



Design and performance optimization of a laboratory scale distiller for high-purity bioethanol production from biomass feedstocks

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Abstract

This study presents the design, fabrication, and performance evaluation of a laboratory-scale packed-column distillation system to produce high-grade hydrous bioethanol from fermented mango (*Mangifera indica*) waste, a locally abundant agricultural residue, using low-cost, locally available materials. The system was engineered as a cost-effective and scalable solution for biomass-based ethanol purification suited to decentralized, small-scale operations. The distillation apparatus incorporates a configurable reflux column utilizing two alternative packing materials steel wool (A1) and Raschig rings (A2) to enhance vapor-liquid contact and improve separation efficiency. Mango waste was collected, prepared, and fermented to produce a crude bioethanol wash, which was then processed at three initial ethanol concentrations (40%, 60%, and 80%, designated B1, B2, and B3, respectively). The two packing materials and three feed concentrations were arranged in a Completely Randomized Design (CRD) in a 2×3 factorial layout, replicated three times (18 experimental runs), and the resulting data were analyzed using two-way ANOVA and linear regression. The results demonstrate that packing material significantly influenced system performance. Raschig rings achieved superior outcomes overall, yielding ethanol purity up to 97.83%, a mean distillation efficiency of 73.37% (compared with 65.45% for steel wool), and a mean ethanol recovery of 41.55% (overall mean across both packing materials: 41.51%). Distillation rates ranged from 2.4 to 3.89 L/h depending on feed concentration and packing configuration. Operational parameters showed a rapid start-up time (5-10 minutes) and efficient thermal performance within a boiling range of 70-83°C. A techno-economic assessment indicates that the system is financially viable for small-scale deployment, with a low capital investment (₱6,500) and a total annual operating cost of ₱51,477 against an annual production capacity of 1,648.8 L, giving a unit production cost of approximately ₱31.22/L. At an assumed selling price of ₱35.00/L, the system generates an estimated annual net income of ₱5,496, a payback period of 1.18 years, and a return on investment of 84.55%. (1 US Dollar = 62 ₱) The study demonstrates the technical and economic feasibility of an optimized packed-column distillation system for purifying mango waste-derived bioethanol, offering a sustainable pathway for decentralized biofuel production and agricultural waste valorization in the Philippines.

Keywords: Mango waste valorization; Bioethanol production; Packed-column distillation; Ethanol recovery; Techno-economic analysis

1. Introduction

The continuous rise in global energy demand, coupled with the depletion of fossil fuel reserves and escalating environmental concerns, has intensified the search for sustainable and renewable energy alternatives. Fossil fuels remain the dominant global energy source; however, their increasing cost, finite availability, and contribution to greenhouse gas emissions make them increasingly unsustainable [1-2]. In the Philippines, this challenge is further exacerbated by the country's heavy dependence on imported petroleum products, making it highly vulnerable to global price fluctuations. Domestic pump prices for gasoline and diesel have risen sharply in recent years, driven in part by geopolitical tensions affecting global oil supply chains. Consequently, key sectors such as transportation, agriculture, and small-scale industries are experiencing substantial economic strain, highlighting the urgency of developing alternative, locally sourced energy solutions.

Bioethanol has emerged as one of the most promising renewable fuel alternatives due to its biodegradability, renewability, and compatibility with existing fuel infrastructure. It is a liquid biofuel produced from various biomass feedstocks, including agricultural residues and organic wastes, through biochemical and thermochemical conversion processes [3]. As an oxygenated fuel, bioethanol promotes more complete combustion, thereby reducing particulate emissions and improving air quality in internal combustion engines

[4], and it has been widely recognized for its potential to reduce net greenhouse gas emissions compared with conventional petroleum fuels [2].

Ethanol has been used as an engine fuel since the earliest internal combustion engines of the late 19th century, and ethanol–gasoline blends are widely used in modern engines without requiring significant modification [5]. Bioethanol also possesses favorable physicochemical properties including a higher-octane number, wider flammability limits, higher flame speed, and greater heat of vaporization than gasoline that enable improved engine performance through higher compression ratios, enhanced combustion efficiency, and reduced knocking [5-6].

In the Philippine context, the abundance of agricultural residues presents a significant opportunity for sustainable bioethanol production. Mango (*Mangifera indica*) waste, in particular, is an underutilized biomass resource generated from fruit-processing activities, including peels, pulp residues, and rejected fruits. These residues are rich in fermentable sugars, making them a suitable feedstock for bioethanol production. Valorizing mango waste in this way not only supports renewable energy generation but also addresses the environmental burden of organic-waste disposal while creating an additional income stream for agricultural communities.

Despite this potential, one of the primary challenges in bioethanol production lies in the efficient and cost-effective purification of ethanol from fermentation mixtures. Distillation remains the most widely employed separation technique; however, conventional distillation systems are often energy-intensive and costly, limiting their applicability in decentralized or small-scale operations [1]. A low-cost, efficient distillation system using locally available materials is therefore essential to enable broader adoption of bioethanol technology, particularly in rural areas.

This study addresses this need through the design, fabrication, and performance evaluation of a laboratory-scale distiller for producing high-grade hydrous bioethanol from fermented mango waste. By optimizing column packing materials and operating conditions, the research aims to improve ethanol recovery, distillation efficiency, and overall system performance while maintaining economic feasibility. Specifically, the study aimed to (1) design and fabricate a laboratory-scale packed-column distillation apparatus suitable for high-purity bioethanol production; (2) evaluate the performance of the developed unit in terms of ethanol recovery, distillation efficiency, and operational parameters under varying feedstock concentrations and packing materials; and (3) conduct a techno-economic assessment of the system to determine its feasibility for small-scale and decentralized bioethanol production. Ultimately, this work contributes to the advancement of sustainable energy technologies that can mitigate the impact of rising fuel prices and enhance energy security in the Philippines.

2. Materials and methods

2.1 Feedstock preparation and fermentation

Mango (*Mangifera indica*) waste consisting of peels, pulp residues, and rejected fruits was collected, washed, and mechanically reduced in size to facilitate extraction of fermentable sugars. The prepared material was mixed with water and inoculated with yeast to initiate fermentation, which was carried out under ambient conditions until the desired ethanol concentration was reached. The resulting crude bioethanol wash was screened and adjusted to three initial ethanol concentrations 40%, 60%, and 80% (v/v) designated B1, B2, and B3, respectively, before being fed into the distillation unit for the performance trials described below.

The following process was done during the conduct of the study:

- Design of the distiller
- Fabrication of the distiller
- Preliminary testing
- Performance testing and data gathering under two different packing materials under three different purity of alcohol
- Analysis of data using analysis of variance and regression analysis.

2.2 Materials and instruments

The following materials and instruments were used in the conduct of the study: Mango (*Mangifera indica*) waste (peels, pulp residues, rejected fruits), yeast inoculum (for fermentation), water, charcoal (furnace fuel), steel wool (packing material, A1), Raschig rings (packing material, A2), hydrometer, thermometer, glass bottle (1,000 mL), timer, and graduated cylinder.

2.3. Experimental design and statistical analysis

The study used a Completely Randomized Design (CRD) in a 2×3 factorial arrangement: two packing materials (A1 = steel wool, A2 = Raschig rings) and three initial ethanol concentrations of the mango-derived feedstock (B1 = 40%, B2 = 60%, B3 = 80%), replicated three (3) times, for a total of 18 experimental runs. The response variables were distillation rate, ethanol recovery, distillation efficiency, alcohol content of distillate, and fuel consumption rate.

The data were subjected to two-way Analysis of Variance (ANOVA) to test the main effects of packing material and feedstock concentration, and their interaction, on each response variable. Where ANOVA indicated a significant effect ($p < 0.05$), means followed by different superscript letters in Tables 1-5 are significantly different at the 5% level. Simple linear regression (least-squares) was used to model distillate volume as a function of distillation time for each packing material (Figures 1 and 2), with goodness of fit reported as the coefficient of determination (R^2).

2.4 Definitions of performance parameters

To allow the results to be reproduced, the performance parameters reported in this study are defined as follows:

Distillation rate (L/h)	= Volume of distillate collected (L) ÷ Total distillation time (h)
Ethanol recovery (%)	= [Volume of ethanol in the distillate ÷ Volume of ethanol in the original feedstock charged to the boiler] × 100
Distillation efficiency (%)	= [Actual ethanol recovered in the distillate ÷ Theoretical ethanol content of the feedstock, based on its initial concentration] × 100
Fuel consumption rate (kg/h)	= Mass of fuel (charcoal) consumed (kg) ÷ Total distillation time (h)
Alcohol content of distillate (%)	= Measured directly with a hydrometer/alcoholmeter, corrected to standard reference temperature

2.5 Methods

Collection and preparation of mango waste feedstock. Fermentation of mango waste to produce crude bioethanol wash. Design of the distiller. Fabrication of the distiller. Preliminary testing. Performance testing and data gathering under two packing materials and three feedstock ethanol concentrations (CRD, 3 replications). Analysis of data using analysis of variance (ANOVA) and regression analysis.

3. Results and discussion

The operational performance of the developed bioethanol distillation unit demonstrated efficient and stable functionality under varying feedstock conditions. The system exhibited a rapid start-up time of 5 to 10 minutes and a total operating duration ranging from 90 to 120 minutes. Boiling of the 3 L feedstock charge, at ethanol concentrations of 40%, 60%, and 80%, began 3 to 5 minutes after start-up, at boiling temperatures ranging from 70°C to 83°C. These values are consistent with the thermodynamic behavior of ethanol-water mixtures, where the presence of ethanol lowers the boiling point of the solution relative to pure water, facilitating earlier vaporization [5]. Other operational parameters coolant flow rate (65.12–172 L/min), distillate volume (700 mL to 2 L), and residual stillage alcohol content (2–5%) indicate effective separation and condensation performance.

3.1 Effect of feedstock concentration on distillation rate

The distillation rate increased with higher ethanol concentration in the feedstock. At 80% ethanol concentration, the highest mean distillation rate, 3.76 L/h, was observed, compared with 3.15 and 3.43 L/h at 40 and 60%, respectively (Table 1). This trend is attributable to the lower boiling point and higher volatility of ethanol relative to water, which enhances vaporization at higher concentrations [6], consistent with Balat et al. [1], who reported that ethanol concentration significantly influences evaporation rate and overall distillation performance.

Table 1 Distillation rate of the bioethanol distiller (L/h)

Packing Material	Distillation rate			
	B1	B2	B3	Mean
A1-Steel wool	2.4	3.37	3.81	3.19 ^a
A2-Raschig rings	3.89	3.49	3.72	3.7 ^b
Mean	3.15 ^x	3.43 ^x	3.76 ^x	3.445

3.2 Influence of packing materials on performance

The type of packing material significantly affected system performance. Raschig rings outperformed steel wool, achieving a higher mean distillation rate (3.70 L/h vs 3.19 L/h) and improved ethanol recovery (41.55% vs 41.47%) (Table 2). This is explained by the larger vapor-liquid contact area and improved mass-transfer efficiency provided by structured packing such as Raschig rings [7]; efficient packing increases the number of theoretical stages within the column and thereby promotes better separation.

Table 2 Ethanol recovery on bioethanol distiller

Packing Material	Ethanol recovery			
	B1	B2	B3	Mean
A1	25 ^k	38.88 ^j	60.55 ⁱ	41.47 ^a
A2	26.11 ^k	42.22 ^j	56.33 ⁱ	41.55 ^b
Mean	51.11 ^z	40.55 ^y	58.44 ^x	41.51

The ethanol recovery was highest at 80% feedstock concentration (58.44% mean), confirming that a higher initial ethanol content improves recovery efficiency. Raschig rings slightly outperformed steel wool overall, although both packing materials showed a broadly similar pattern across concentrations. In terms of distillate quality, the system achieved high ethanol purity, with mean values of 96.44% for steel wool and 97.14% for Raschig rings (Table 3). These values fall within the expected range for hydrous ethanol

distillation and indicate effective separation; Demirbas [3] notes that achieving ethanol purity above 95% through conventional distillation reflects efficient column design and adequate reflux conditions.

Table 3 Alcohol content of distillate on bioethanol distiller

Packing Material	Purity of Ethanol			
	B1	B2	B3	Mean
A1	96.83 ^j	95.5 ^m	97 ^j	96.44 ^b
A2	96.1 ^l	97.5 ⁱ	97.83 ⁱ	97.14 ^a
Mean	96.47 ^y	96.5 ^x	97.415 ^y	96.79

The distillation efficiency was significantly higher for Raschig rings (73.37%) than for steel wool (65.45%) (Table 4). This improvement is attributed to better mass-transfer characteristics and reduced channeling in structured packing. The finding is consistent with established distillation theory, in which column efficiency depends strongly on packing geometry and surface area [7], and suggests that optimizing packing material is critical to improving performance in small-scale distillation units.

Table 4 Distillation efficiency on bioethanol distiller

Packing Material	Distillation efficiency			
	B1	B2	B3	Mean
A1	60.52 ^k	61.81 ^j	74.03 ^j	65.45 ^b
A2	80.17 ⁱ	68.63 ^j	71.33 ^j	73.37 ^a
Mean	70.34 ^x	65.22 ^y	72.68 ^x	69.41

Distillation efficiency was significantly higher when using Raschig rings (73.37%) compared to steel wool (65.45%). This improvement is attributed to better mass transfer characteristics and reduced channeling effects in structured packing materials. The findings align with established distillation theory, where column efficiency is highly dependent on packing geometry and surface area [7]. The results suggest that optimizing packing materials is critical for enhancing system performance in small-scale distillation units.

The result in Table 5 showed that the fuel consumption rate ranged from 3.19 kg/h (steel wool) to 3.7 kg/h (Raschig rings), with no statistically significant difference between treatments. This indicates that packing material has minimal influence on energy consumption, which is primarily governed by furnace efficiency and heat transfer rate. Increased heat input accelerates vaporization, leading to higher distillation rates, as supported by thermodynamic principles of phase change [6].

Table 5 Fuel (Charcoal) consumption rate (kg/h)

Packing Material	Fuel (Charcoal) consumption rate			
	B1	B2	B3	Mean
A1	2.95	3.20	3.42	3.19 ^a
A2	3.40	3.65	4.05	3.7 ^a
Mean	3.18	3.43	3.74	3.44

The effect of the fuel consumption rate is depends to the capacity of the furnace to produce heat. The more heat the faster is the vaporization of feedstock. Fast vaporization provides higher amount of vapor which is then condensed at the condenser.

The bioethanol production was collected by every 250 ml on the distiller. The graphical representation showed in Figure 1. Is the bioethanol production by using steel wool as the packing material on the reflux column with respect to the distillation time.

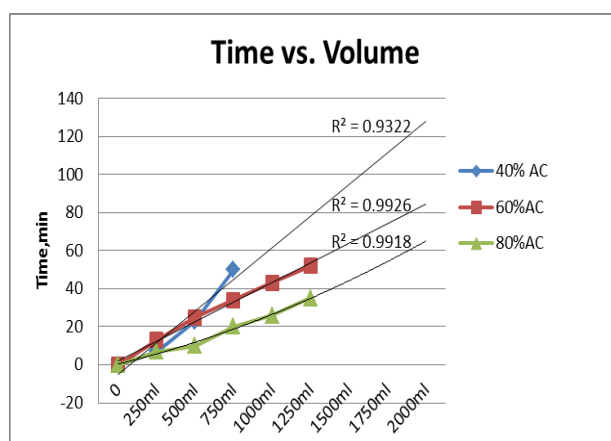


Figure 1 Regression of bioethanol distillate volume vs. distillation time - steel wool packing (A1). Data points correspond to feedstock ethanol concentrations of 40%, 60%, and 80% (v/v)

As expected, the distillate volume increases with distillation time for all three feed concentrations, and the rate of increase (slope) is higher for feedstocks with greater initial alcohol content, since a higher-alcohol feed vaporizes more readily and sustains a higher distillate output over the same period. In Figure 2 shows the corresponding regression for the Raschig-rings configuration.

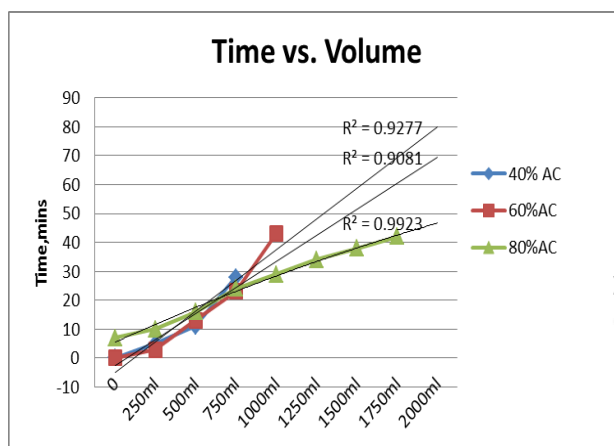


Figure 2 Regression of bioethanol distillate volume vs. distillation time - Raschig rings packing (A2). Data points correspond to feedstock ethanol concentrations of 40%, 60%, and 80% (v/v)

3.3 Techno-economic analysis

The costs incurred in operating the CBED and RHG is presented in Table 6. After the computations the cost involved are investment cost of ₱6500, total cost of ₱51,477 and production cost of ₱35/ L. The net income that could be obtained is from ₱5,496 each year of producing high grade hydrous bioethanol of using the unit. Payback period is within 1.18 y and return on investment of 84.55%. (1 US Dollar = 62 ₱)

Table 6 Techno-economic analysis of the bioethanol distillation unit

Cost Item	Amount (₱)	Basis
Investment Cost (IC)	6,500	One-time
Material cost (MC)	6,000	
Labor cost (fabrication, LC)	500	
Fixed Cost (FC), per year	3,055	Per year
Depreciation (D)	1,170	
Interest on investment (IOI)	195	
Insurance (I)	1,690	
Variable Cost (VC), per year	48,617	Per year
Fuel cost (fC)	1,715	
Repair & maintenance (R&M)	195	
Labor cost, operation (LC)	20,000	
Water cost (WC)	26,707	
Total Cost (TC = FC + VC)	51,477	Per year
Annual Capacity (C)	1,648.8 L/yr	
Unit Production Cost (TC ÷ C)	₱31.22 /L	
Assumed Selling Price	₱35.00 /L	Estimated
Annual Net Income	5,496	
Payback Period	1.18 years	
Return on Investment (ROI)	84.55%	

IC – Investment cost; MC – Material cost; LC – Labor cost; FC – Fixed cost (Php/yr); D – Depreciation; IOI – Interest on investment; I – Insurance; VC – Variable cost (Php/yr); fC – Fuel cost; R&M – Repair and maintenance; WC – Water cost; C – Capacity (L/yr). (1 US Dollar = 62 ₱)

4. Conclusions

This research study demonstrated the design, fabrication, and performance evaluation of a laboratory-scale packed-column distillation system for producing high-grade hydrous bioethanol from fermented mango (*Mangifera indica*) waste using locally available materials. The developed distiller exhibited stable and efficient operation, confirming its applicability as a low-cost, scalable solution for biomass-based ethanol purification. The distillation rate was directly influenced by both the volume and ethanol concentration of the feedstock, with higher concentrations facilitating faster vaporization and greater distillate yield. System performance particularly ethanol recovery and distillation efficiency were strongly dependent on the packing material used: Raschig rings significantly enhanced vapor–liquid interaction relative to steel wool, resulting in higher ethanol purity (up to 97.83%), improved recovery, and greater overall efficiency.

From an economic perspective, the system proved financially viable for small-scale deployment, requiring a relatively low capital investment (₱6,500) and yielding a unit production cost of approximately ₱31.22/L at an assumed selling price of ₱35.00/L (1 US Dollar = 62 ₱). The resulting payback period of 1.18 years and return on investment of 84.55% indicate strong potential for adoption

in decentralized, rural bioethanol production. Because mango waste was the actual feedstock tested in this study, the developed distillation technology has been demonstrated, rather than merely proposed, as a viable route for valorizing this specific agricultural residue; its extension to other biomass feedstocks (e.g., pineapple, banana, or onion waste) remains a direction for future work rather than a claim of this study.

5. Recommendations and future directions

Based on the findings of this study, the following recommendations and future research directions are proposed:

1. Future work should focus on scaling up the distillation system to pilot- and community-level applications, specifically targeting mango waste as the primary feedstock. Given the abundance of mango-processing residues in the Philippines, larger-scale integration can significantly enhance bioethanol production while addressing agricultural waste management challenges.

2. The system should be further optimized for co-processing of mango waste with other high-value agricultural residues, such as pineapple peels, banana waste, sugarcane bagasse, and onion (*Allium cepa*) waste, which is currently under ongoing investigation. Onion waste, generated in significant quantities from food processing and market discard, contains fermentable carbohydrates that can be utilized for bioethanol production. Co-fermentation and co-distillation of these biomass sources can enhance substrate diversity, improve fermentable-sugar availability, and increase overall ethanol yield, while also providing a more stable, year-round supply of raw material and reducing seasonal dependency.

3. The use of Raschig rings is recommended given their superior performance in achieving high ethanol purity and efficiency; further studies may explore advanced or hybrid packing materials to maximize mass-transfer efficiency and reduce energy requirements.

4. A comprehensive life-cycle assessment (LCA) and techno-economic analysis should be conducted for large-scale implementation to evaluate environmental benefits, carbon-reduction potential, and long-term economic sustainability.

Future studies should also focus on optimizing pretreatment methods, fermentation efficiency, and distillation performance for mixed-feedstock systems, particularly evaluating the synergistic effects of mango and onion waste on sugar-conversion efficiency and ethanol recovery. To improve productivity and thermal efficiency, the use of continuous-type furnaces, biomass gasifiers, or electric heating systems is recommended, as these can provide a stable heat source, reduce fuel-consumption variability, and enhance overall system performance.

6. References

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