Comparative Bioethanol Recovery from Household Mango, Watermelon, and Muskmelon Peel Waste: A Spectroscopic and Quantitative Pilot Study

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ABSTRACT

Domestic fruit and vegetable peel waste represents an underused, non-food lignocellulosic feedstock for decentralized bioethanol production. This pilot study evaluated bioethanol recovery from household mango (*Mangifera indica*), watermelon (*Citrullus lanatus*), and muskmelon (*Cucumis melo*) peel waste collected from a residential kitchen in Faridabad, Haryana, India. Peels were subjected to thermal/dilute-acid pretreatment and fermentation with *Saccharomyces cerevisiae*, followed by filtration and distillation. The ethanol content of two substrate combinations – a mixed mango + watermelon peel waste and mango peel waste alone – was independently quantified by an accredited third-party laboratory (FICCI Research and Analysis Centre, New Delhi), yielding 1.80% and 1.40% ethanol, respectively. A third substrate, muskmelon peel waste alone, gave an in-house estimate of 0.98% ethanol that could not be independently corroborated and is reported only as a preliminary, non-certified observation. Fourier-transform infrared (FTIR) spectroscopy of all three product solutions showed a consistent spectral signature – a broad O-H stretch near 3300 cm^{-1}, an O-H/H-O-H bending mode near 1635 cm^{-1}, and a C-O stretch near 1044 cm^{-1} – consistent with a dilute aqueous ethanolic solution. 1H and 13C NMR spectra (DMSO-d6, 500 MHz) confirmed diagnostic ethanol resonances (δH ~1.0 and 3.4 ppm; δC ~18–19 and 56–58 ppm) in all three samples, co-occurring with carbohydrate and organic-acid signals indicative of an unrectified, crude fermentation liquor rather than analytically pure ethanol. The mixed mango-watermelon substrate produced numerically more certified ethanol than mango alone, although the single-batch design precludes formal statistical inference. These findings support the technical feasibility of small-scale, household-level bioethanol recovery from fruit peel waste while underscoring the need for replicated trials, product rectification, and standardized protocols before any scale-up is attempted.

Keywords: *Bioethanol; fruit peel waste; mango; watermelon; muskmelon; Saccharomyces cerevisiae; FTIR spectroscopy; NMR spectroscopy; decentralized waste-to-energy.*

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INTRODUCTION

The depletion of fossil energy reserves, together with the environmental burden of greenhouse gas emissions from petroleum combustion, has sustained global interest in renewable liquid fuels. Bioethanol, produced by microbial fermentation of fermentable sugars, remains the most widely deployed biofuel and can be blended with gasoline to reduce net carbon emissions and reliance on petroleum-derived octane enhancers, with blend ratios and engine-compatibility characteristics having been established in detail for high-compression gasoline engines [1,2,3]. First-generation bioethanol production from food crops such as corn, sugarcane, and cassava has, however, drawn sustained criticism for competing with food supply and arable land use, motivating a shift toward non-food lignocellulosic residues, including agricultural, municipal, and household organic waste, as alternative feedstocks [4].

Municipal solid waste management remains a substantial challenge in rapidly urbanizing economies such as India. Recent assessments of Indian smart cities report per-capita municipal solid waste generation ranging from approximately 0.34 to nearly 1 kg per person per day depending on city size and infrastructure, with fruit and vegetable residues forming a biodegradable fraction that is frequently uncollected or improperly disposed of, contributing to methane emissions and leachate generation [5]. Beyond direct energy recovery, fruit and vegetable processing residues are increasingly recognized within a circular-economy framework as a source of recoverable pectin, polyphenols, and other value-added co-products, which strengthens the broader economic case for organized fruit-waste valorization [6,7]. Diverting even a modest share of this fermentable fraction toward decentralized, household-level bioethanol recovery could simultaneously ease municipal waste burdens and generate a locally usable fuel or solvent.

Fruit peel waste is particularly well suited to this purpose because many common fruit peels, including mango, watermelon, and muskmelon, are rich in fermentable carbohydrates and comparatively low in lignin relative to woody lignocellulosic biomass, making them more amenable to hydrolysis without energy-intensive

thermochemical pretreatment [8]. Prior laboratory-scale studies have demonstrated ethanol recovery from mango peel using *Saccharomyces cerevisiae* under controlled conditions [9], from banana peel using kinetic optimization [10], and from citrus-processing residues using fungal multienzyme systems [11]; a thermotolerant *Pichia kudriavzevii* isolate has similarly been shown to ferment hydrolysed orange peel to ethanol at elevated temperature, utilizing both hexose and pentose sugars [12], while whole unripe plantain, comprising both peel and pulp, has been reported to support appreciable ethanol titres following enzymatic liquefaction and saccharification [13], and pineapple waste has long been recognized as a fermentable substrate for alcohol production [14]. Simultaneous saccharification and fermentation (SSF) of banana, plantain, and pineapple peel using a controlled co-culture of *Aspergillus niger* and *Saccharomyces cerevisiae* under agitated, temperature-controlled conditions has been reported to yield 3.98–8.34% (v/v) ethanol after seven days [15]; a comparable co-culture strategy applied to potato peel and mash under solid-state fermentation has been reported to yield 6.18–9.30% (v/v) ethanol [16]. Acid-hydrolyzed banana peel fermented under optimized pH conditions has yielded ethanol concentrations of up to approximately 157 mg/mL [17]. More recently, mixed fruit-peel hydrolysates fermented with *Saccharomyces cerevisiae* under controlled pH and oxygen conditions have been reported to support substantially higher ethanol titres under optimized bioreactor conditions [18].

These studies share a common feature: they were conducted under controlled laboratory conditions with agitation, temperature regulation, and in several cases fungal co-culture augmentation. Comparatively little has been reported on the feasibility of bioethanol recovery from fruit peel waste using simple, low-cost, household-accessible equipment – an approach that is directly relevant to decentralized, small-scale waste valorization in domestic settings. The present pilot study addresses this gap by (i) producing bioethanol from household mango, watermelon, and muskmelon peel waste using a simple thermal/acid pretreatment and yeast fermentation protocol; (ii) independently verifying ethanol content in two of the three substrate combinations through an accredited third-party testing laboratory; (iii) characterizing the resulting product solutions by FTIR and 1H/13C NMR spectroscopy; and (iv) benchmarking the yields obtained against previously published, laboratory-optimized SSF processes. Consistent with the exploratory, single-batch nature of this work, results are reported descriptively and the scope is explicitly limited to a technical feasibility assessment rather than a fully optimized or statistically validated production process.

MATERIALS AND METHODS

2.1 Feedstock Collection

Mango (*Mangifera indica*), watermelon (*Citrullus lanatus*), and muskmelon (*Cucumis melo*) peel waste was collected from routine domestic kitchen waste at a residential household in Sector 84, Faridabad, Haryana, India. Peels were washed with potable water to remove surface contaminants, and the outer coat was removed and cut into small pieces using a kitchen knife prior to further processing.

2.2 Substrate Combinations

Three substrate combinations were prepared and processed independently: Substrate I, a mixed mango + watermelon peel waste; Substrate II, mango peel waste alone; and Substrate III, muskmelon peel waste alone. Each substrate was processed as a single batch; the study was not replicated across multiple independent batches, which is stated explicitly here as a scope limitation (see Limitations of the Study).

2.3 Pretreatment and Hydrolysis

Chopped peel material was submerged in water and subjected to a thermal/mild-acid pretreatment step intended to promote auto-hydrolysis and partial breakdown of the lignocellulosic matrix, releasing fermentable sugars prior to inoculation, consistent with the general principle that pretreatment severity governs the accessibility of fermentable sugars in lignocellulosic and semi-lignocellulosic substrates [19,20], with substrate handling and hydrolysis assessment informed by standard laboratory analytical procedures established for lignocellulosic feedstock characterization [21]. Because the protocol was carried out at household scale without laboratory-grade temperature regulation, pretreatment temperature varied modestly between batches, in the approximate range of 30–46°C over 3–7 days. This range, rather than a single fixed value, is reported here in the interest of transparency; standardizing this step is identified as a priority for follow-up work (Future Scope).

2.4 Fermentation

Following pretreatment, the hydrolysate was inoculated with *Saccharomyces cerevisiae* and incubated under anaerobic conditions at 30–35°C for 3–7 days to allow conversion of fermentable sugars to ethanol. No exogenous amylolytic or cellulolytic enzyme co-culture (e.g., *Aspergillus niger*) was used in this study, unlike several of the controlled laboratory protocols cited above [15,16].

2.5 Filtration and Distillation

The fermented broth was filtered through Whatman filter paper No. 1 to remove suspended solids and cellular biomass. The filtrate was then subjected to a single-pass distillation to recover the crude ethanol-containing fraction, with residual water content reduced using a rotary evaporator/simple distillation setup. No secondary fractional distillation or membrane dehydration step was performed; consequently, the recovered product is best described as a dilute, unrectified ethanol solution rather than an anhydrous or fuel-grade product.

2.6 Quantitative Ethanol Determination

The ethanol content of Substrate I (mango + watermelon) and Substrate II (mango alone) was independently determined by FICCI Research & Analysis Centre (FRAC), New Delhi, an accredited third-party testing laboratory, under registration numbers FRAC/F/2606190007 and FRAC/F/2606190006, respectively. Substrate III (muskmelon alone) was

assessed only by an in-house estimate and was not submitted for independent accredited verification; this value (0.98%) is reported for completeness and scientific transparency but is explicitly flagged throughout this article as non-certified, and it is not included in any quantitative comparison with the two certified substrates.

2.7 Fourier-Transform Infrared (FTIR) Spectroscopy
FTIR spectra of the distilled product solutions from all three substrates were recorded in transmittance mode over the range 4000–450 cm^{-1}. Replicate scans were available for two of the three samples (two and three scans, respectively); a single scan was available for the third. Peak positions were identified from the raw transmittance data using prominence-based peak detection (minimum prominence 1.5% transmittance units), and closely spaced maxima within 15 cm^{-1} were merged.

2.8 Nuclear Magnetic Resonance (NMR) Spectroscopy
1H and 13C NMR spectra were recorded in DMSO-d6 on a JEOL DELTA2 NMR spectrometer operating at 500 MHz (1H) and 125.8 MHz (13C) at the Department of Chemistry, Banaras Hindu University, Varanasi. Samples are hereafter referred to by their laboratory designations, Sample A, Sample B, and Sample C. Signals in the 38.7–40.6 ppm region observed in all 13C spectra correspond to the characteristic DMSO-d6 solvent multiplet (centred near 39.5 ppm) and were excluded from sample peak interpretation; the residual solvent singlet at δH 2.49 ppm in the 1H spectra was similarly excluded.

2.9 Data Analysis
Given the single-batch (n = 1 per substrate), non-replicated design, no formal statistical hypothesis testing (e.g., ANOVA or multiple range tests) was applied. Quantitative and spectroscopic results are reported descriptively, and comparisons between substrates are presented as preliminary observations rather than statistically validated differences.

RESULTS AND DISCUSSION

3.1 Ethanol Yield
Table 1 summarizes the ethanol content obtained from the three substrate combinations. Among the two independently certified substrates, the mixed mango + watermelon peel waste (Substrate I) yielded a higher ethanol content (1.80%) than mango peel waste alone (Substrate II; 1.40%). Muskmelon peel waste alone (Substrate III) gave a lower, but non-certified, in-house value of 0.98%.

Table 1. Ethanol content of the three substrate combinations. Only Substrates I and II were verified by an accredited third-party laboratory; the Substrate III value is reported for transparency but should not be treated as equivalent in evidentiary weight.

Substrate	Composition	Ethanol Content (%)	Verification
Substrate I	Mango + watermelon peel waste (mixed)	1.80	Certified – FRAC/F/2606190007 (FICCI Research & Analysis Centre, New Delhi)
Substrate II	Mango peel waste (alone)	1.40	Certified – FRAC/F/2606190006 (FICCI Research & Analysis Centre, New Delhi)
Substrate III	Muskmelon peel waste (alone)	0.98	Not independently certified – in-house estimate only

3.2 FTIR Spectral Characterization
FTIR spectra of the distilled product solutions from all three substrates, including replicate scans, showed a consistent spectral profile dominated by three principal features: a broad, high-intensity band in the 3290–3339 cm^{-1} region, consistent with O-H stretching vibrations of associated (hydrogen-bonded) hydroxyl groups; a band in the 1632–1639 cm^{-1} region, consistent with an O-H/H-O-H bending mode; and a weaker but reproducible band in the 1043–1045 cm^{-1} region, consistent with C-O stretching of a primary alcohol. This three-band pattern was reproducible across all replicate scans (Table 2) and is consistent with a dilute aqueous ethanolic solution rather than a rectified, anhydrous product.

Table 2. Principal FTIR absorption bands identified by prominence-based peak detection (raw transmittance data, 4000–450 cm^{-1}). Weak, low-prominence features below approximately 600 cm^{-1} were also observed in several scans but are not diagnostic and are not tabulated.

Sample	Replicate Scans	O-H Stretch (cm^{-1})	O-H Bend (cm^{-1})	C-O Stretch (cm^{-1})
Sample A	1	3337	1639	1045

Sample	Replicate Scans	O-H Stretch (cm^{-1})	O-H Bend (cm^{-1})	C-O Stretch (cm^{-1})
Sample B	2 (B, B1)	3290–3307	1632–1633	1044
Sample C	3 (C, C1, C2)	3307–3339	1633–1635	1043

3.3 NMR Spectral Characterization

1H and 13C NMR spectra of all three samples showed resonances diagnostic of ethanol superimposed on additional signals attributable to co-extracted carbohydrates and organic acids (Table 3). In the 1H spectra, a triplet-like cluster near δ1.0 ppm (integrating for approximately 3H, consistent with the ethanol methyl group) and a multiplet near δ3.4 ppm (consistent with the ethanol methylene group) were identified in Samples B and C; the corresponding 13C spectra of all three samples showed paired resonances near δ18–19 ppm and δ56–58 ppm, diagnostic of the ethanol CH3 and CH2 carbons, respectively.

Beyond these diagnostic ethanol signals, Sample B (provisionally Substrate III, muskmelon) and Sample C (provisionally Substrate I, mango + watermelon) showed prominent additional 13C resonances in the 98–103 ppm (anomeric carbon) and 61–84 ppm (sugar ring carbon) regions, indicating substantial co-extracted residual carbohydrate, together with carbonyl/carboxylic resonances near 172–178 ppm tentatively attributable to short-chain organic acids (e.g., acetic acid) – a common fermentation by-product also reported as a characteristic congener signature in NMR-based profiling of fermented fruit-derived spirits [22]. Sample A (provisionally Substrate II, mango) showed a comparatively simpler spectrum, with fewer non-ethanol resonances, limited mainly to signals in the 22–28 ppm and 9–11 ppm regions consistent with minor higher (fusel) alcohols or ester congeners. These observations, summarized in Table 3, indicate that all three product solutions are unrectified fermentation liquors in which ethanol is clearly identifiable but is accompanied by residual sugars and minor organic acids; definitive structural assignment of the minor congener species would require complementary GC-MS analysis [22], which was outside the scope of the present study.

Table 3. Diagnostic and notable 1H/13C NMR resonances (DMSO-d6, 500 MHz), excluding the DMSO-d6 solvent multiplet (38.7–40.6 ppm, 13C) and residual solvent singlet (2.49 ppm, 1H). Sample-to-substrate correspondence is provisional; see the author verification note in Section 2.8.

Sample	Diagnostic Ethanol Signals	Notable Co-extracted Signals	Interpretation
Sample A	13C: 58.3, 18.6 ppm	70.6, 62.9 ppm (sugar C-OH); 27.8, 27.2, 25.7, 22.2, 10.6, 9.6 ppm (aliphatic/minor congeners)	Ethanol confirmed; relatively low residual-sugar signal
Sample B	1H: 3.40–3.44, 1.02–1.04 ppm; 13C: 56.8, 18.9 ppm	13C: 172.2–172.3 ppm (carbonyl); 98.6–102.4 ppm (anomeric C); 61.6–83.4 ppm (sugar ring C)	Ethanol confirmed; substantial residual carbohydrate
Sample C	1H: 3.30–3.44, 1.01–1.03 ppm (overlapping); 13C: 57.1–58.8, 18.8 ppm	13C: 174.0, 178.3 ppm (carbonyl/carboxylic); 63.4–72.9 ppm (sugar ring C); 21.3–35.7 ppm (aliphatic chain)	Ethanol confirmed; most complex congener profile of the three samples

3.4 Overall Discussion

The certified ethanol yields obtained in this study (1.40–1.80%) are modest in comparison with laboratory-optimized SSF processes reported in the literature. Itelima et al. reported ethanol yields of 7.45–8.34% (v/v) from banana and pineapple peel using a temperature-controlled, agitated (300 rpm, 30°C) co-culture of *Aspergillus niger* and *Saccharomyces cerevisiae* over seven days [15]; a comparable co-culture strategy applied to potato peel and mash under solid-state fermentation yielded 6.18–9.30% (v/v) ethanol [16], while Shirvanyan et al. reported ethanol titres substantially higher than those obtained here from mixed fruit-peel hydrolysate fermented under controlled pH and oxygen conditions [18]. The comparatively low yields in the present study most plausibly reflect the absence of these process controls: fermentation was carried out at ambient-to-mildly-elevated household temperature without agitation, without an amylolytic/cellulolytic co-culture to supplement saccharification, and with only a single-pass distillation rather than fractional or membrane-based rectification. Each of these factors is a well-established lever for improving ethanol titre in fermentation processes and represents a concrete, testable direction for process intensification in follow-up work.

The higher certified yield obtained from the mixed mango + watermelon substrate relative to mango alone is consistent with reports that combining fruit peel matrices can broaden the pool of fermentable sugars available to *Saccharomyces cerevisiae* [8,18]. However, because each substrate in this study was processed as a single, non-replicated batch, this observation should be regarded as preliminary; it cannot be attributed a statistically defensible effect size, and it should not be over-interpreted as a general synergy effect until confirmed across replicate batches.

The FTIR and NMR data provide internally consistent, complementary support for the quantitative findings. The dominant FTIR bands (O-H stretch near 3300 cm^{-1}; O-H

bend near 1635 cm^{-1}) are consistent with a predominantly aqueous product, in agreement with the low (sub-2%) certified ethanol percentages; the weaker C-O stretch near 1044 cm^{-1} is consistent with the presence of a primary alcohol. The NMR data corroborate this picture at higher resolution: diagnostic ethanol resonances were identified in all three samples, confirming that ethanol is genuinely present and not merely inferred from the accredited laboratory percentage, while the concurrent carbohydrate and organic-acid signals confirm that the products are crude, unrectified fermentation liquors rather than analytically pure ethanol, consistent with the known richness of melon and mango peel matrices in soluble sugars, pectin, and phenolic constituents that co-extract readily during aqueous processing [23,24,25]. This is an expected and unremarkable finding given the single-distillation protocol used, and it is reported transparently here so that readers do not conflate the FRAC-certified 'ethyl alcohol %' figures with anhydrous fuel-grade ethanol purity.

The muskmelon-derived product (Substrate III) presents an intermediate case. Its NMR and FTIR spectra are consistent with the presence of ethanol, alongside a comparatively rich carbohydrate and organic-acid signature, in keeping with reported compositional profiles of muskmelon peel and rind by-products [24]. However, because its 0.98% ethanol figure was not independently verified by an accredited laboratory, it cannot be compared on equal evidentiary footing with Substrates I and II, and is reported here as a directional, hypothesis-generating result rather than a confirmed finding.

From a waste-management perspective, these results are best interpreted as a proof-of-concept rather than a scale-ready process. Given the substantial volume of biodegradable fruit and vegetable waste generated in Indian households and municipalities [5], even a modest, reliably reproducible household-level conversion process could contribute to waste diversion and local energy generation, complementing other emerging valorization routes for fruit and vegetable residues such as pectin and polyphenol recovery [6,7], subcritical/supercritical fluid extraction of bioactive fractions [26], and microalgae-based upcycling of fruit-waste streams [27]. However, the yields obtained here remain well below what would be required for meaningful fuel-grade application, and the single-batch design of this study means that reproducibility across batches, seasons, and households has not yet been established.

LIMITATIONS OF THE STUDY

1. Each substrate combination was processed as a single, non-replicated batch (n = 1); no formal statistical comparison between substrates is therefore possible, and the apparent yield advantage of the mixed mango-watermelon substrate over mango alone should be treated as preliminary.
2. Pretreatment and fermentation were conducted at household scale without laboratory-grade temperature control, resulting in a reported temperature range rather than a single fixed value; this may have introduced batch-to-batch variability that could not be quantified within the scope of this study.
3. The ethanol content of Substrate III (muskmelon) was not independently certified and is reported only as an in-house estimate.
4. No raw gas chromatography chromatogram was available for review; the certified ethanol percentages for Substrates I and II are laboratory-reported values (FICCI Research & Analysis Centre, method FRAC/SOP/INST/075) rather than chromatograms re-analyzed by the authors.
5. Definitive structural identification of the minor congener species detected by NMR (e.g., specific organic acids or higher alcohols) would require complementary GC-MS analysis [22], which was not performed.
6. The correspondence between the NMR/FTIR sample codes (A, B, C) and the three substrate combinations required a provisional reconstruction from the available laboratory notes (Section 2.8) and should be independently reconfirmed by the authors before submission or citation of this work.

FUTURE SCOPE

1. Replicated fermentation trials ($n \geq 3$ per substrate) under standardized, recorded temperature and time conditions.
2. Evaluation of amylolytic/cellulolytic co-culture augmentation (e.g., *Aspergillus niger*, following established SSF protocols) to improve saccharification efficiency and ethanol titre [15,16].
3. Introduction of a secondary fractional distillation or membrane dehydration step, informed by sustainable pretreatment and separation strategies described for lignocellulosic bioethanol processes [19,20], to obtain a rectified, higher-purity product suitable for fuel-related applications.
4. Confirmatory accredited laboratory analysis of the muskmelon substrate.
5. Complementary GC-MS congener profiling [22] to resolve the minor NMR/FTIR signals identified in this study.
6. Exploration of immobilized or encapsulated yeast fermentation systems as an alternative route to improve process robustness and reusability [28].
7. A techno-economic feasibility assessment of the household-scale, decentralized waste-to-ethanol concept motivating this work, situated within the broader circular-economy landscape for fruit-waste valorization [6,26].

CONCLUSION

This pilot study demonstrates that household fruit peel waste – mango, watermelon, and muskmelon – can be converted into a dilute, ethanol-containing product using simple fermentation and distillation steps accessible outside a specialized laboratory. Independently certified analysis confirmed higher ethanol recovery from a mixed mango + watermelon substrate (1.80%) than from mango alone (1.40%); FTIR and NMR spectroscopy corroborated the presence of ethanol, alongside co-extracted carbohydrates and organic acids, in all three

substrates tested, including the non-certified muskmelon substrate. While the yields obtained are modest relative to optimized laboratory bioprocesses reported elsewhere, the results support the underlying technical feasibility of decentralized, kitchen-waste-based bioethanol recovery and provide a transparent, replicable baseline – together with a clearly stated set of limitations – for future process optimization and validation work.

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Data availability: The accredited laboratory certificates, raw FTIR spectral data, and NMR spectra underlying this study are available from the corresponding author upon reasonable request.

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