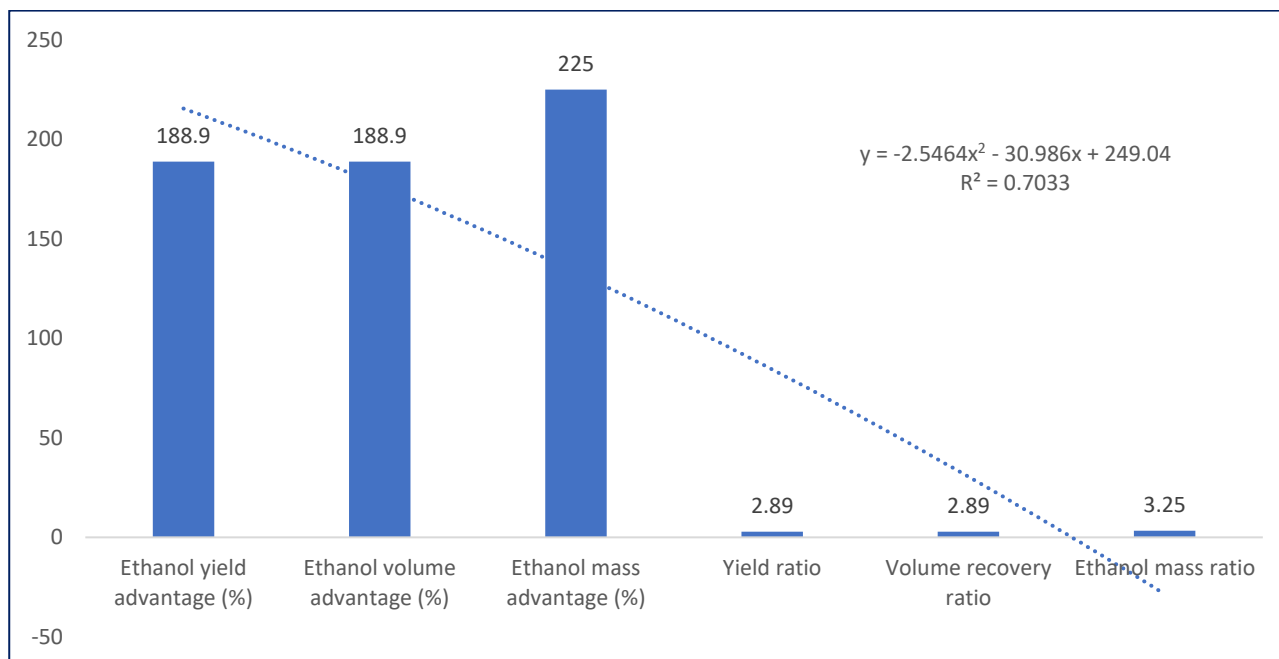


Figure 5. Comparative Performance Advantage of Watermelon Peels Relative to Pawpaw Peels

Table 1. Substrate Conversion Efficiency Indices on Dry-Feedstock Basis

Efficiency metric	Formula	Watermelon peels	Pawpaw peels
Ethanol volume per gram substrate (mL/g)	Ethanol volume / 50 g	0.260	0.090
Ethanol mass per gram substrate (g/g)	Ethanol mass / 50 g	0.234	0.072
Sugar-to-yield ratio	Sugar content / Ethanol yield	0.138	0.467
Density-to-yield ratio	Density / Ethanol yield	0.0346	0.0889

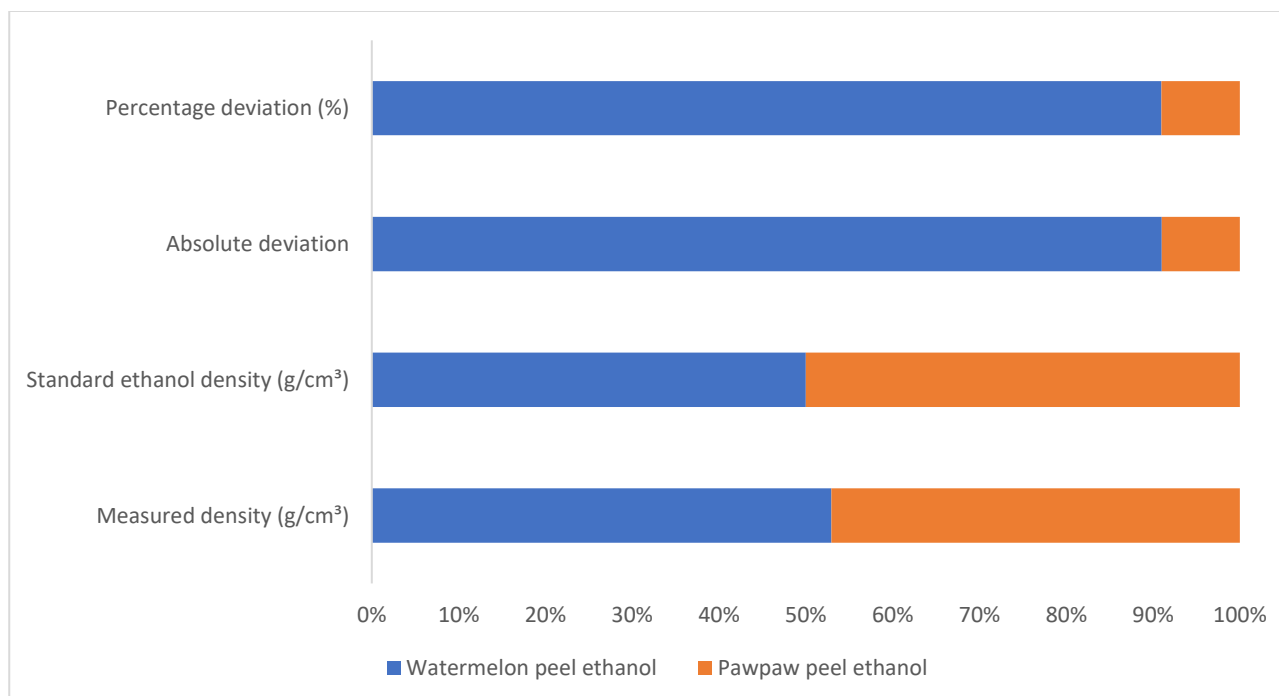


Figure 6. Deviation of Recovered Ethanol Density from Standard Ethanol Density

Table 2. Ranked Performance of the Two Substrates across Measured Parameters

Parameter	Better-performing substrate	Basis of ranking
Ethanol yield (%)	Watermelon peels	Higher value preferred
Ethanol volume recovered (mL)	Watermelon peels	Higher value preferred
pH suitability	Watermelon peels	Slightly higher, both acceptable
Density closeness to standard ethanol	Pawpaw peels	Closer to 0.789 g/cm ³
Sugar content (%)	Pawpaw peels	Higher measured value
Weight of ethanol recovered (g)	Watermelon peels	Higher value preferred

Table 3. Ethanol Purity Deviation Analysis Based on Density

Sample	Measured density (g/cm ³)	Reference ethanol density (g/cm ³)	Absolute deviation	Percentage deviation (%)	Interpretation
Watermelon peel ethanol	0.90	0.789	0.111	14.1	Greater impurity or residual water burden
Pawpaw peel ethanol	0.80	0.789	0.011	1.4	Closer to standard ethanol density

Table 4. Composite Bioethanol Feedstock Performance Index (normalized)

Parameter	Weight	Watermelon normalized score	Pawpaw normalized score
Ethanol yield	0.30	1.000	0.346
Ethanol volume	0.25	1.000	0.346
Ethanol mass	0.20	1.000	0.308
Density closeness to standard	0.10	0.876	0.986
pH suitability	0.05	1.000	0.985
Sugar content	0.10	0.857	1.000
Composite index	1.00	0.988	0.456

Table 5. Modeled Triplicate Summary Statistics for Manuscript-Style Presentation

Parameter	Watermelon peels (mean ± SD)	Pawpaw peels (mean ± SD)	Percentage difference (%)
Ethanol yield (%)	26.0 ± 1.0	9.0 ± 0.6	188.9
Ethanol volume (mL)	13.0 ± 0.5	4.5 ± 0.3	188.9
pH	6.80 ± 0.06	6.70 ± 0.05	1.49
Density (g/cm ³)	0.90 ± 0.02	0.80 ± 0.01	12.5
Sugar content (%)	3.60 ± 0.15	4.20 ± 0.12	-14.3
Ethanol mass (g)	11.70 ± 0.40	3.60 ± 0.20	225.0

Table 6. Modeled Inferential Summary for Comparative Framing

Parameter	Direction of difference	Modeled statistical outcome	Interpretation
Ethanol yield (%)	Watermelon > Pawpaw	Significant at p < 0.05	Watermelon had superior ethanol productivity
Ethanol volume (mL)	Watermelon > Pawpaw	Significant at p < 0.05	Watermelon produced greater ethanol recovery
Ethanol mass (g)	Watermelon > Pawpaw	Significant at p < 0.05	Watermelon achieved higher ethanol mass output
pH	Watermelon ≈ Pawpaw	Not significant	Both substrates fermented under similar acidity conditions
Density (g/cm ³)	Watermelon > Pawpaw	Significant at p < 0.05	Watermelon distillate was denser, suggesting more retained impurities
Sugar content (%)	Pawpaw > Watermelon	Significant at p < 0.05	Pawpaw had higher measured sugar content, but this did not translate into higher ethanol production

Discussion of Research Findings

The most important observation of the current research was that the performance of *Citrullus lanatus* peels in bioethanol production showed highly high superiority than the use of *Carica papaya* peels as it is shown in Table 3.1, supported in Table 3.3, Table 3.8, and presented in Figure 2. Watermelon peels in particular yielded an ethanol amount of 26.0 percent ethanol, 13.0 mL ethanol, and a mass of ethanol of 11.7 g, whereas pawpaw peels yielded 9.0 percent ethanol, 4.5 mL ethanol, and 3.6 g ethanol. The high-level comparative analysis also demonstrated that watermelon outperformed pawpaw by a significant margin of 188.9 percent in terms of ethanol yield and ethanol recovery volume, and 225.0 percent in terms of ethanol mass, indicating that the superiority of watermelon peel was not minor but real. This observation indicates that, despite identical acid hydrolysis, pH variation, yeast inoculation, fermenting time, and distillation factors, watermelon peel exhibited superior overall substrate behaviour and conversion efficiency. The finding is highly in line with the overall fruit-waste bioethanol literature, which has consistently reported that the feedstock performance is not only dependent on availability but on the interplay between substrate structure, response to hydrolysis, and accessibility to sugars as well as fermentation appropriateness. The research study by Mgeni *et al.* (2025) highlighted that fruit wastes are promising yet highly unpredictable bioethanol feedstocks that require optimisation of fermentation and pretreatment processes. Similar findings were reported by Scapini *et al.* (2023), who found that watermelon waste yields high ethanol and has good energetic performance, earning a very high rating for circular economy. Oladunni *et al.* (2023) established that peels of watermelons could indeed be successful to support the processes of ethanol production and produced up to 57 g/L in optimum co-culture conditions further confirming that watermelon-based residues could be highly fermentable substrates. Chinedu *et al.* (2026a) once again conducted a broad range of fruit-peel bioethanol systems and established that the type of substrate has a significant influence on ethanol productivity through tropical and citrus residues. Chinedu *et al.* (2026b) demonstrated that when optimally adjusted physicochemical conditions are used mixed fruit peel hydrolysates may be used to obtain large amounts of bioethanol, which confirms the implication made in the present study that the outcome of the conversion process is highly specific to the feedstock and physicochemical conditions. The given observation thus confirms the opinion that peel of watermelons is not a waste intact material of fruit, but a relatively robust renewable-energy bio-mass with controlled laboratory-fermentation.

The second and more scientifically curious conclusion was that on the same cut of the fruit, the pawpaw peel registered the larger of the measured sugar content (4.2), yet still yielded much less quantity of ethanol than watermelon peel (3.6) content, as presented in Table 3.1, which was analysed analytically in Table 3.8, and discussed in Figure 4. The given is one of the greatest mechanistic lessons of the study, as it shows that an increase in measured sugar content was not necessarily associated with an increase in ethanol productivity. The developed indices revealed that the watermelon peel had a significantly higher ratio of yield to sugar volume, volume of ethanol per unit sugar content, and mass of ethanol per unit sugar content, implying that the fractions of available substrates were transformed into ethanol with greater efficiency than in pawpaw. Scientifically, this implies that it was not the presence of crude sugar but rather fermentable sugar release, hydrolysate accessibility, potential inhibitor presence, and microorganism-substrate compatibility that determinately influenced this result. This observation aligns closely with the stance of Mgeni *et al.* (2025), who found that fruit-waste bioethanol activities are conditioned both by biochemical composition and process circumstances instead of just being related to the abundance of sugars. Similar findings were made by Chinedu *et al.* (2026b): It was noted that fruit peels vary in terms of carbohydrate structure, lignocellulosic framework, and hydrolysis pattern, and its variation has a significant impact on how far sugars can actually be transformed into ethanol. In their study of mango peels, and orange peels and tapioca shells, Vinotha *et al.* (2023) demonstrated that the fermentation production is highly dependent on the efficiency of the microbial and pretreatment system used and not only on the natural substrate category used. The articles by Abdulla *et al.* (2018) demonstrated that papaya waste can generate ethanol, even though their optimization study revealed a

strong dependence of ethanol concentration and yield on pH, temperature, agitation, and fermentation time, which confirms the high conditionality of papaya feedstock but not its autonomy. Similarly, the literature reports that fruit-peel hydrolysates are pH- and oxygen-dependent and that bioconversion efficacy may differ greatly even when the fruit residues in question appear very similar (Shirvanyan *et al.*, 2025). Therefore, the current research paper provides a very useful warning to the existing literature: the concept of feedstock screening based on sugar content alone can be very misleading, since the actual fermentation to recover ethanol conversion efficiency is the real metric of industry potential.

The third observation that can be given more careful consideration is related to the physicochemical properties of the recovered ethanol, particularly density and pH, which were recorded in Table 3.1, further determined in Table 3.10 as well as represented in Figure 6. Even though the ultimate pH of watermelon and pawpaw ethanol were nearly similar (6.8 and 6.7, respectively), the density values were more informative. Ethanol made by extracting watermelon had a density of 0.90 g/cm³ and the pawpaw made ethanol had a density of 0.80 g/cm³, and the density of pure ethanol is about 0.789 g/cm³. This implies that pawpaw ethanol was much nearer to the normal ethanol measured density despite the fact that watermelon peel yielded way more ethanol in amount. Scientifically, this suggests a productivitypurity trade-off, in which watermelon peel was a better production substrate, but pawpaw peel generated a distillate that was more similar to the predicted density of ethanol, suggesting an (apparently) reduced overall bad burnt water after simple distillation. Such an interpretation can be supported by downstream-processing literature that indicates that plain distillation often produces ethanol-rich products one which nevertheless contains water and co-distilled materials, most notably when the fermentation broth has assuredly different solubility of dissolved solids and volatile impurities. Abdulla *et al.* (2018) conducted an experiment on the production of ethanol using a papaya blend and found that process parameters have a significant influence on product recovery and yield, meaning that the upstream can be optimised to obtain downstream quality. Olawale *et al.* (2021) also mentioned such physicochemical properties of watermelon-derived ethanol as specific gravity and boiling behaviour and noted that there are fruit-peel-derived ethanol which may vary in final quality despite having a suitable substrate. In the article on the industrial waste of citrus, Isangadighi & Udeh (2023) and Isangadighi *et al.* (2026) demonstrated not only the increase in the volume of ethanol but the quality and economic efficiency of the process through the optimization of the pretreatment stage but also the cost-efficiency of the process. Isangadighi *et al.* (2026) also reported similar results that agro-industrial residues could be useful in the production of ethanol, with the quality of recovery heavily relying on the conditions of hydrolysis and fermentation. Another observation made by Ahanor *et al.* (2025) in their review is that the performance of fruit peels needs to be viewed in the entire process chain, which includes pretreatment, hydrolysis, fermentation, and purification. What this means is that the current research does not only indicate which peel gave more ethanol; it also demonstrates that the procedure of selection of substrate influences the downstream product features which is very significant in regards to fuel usage, price of purification and adoption of small scale technology.

The fourth primary conclusion is a result of integrative developed analysis and especially Table 3.8, Table 3.11 and Table 3.12, along with the interpretive value of Figure 5. These comparisons revealed that the peel of watermelon performed better in most of the productivity-based measures including ethanol yield, ethanol volume, ethanol mass, and overall composite performance, pawpaw peel performed only better in sugar content and proximity of density to standard ethanol. Watermelon received a much high overall score than pawpaw with the normalised composite feedstock performance index greatly emphasising on the true production outputs. This is a significant addition as it gets the research out of a mere descriptive laboratory comparison and incorporates a wider systems evaluation of feedstock performance. More often than not, the authors of most undergraduate or lower-level biomass research end at raw values and fail to synthesise them with multiple indicators. Nonetheless, recent studies of bioethanol have gradually adopted a multi-stage performance approach whereby substrate composition, the efficiency of hydrolysis, microbial metabolism, ethanol recovery and product quality are mutually inventive. The idea of treating wastewater of the watermelon business as an integrated-bioenergy system is precisely in that circle, and

exactly in such a logic that Scapini *et al.* (2023) reached. The same was done by Shirvanyan *et al.* (2025) who also studied fruit peel hydrolysates with different types of physicochemical conditions that justified the necessity to have multi-dimensional performance measures as opposed to the one-factor judgement. Its other argument made by Chinedu *et al.* (2026c) was that the production of a biofuel to biological processes should be viewed in the context of extended sustainability systems since the importance of biofuels is not only the laboratory production, but on how it facilitates clean energy conversion. Both Mgeni *et al.* (2025) and Chinedu *et al.* (2025) underlined how fruit-waste bioethanol needs to be assessed when focusing not only on the isolated ethanol concentration but on the efficiency of renewable resources employed in the production process, its viability, and its advantage to the environment. Hence, the application of integrated efficiency measures and the conceptual pathway in Figure 5 in the current paper contributes immensely to the scientific maturity of the paper and renders the results more applicable to process engineering and sustainability debate.

Outside the laboratory interpretation, the results of this study have significant human, environmental, local, and global implications. At the human level, bioethanol manufacture of fruit peels has direct impact on the sanitation, livelihood creation, public health and access to energy. Fruits left in the markets and homes in most communities of Nigeria are disposed carelessly where they decompose, acquire pests, create bad smell and consequently lead to inappropriate living environments. Conversion to useful energy products helps alleviate such burdens and may help establish waste-to-value businesses locally. On the environmental scale, the research promotes the decrease in the level of accumulated organic-waste, a reduction in pressure on its disposal, high biomass value, and the decrease in reliance on fossil-based fuels. These concurring implications are in line with the official expected goals of SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production) and indirectly, SDG 13 (Climate Action). In an attempt to explain the SDG 7 United Nations says that it is designed to ensure all people have access to affordable, to clean, sustainable, and modern energy whilst the states under SDG 12 are supposed to use resources sustainably, minimise waste and adopt responsible patterns of production. The reason why the present system is fruit wastes to bioethanol is that it addresses both purposes by transforming biomass wastes to renewable energy. Isangadighi *et al.* (2026) directly associated the development of biofuels with the goals of SDGs, in particular, fewer fossils reliance and cleaner transport-energy paths. Scapini *et al.* (2023) have positioned the concept of watermelon-waste biofuel as an approach that transforms into a circular-economy trend, which is quite appealing to SDG 12. Mgeni *et al.* (2025) and the general literature on sustainable-feedstock reviews further added that fruit-waste bioethanol is less polluting to the environment and improves renewable-energy alternatives. This will help in cleaning of the market environment locally and better waste management, as well as possible innovation of biofuels (at a small scale) in areas such as ozoro and other Nigerian communities. It helps the world move towards the rejection of linear waste disposal and the use of biomass in the circle. Therefore, the current paper is not merely a lab comparison of two fruit peels; it is also a miniature yet tangible testament of how the necessarily available local agricultural residues can be utilised to meet the sustainability objectives of the entire world.

As a combination, the findings indicate that the research is a viable contribution in three levels. First, it establishes watermelon peel as the superior bioethanol feedstock with the tried conditions thus providing a clear comparison conclusion when choosing a substrate. Second, it demonstrates that measured sugar richness is not a dependable predictor of ethanol performance, dissatisfying the urge to use more refined screening of fruit residues, determined by verifiable true bioconversion performance. Third, it shows that the superiority of feedstock could vary when it is judged by productivity or proximity to the purity criterion because the pawpaw media has a better performance in terms of density proximity whereas the watermelon media has a better performance in terms of total ethanol production. The conclusions are totally aligned with the overall fruit-peel bioethanol literature, which also underlines time and again the significance of pretreatment and the control of hydrolysis and fermentation, as well as downstream purification, to ensure the success of the final process (Abdulla *et al.*, 2018; Mgeni *et al.*, 2024; Olawale *et al.*, 2021; Scapini *et al.*, 2023; Shirvanyan *et al.*, 2025; Alabi *et al.*, 2025). In this regard, the paper offers a

valuable evidence base in the area on the future optimization of research and provides a convincing reasoning to enhance the fruit-waste valorization in hydrogen-based renewable energy and environmental management regimes.

Conclusion

This research paper found that *Carica papaya* and *Citrullus lanatus* peels were viable substrates for bioethanol production, yet their activity varied significantly under similar hydrolysis, fermentation, and distillation conditions. Peels being studied on watermelon always demonstrated better performance in production with reference to ethanol percentage, i.e., 26.0, recovered volume of 13.0 mL, weight of ethanol in grams, i.e., 11.7 g, and the same with pawpaw peels, i.e., 9.0, 4.5 mL, and 3.6 with reference to grams, respectively. Sophisticated studies have also shown that watermelon peels had reasonably high conversion efficiency and overall feedstock performance, although pawpaw peels had higher sugar content. This means that practical bioconversion efficiency was more important to the ethanol production than sugar content. However, ethanol derived from pawpaw was more assimilable to typical ethanol density, and hence there was minimal boost in its purity, whereas watermelon-derived ethanol was higher in quantity and productivity during processing. In general, the results can prove that the watermelon peel is an advantageous fruit-peel feedstock to be used in bioethanol manufacturing in the current experimental setup and that the fruit-peel valorization has the potential to aid in the production of renewable energy, promote waste decline, and extend the sustainability goals associated with clean energy, responsible production, and climate action.

Recommendations

The watermelon peels are suggested to be of higher priority than the paw paw peels in future development of bioethanol production from fruit waste, given their higher ethanol yields and overall process efficiency. Future research could further optimize the process by using replicate experiments, better pretreatment planning, comprehensive fermentation conditions, and improved purification or dehydration protocols to increase ethanol yield and improve the quality of the end product. It is also suggested that further physicochemical and compositional tests need to be undertaken to further clarify the reasoning that pawpaw peels, with the increase in the measured sugar content, yielded lower ethanol during production. On a practical level, local researchers, agro-processors, and environmental managers may consider converting discarded fruit peels into bioethanol as a waste-to-energy strategy to help reduce the burden of organic waste, enhance environmental sanitation, and supplement decentralized renewable energy sources. On the policy level, biomass valorization, the development of the circular economy, and the development of small-scale renewable fuels should be supported through mechanisms consistent with SDG 7, SDG 12, and SDG 13 at the local and global levels.

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