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PRODUCTION OF ETHANOL FROM FRUIT AND VEGETABLE WASTE: A SUSTAINABLE APPROACH TO BIOFUEL GENERATION IN PAKISTAN

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Abstract
Pakistan faces a severe energy crisis with increasing demand for fossil fuels and significant environmental concerns from waste disposal. Fruit and vegetable waste represents a substantial biomass resource that can be converted into ethanol, providing both waste management and renewable energy solutions. This study aimed to assess the feasibility and efficiency of producing ethanol from fruit and vegetable waste through saccharification and fermentation processes using Saccharomyces cerevisiae. Six waste samples (banana, mango, papaya, potato, tomato, and carrot) were collected, processed, and subjected to fermentation. Each 500g sample was mixed with 1500mL distilled water, and 20g of Saccharomyces cerevisiae yeast with 20g urea was added. Fermentation was conducted at 30-35°C for 72 hours, followed by distillation and dehydration processes. Performance analysis included pH, temperature, strength, density, absorbance, and potassium permanganate tests. Ethanol production was successful from all samples, with strength values ranging from 17-22% (w/w). Fruit peels (banana, mango, papaya) showed superior performance with higher sugar content and better fermentation characteristics compared to vegetable waste. The highest ethanol strength was achieved from mango (22%) and papaya (21%), while carrot showed the lowest yield (17%). All samples met density standards (0.58-0.88 g/cm³), and most exhibited acceptable pH levels (6-8). Fruit and vegetable waste can be effectively converted into ethanol, offering a sustainable solution for both waste management and biofuel production in Pakistan. The process demonstrates economic viability and environmental benefits, supporting the country's transition toward renewable energy sources.

INTRODUCTION

Pakistan faces a critical energy crisis that has significantly impacted all sectors of society. With a growing population and rapid industrialization, the country's energy demand continues to escalate, while fossil fuel resources remain limited and environmentally detrimental [1]. The energy sector's reliance on imported petroleum products has created economic vulnerabilities and contributed to environmental degradation through greenhouse gas emissions [2].

Concurrently, Pakistan generates approximately 87,000 tonnes of municipal waste daily, with major urban centers like Karachi producing 13,500 tonnes per day [3]. A significant portion of this waste comprises fruit and vegetable residues, with annual losses estimated at 2.20 million tons of vegetables and 2.8-3.0 million tons of fruits, representing 30% and 40% of total production respectively [4]. This substantial waste generation presents both environmental challenges and opportunities for sustainable resource utilization.

Bioethanol production from agricultural and food waste has emerged as a promising solution to address both energy security and waste management concerns. Ethanol, as a renewable biofuel, offers several advantages including reduced greenhouse gas emissions, domestic production potential, and compatibility with existing transportation infrastructure when blended with gasoline [5].

The conversion of fruit and vegetable waste into ethanol through fermentation processes represents an innovative approach to waste valorization. These materials contain significant amounts of fermentable sugars, including glucose, sucrose, and fructose, making them suitable substrates for ethanol production [6]. Furthermore, utilizing waste materials for biofuel production reduces the need for dedicated energy crops, thereby addressing food security concerns while providing economic benefits.

This study addresses the critical need for sustainable waste management and renewable energy production in Pakistan by investigating the feasibility of ethanol production from locally available fruit and vegetable waste. The research aims to contribute to Pakistan's energy security while providing an environmentally sound solution to waste disposal challenges.

2. Literature Review

Recent research has demonstrated the significant potential of fruit and vegetable waste for ethanol production. Khandaker et al. [5] conducted comprehensive studies on ethanol production from fruit and vegetable waste using Saccharomyces cerevisiae, achieving successful fermentation with the highest yields from pineapple and potato wastes. Their work established the technical feasibility of converting agricultural waste into valuable biofuels.

The composition of fruit and vegetable waste makes them particularly suitable for ethanol production. Abdel Salam [6] identified that fruit waste contains high levels of glucose, sucrose, and fructose sugars, making them excellent substrates for fermentation processes. This finding is particularly relevant for Pakistan, where substantial quantities of such waste are generated annually.

Several studies have focused on optimizing fermentation conditions for maximum ethanol yield. Suryaprabha et al. [7] demonstrated that optimal ethanol production from fruit waste can be achieved using Saccharomyces cerevisiae at 33°C, while Rahmath Abdulla et al. [8] found that maximum ethanol yield was achieved at pH 5, with a fermentation time of 48 hours and temperature of 30°C.

The economic and environmental benefits of utilizing waste materials for ethanol production have been well-documented. Isa and Ganda [9] emphasized that biomass-based energy production can minimize dependency on fossil fuels while promoting sustainable growth. Their research highlighted the importance of implementing supportive policies and regulations for widespread biomass utilization.

Pakistan's specific context has been addressed by several researchers. Khichi [10] analyzed Pakistan's energy scenario and concluded that the country possesses abundant biomass resources suitable for biofuel production. They recommended leveraging these resources to reduce fossil fuel dependence and overcome energy shortages while providing environmental benefits.

3. Methodology

The overall process for converting fruit and vegetable waste into ethanol is illustrated in Figure 1. The methodology involved sample collection, processing, fermentation, distillation, and analysis.

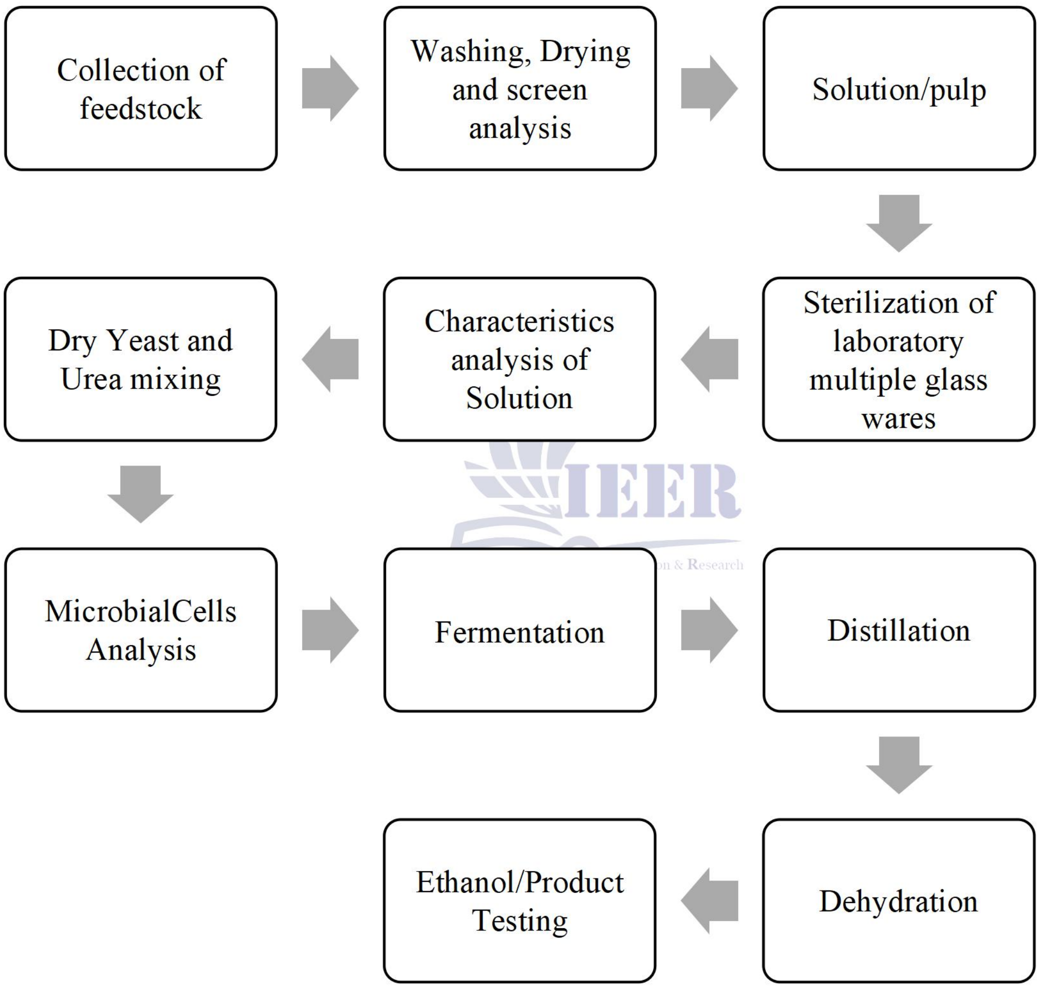

Figure 1: Process flow sheet for ethanol production from fruit and vegetable waste

3.1 Sample Collection and Preparation

Six types of fruit and vegetable waste were selected for this study: banana, mango, papaya (fruit peels), and potato, tomato, carrot (vegetable waste). Fruit peels were collected from local juice shops in Nawabshah, while vegetable waste samples were obtained from the Nawabshah vegetable market. Each sample was collected in sterilized plastic bags and transported to the distillery laboratory of Habib Sugar Mill, Nawabshah.

3.2 Processing and Preparation

All samples were thoroughly washed with distilled water to remove dirt and impurities, then dried in an oven at 50°C for 2-3 hours. Each dried sample (500g) was ground using an Annex-type grinder to create uniform particles. The ground material was mixed with 1500mL of distilled water at 25°C to prepare the fermentation substrate.

3.3 Fermentation Process

The fermentation process was initiated by adding 20g of dry Saccharomyces cerevisiae yeast and 20g of urea to each 2000mL sample to promote yeast culture growth. Fermentation was conducted at room temperature (30-35°C) for 72 hours, with pH maintained below 5.0. Microbial cell analysis was performed using an Optech microscope to monitor fermentation progress.

3.4 Distillation and Purification

After fermentation, 250mL of the fermented solution was subjected to distillation using a distillation unit with a heating mantle, distillation head, and condenser. The distillation process lasted approximately 45 minutes, with vapors collected in glass cylinders. The recovered distillate was then dehydrated using sodium oxide (NaO) powder to remove water content and impurities.

3.5 Analytical Methods

Characterization of Substrates: Brix content was determined using a Brix hydrometer, reducing sugars were analyzed through titration with Fehling solution, and total sugars were measured using acid hydrolysis followed by titration. Volatile acids were determined through distillation and titration with 0.2N NaOH. pH was measured using a Lovibond SensoDirect pH 110 meter, and temperature was monitored using a digital thermometer.

Ethanol Analysis: The produced ethanol was analyzed for pH, temperature, strength (% w/w), density (g/cm³), absorbance, and potassium permanganate content using an Anton Paar DMA 4500M Digital Density Meter and Genesys 10S UV-VIS spectrophotometer.

4. Results

4.1 Substrate Characteristics

The analysis of substrate characteristics revealed significant variations among the different waste materials. Brix values ranged from 4 (potato) to 25 (papaya and carrot), with fruit peels generally showing higher sugar content than vegetable waste. Reducing sugar content varied from 12.5% (carrot) to 14.7% (papaya), while total sugar content ranged from 40% (potato) to 48% (carrot), as detailed in Table 1. A comparison of the Brix values is shown in Figure 2.

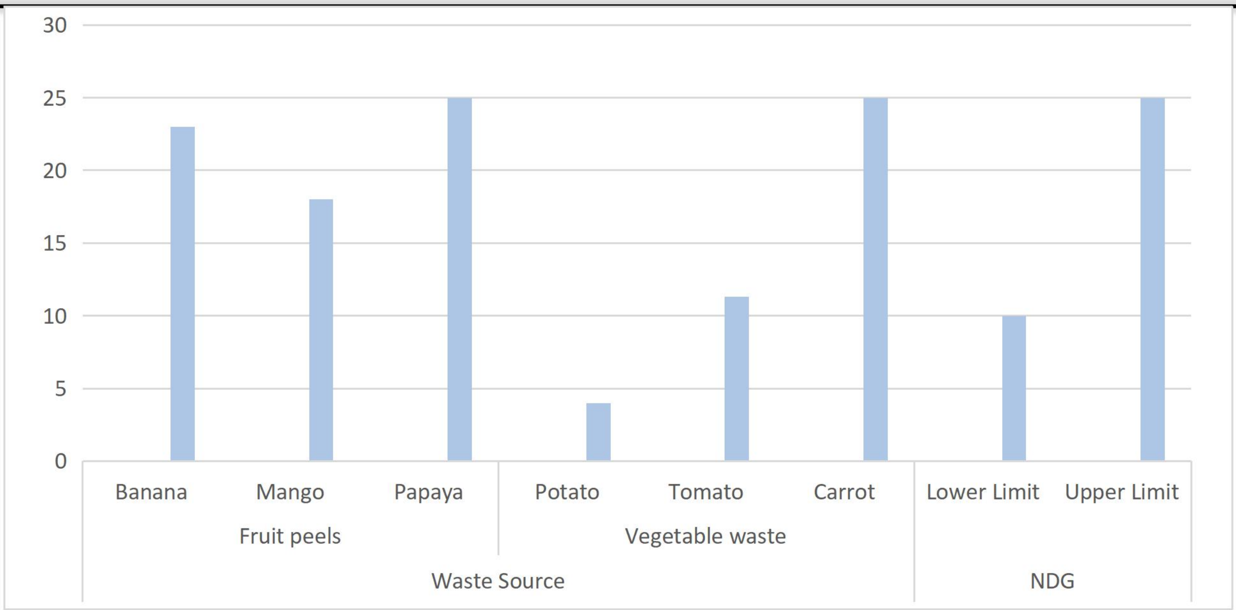

Figure 2: Comparison of Brix values among different waste materials

Table 1: Substrate Characteristics Analysis

Sample	Brix	Reducing Sugar (%)	Total Sugar (%)	pH	Temperature (°C)
Banana	23	14.6	44	6.2	30
Mango	18	14.5	45.75	6.3	30
Papaya	25	14.7	46	6.5	30
Potato	4	13.8	40	6.7	30
Tomato	11.3	13.6	42	5.4	30
Carrot	25	12.5	48	5.5	30

4.2 Ethanol Production and Recovery

Ethanol production was successful from all six waste materials, with varying yields and quality parameters. The dehydration process effectively removed water content, with recovery rates ranging from 60% (carrot) to 80% (papaya and potato) (Table 2). The recovery rates for each substrate are visualized in Figure 3.

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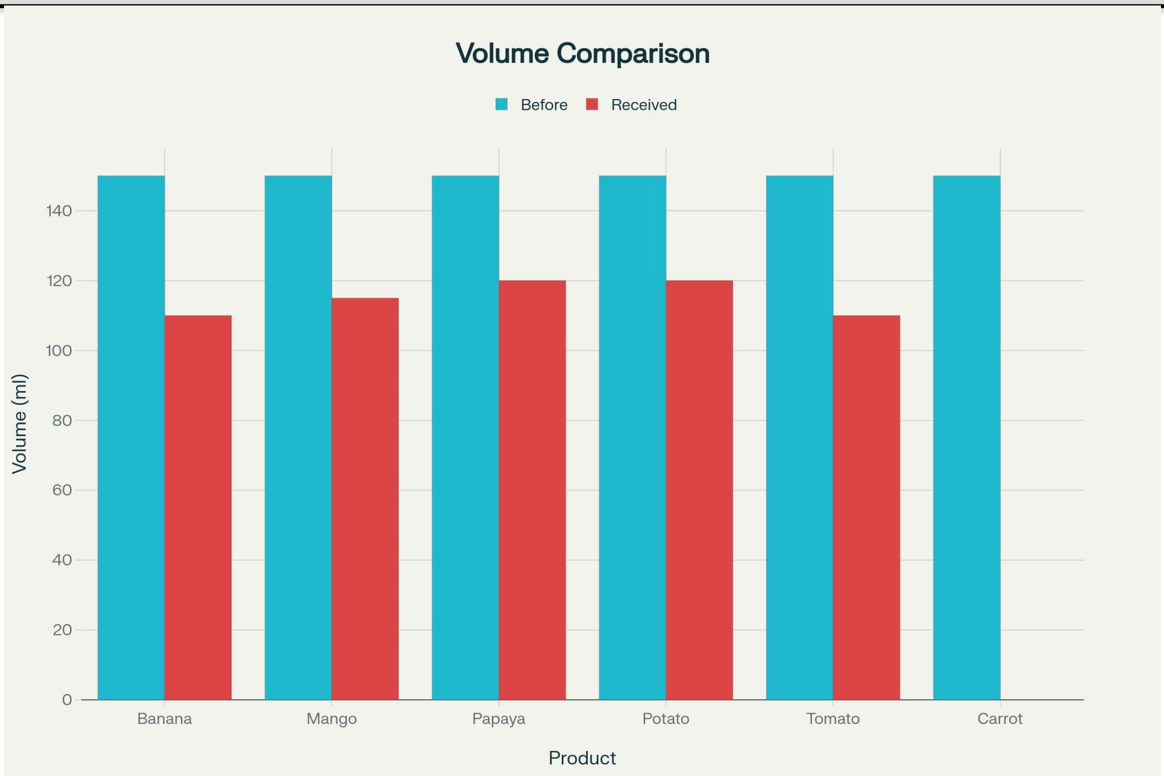

Figure 3: Recovery rates during dehydration process

Table 2: Ethanol Recovery and Water Removal

Sample	Initial Volume (mL)	Recovered Volume (mL)	Recovery Rate (%)
Banana	150	110	73.3
Mango	150	115	76.7
Papaya	150	120	80.0
Potato	150	120	80.0
Tomato	150	110	73.3
Carrot	150	90	60.0

4.3 Ethanol Quality Analysis

The produced ethanol exhibited varying quality parameters across different waste sources. Strength values ranged from 17% (carrot) to 22% (mango), with fruit peels generally producing higher strength ethanol compared to vegetable waste (Table 3). Figure 4 illustrates the comparative strength of ethanol produced from different substrates.

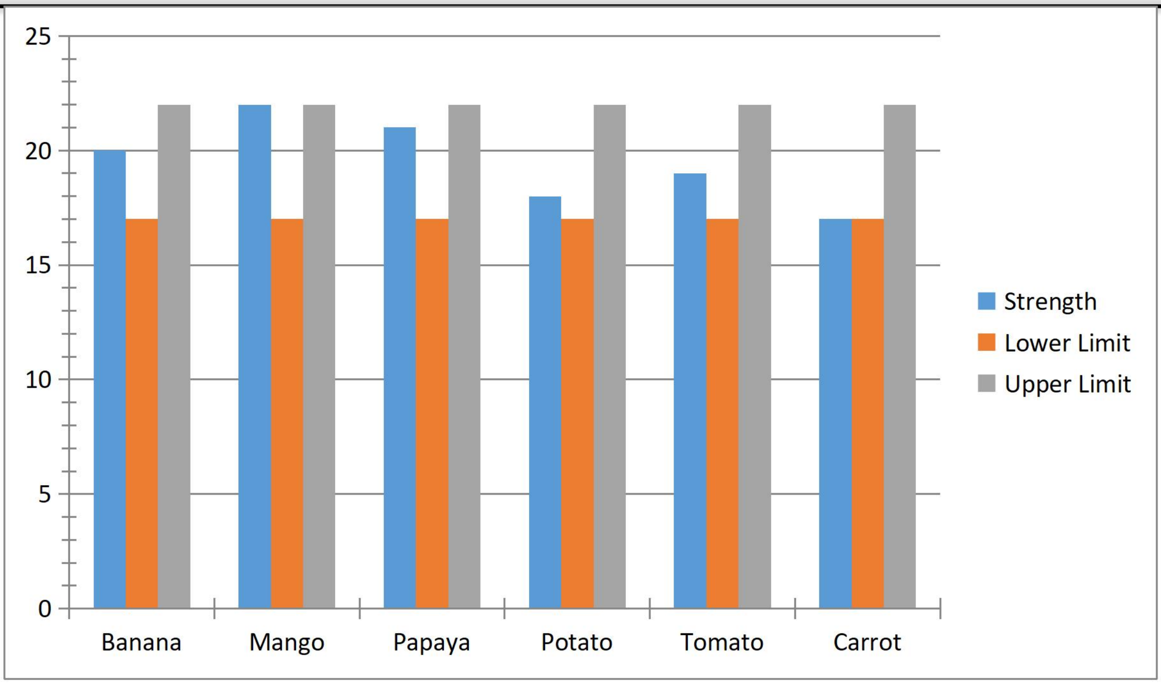

Figure 4: Ethanol strength comparison across different substrates

Table 3: Ethanol Quality Parameters

Sample	pH	Temperature (°C)	Strength (% w/w)	Density (g/cm³)	$KMnO_4$ (min)
Banana	6.1	32	20	0.789	18.2
Mango	6.6	32	22	0.80	16.0
Papaya	6.9	32	21	0.58	17.5
Potato	6.8	32	18	0.789	16.5
Tomato	5.6	32	19	0.88	17.8
Carrot	5.4	32	17	0.79	15.5

4.4 Absorbance Analysis

Absorbance measurements at different wavelengths (220nm, 230nm, 240nm, 270nm) revealed variations in ethanol purity. Most samples showed acceptable absorbance values, with potato and mango exhibiting slightly higher values at specific wavelengths, indicating potential impurities. The absorbance spectra for the samples are presented in Figure 5.

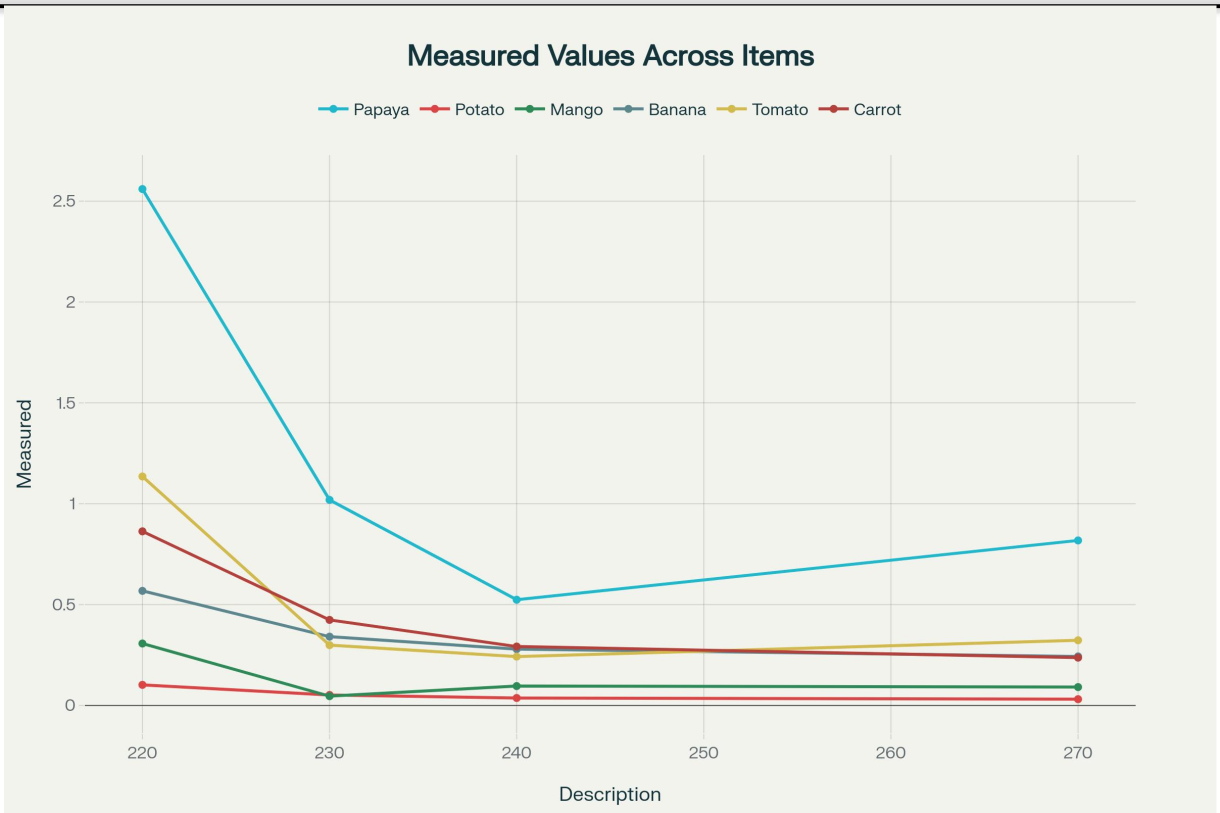

Figure 5: Absorbance spectra of produced ethanol samples

5. Discussion

5.1 Substrate Suitability and Performance

The results demonstrate that fruit and vegetable waste can serve as effective substrates for ethanol production, with fruit peels generally outperforming vegetable waste in terms of sugar content and fermentation efficiency. The higher Brix values observed in fruit peels (18-25) compared to most vegetable waste (4-11.3) correlate with better ethanol yields, supporting the findings of previous studies [5].

The variation in reducing sugar content among samples can be attributed to the inherent chemical composition of different waste materials. Fruit peels, particularly papaya and banana, showed higher reducing sugar content (14.6-14.7%), which is crucial for efficient fermentation processes. The lower values observed in tomato (13.6%) and carrot (12.5%) may be due to their lower sugar content and different carbohydrate composition.

5.2 Ethanol Production Efficiency

The ethanol strength results (17-22% w/w) are within acceptable ranges for biofuel applications, with mango and papaya showing the highest yields. These values are comparable to those reported in similar studies [7, 8], confirming the technical feasibility of the process.

The recovery rates during dehydration varied significantly among samples, with papaya and potato showing the highest recovery (80%), while carrot exhibited the lowest (60%). This variation may be attributed to differences in water content and the efficiency of the dehydration process for different substrates.

5.3 Quality Assessment and Standards Compliance

The produced ethanol met most quality standards, with density values within the acceptable range (0.58-0.88 g/cm^3) and pH levels generally within the standard limits (6-8). The potassium permanganate test results, which indicate ethanol purity, showed that most samples met the standard time requirement (18.5 minutes), with mango, papaya, and potato performing particularly well.

5.4 Economic and Environmental Implications

The successful production of ethanol from fruit and vegetable waste presents significant economic and environmental benefits for Pakistan. This approach addresses the dual challenges of waste management and energy security while providing a sustainable alternative to fossil fuels. The utilization of locally available waste materials reduces import dependency and creates opportunities for rural economic development.

5.5 Limitations and Challenges

Several limitations were identified in this study. The relatively low ethanol strength (17-22%) compared to commercial standards may require further optimization of fermentation conditions or the use of alternative yeast strains. Additionally, the variation in substrate quality and composition presents challenges for consistent production at industrial scales.

6. Conclusion

This study successfully demonstrated the feasibility of producing ethanol from fruit and vegetable waste in Pakistan. The research achieved ethanol production from all six tested waste materials, with fruit peels showing superior performance compared to vegetable waste. The highest ethanol strength was obtained from mango (22%) and papaya (21%), while the process met most quality standards for biofuel applications.

The findings support the potential for large-scale implementation of waste-to-ethanol conversion in Pakistan, offering solutions to both waste management challenges and energy security concerns. The process demonstrates economic viability and environmental benefits, contributing to the country's transition toward renewable energy sources.

Future research should focus on optimizing fermentation conditions, exploring alternative yeast strains, and developing cost-effective processing methods for industrial-scale implementation. The integration of this technology with existing waste management systems could significantly contribute to Pakistan's sustainable development goals.

Acknowledgments

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