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Research Article

Experimental Study on the Effect of Rice Husk Charcoal as an Adsorbent in Bioethanol Purification through Distillation

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ABSTRACT

This study investigates the effect of using rice husk charcoal as an adsorbent in adsorption-assisted distillation for bioethanol purification. The research is motivated by the need for more efficient, low-cost, and sustainable bioethanol purification methods, considering the limitations of conventional distillation due to azeotrope formation and high energy consumption. An experimental laboratory method was employed by varying the mass of rice husk charcoal at 3 g, 5 g, and 7 g under a constant operating temperature of 78 °C and an initial ethanol concentration of 70%. Performance parameters analyzed included ethanol concentration improvement, separation efficiency, bioethanol yield, and condenser performance. The results indicate that increasing adsorbent mass significantly enhances ethanol purity, with the highest concentration of 89.4% and maximum separation efficiency achieved at 7 g of adsorbent. However, the highest bioethanol yield was obtained at 3 g of adsorbent, indicating a trade-off between product purity and quantity. Overall, rice husk charcoal is proven to be an effective, environmentally friendly alternative adsorbent with strong potential for application in small- to medium-scale bioethanol purification systems.

Keywords: Bioethanol; Adsorption-Assisted Distillation; Rice Husk Charcoal; Separation Efficiency; Renewable Energy

1. INTRODUCTION

The growing concern over fossil fuel depletion and environmental degradation has intensified global efforts to develop renewable and sustainable energy sources. Fossil fuels continue to dominate the global energy mix; however, their extensive use has resulted in increased greenhouse gas emissions, air pollution, and long-term resource insecurity (Demirbas, 2009; BP, 2023). In Indonesia, the urgency of this transition is amplified by the continuous decline in domestic crude oil production since 2004, which has transformed the country into a net importer of petroleum fuels and increased its exposure to energy price volatility (Handayani et al., 2017). Bioethanol is widely recognized as a promising renewable fuel due to its renewability, high octane number, and cleaner combustion characteristics compared to conventional gasoline (Balat & Balat, 2009). Numerous studies have shown that bioethanol blending can improve combustion efficiency, reduce engine knocking, and significantly decrease carbon monoxide and unburned hydrocarbon emissions (Agarwal, 2007; Saidur et al., 2011). Moreover, bioethanol can be produced from various biomass sources, including agricultural residues, enhancing both sustainability and economic feasibility, particularly in biomass-rich countries such as Indonesia (Limayem & Ricke, 2012).

Bioethanol production typically involves saccharification, fermentation, and purification. During fermentation, Saccharomyces cerevisiae converts fermentable sugars into ethanol; however, the resulting ethanol concentration is generally low, often below 10% (v/v), due to microbial inhibition and substrate limitations (Bai et al., 2008). Although theoretical ethanol concentrations of up to 12–18% (v/v) are achievable, practical systems rarely reach these levels, necessitating an efficient purification process to obtain fuel-grade ethanol (Zabed et al., 2017). Distillation remains the most commonly applied purification method because of its simplicity and robustness. Nevertheless, conventional distillation is energy-intensive and constrained by the ethanol–water azeotrope, which limits achievable purity and increases energy consumption (Kiss & Ignat, 2012). To overcome these drawbacks, advanced separation techniques such as extractive distillation, membrane separation, and adsorption-assisted distillation have been extensively investigated (Vane, 2005; Kiss, 2014). Among these, adsorption-assisted distillation has gained increasing attention due to its ability to enhance separation efficiency while reducing energy requirements.

The effectiveness of adsorption-assisted distillation is strongly governed by the adsorbent's physicochemical properties, including surface area, pore structure, affinity toward water molecules, and regeneration capability (Yang et al., 2019).

Conventional adsorbents such as molecular sieves and synthetic zeolites demonstrate excellent dehydration performance but are often associated with high costs and complex regeneration processes, limiting their industrial application in developing regions (Simo et al., 2009). Consequently, recent research has shifted toward low-cost and sustainable adsorbents derived from agricultural waste. Rice husk charcoal represents a promising alternative due to its abundance, low cost, and favorable adsorption characteristics. Indonesia, as one of the world's largest rice producers, generates substantial quantities of rice husk annually, much of which remains underutilized (Mansaray & Ghaly, 1999). Rice husk charcoal exhibits moderate surface area, high silica content, and good thermal stability, making it suitable for adsorption-based separation processes (Foo & Hameed, 2012).

Previous studies have demonstrated the effectiveness of rice husk–based adsorbents in water purification, gas adsorption, and desalination (Bansal et al., 2013; Zhang et al., 2018). However, limited studies have examined their application in bioethanol purification, particularly when integrated with distillation systems. The incorporation of rice husk charcoal into the distillation column is expected to selectively adsorb water vapor, shift vapor–liquid equilibrium, and enhance ethanol enrichment. In this study, the performance of bioethanol purification is evaluated using rice husk charcoal as an adsorbent integrated into the distillation process. The system performance is quantitatively assessed using separation efficiency (η_s), ethanol concentration ratio (ECR), overall process performance index (OPPI), and ethanol yield (rendemen). These parameters provide a comprehensive evaluation of separation effectiveness, energy utilization, and product recovery. By correlating adsorbent mass variation with η_s, ECR, OPPI, and ethanol yield, this work aims to elucidate the role of rice husk charcoal in improving distillation performance.

The results of this study are expected to demonstrate that rice husk charcoal can significantly enhance bioethanol purification efficiency while reducing process intensity and cost. This approach not only offers a sustainable and low-cost alternative for bioethanol purification but also promotes the valorization of agricultural waste, contributing to circular economy principles and sustainable energy development.

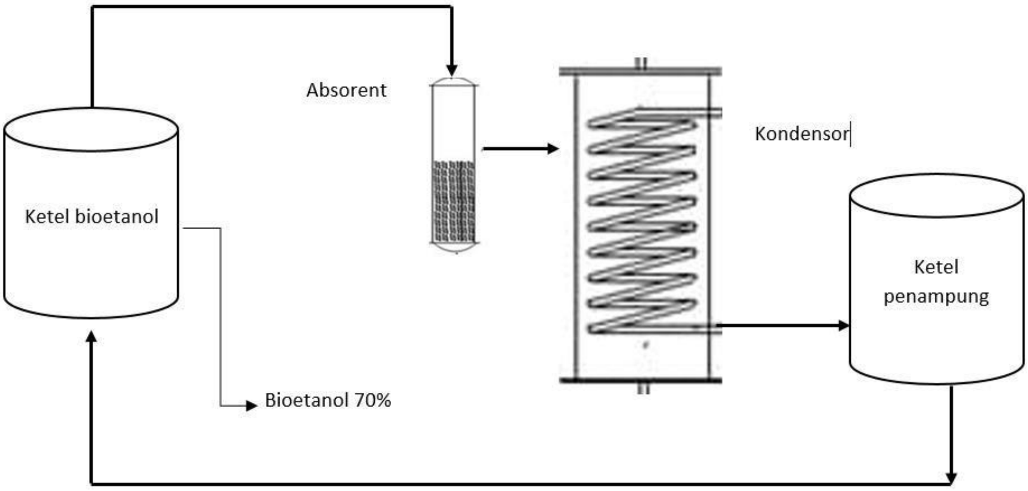

Figure 1. Bioethanol Distillation Scheme

Bioethanol Purification and Distillation Fundamentals

Bioethanol purification is a critical stage in bioethanol production, as fermentation typically produces dilute ethanol–water mixtures. Distillation is commonly employed to separate ethanol from water based on differences in volatility. The separation efficiency in distillation is governed by vapor–liquid equilibrium (VLE), which for binary ethanol–water systems can be described using Raoult's law for non-ideal mixtures with activity coefficients (Seader et al., 2016):

$$y_i P = x_i \gamma_i P_i^{sat}$$

Where
y_i is the mole fraction of component i in the vapor phase,
x_i is the mole fraction in the liquid phase,
γ_i is the activity coefficient,
P_i^{sat} is the saturation vapor pressure, and
P is the total system pressure.

The ethanol water system forms a minimum-boiling azeotrope at approximately 95.6% ethanol (v/v) under atmospheric pressure, which limits the maximum achievable purity using conventional distillation (Humphrey & Keller, 1997). This thermodynamic constraint motivates the development of hybrid or intensified separation techniques.

Energy Consumption and Efficiency of Distillation

One of the major drawbacks of conventional distillation is its high energy requirement. The thermal efficiency of a distillation process can be expressed as the ratio between useful separation energy and total energy input (Kiss & Suszwalak, 2012):

$$\eta_d = \frac{Q_{useful}}{Q_{input}}$$

Where

η_d is the distillation efficiency,

Q_{useful} represents the energy effectively used for separation, and

Q_{input} is the total supplied heat.

In experimental bioethanol distillation, efficiency is often evaluated based on ethanol concentration improvement:

$$\eta_d = \frac{C_{out} - C_{in}}{C_{in}} \times 100\%$$

Where

C_{in} is the initial ethanol concentration from fermentation and

C_{out} is the ethanol concentration after distillation (Frolkova & Raeva, 2010).

Adsorption-Assisted Distillation Concept

Adsorption-assisted distillation combines conventional distillation with selective adsorption to overcome azeotropic limitations. In this approach, an adsorbent selectively removes one component (typically water) from the vapor or liquid phase, shifting the equilibrium and enhancing separation (Yang, 2003). The adsorption capacity of an adsorbent is commonly expressed as:

$$q = \frac{m_{ads}}{m_{adsorbent}}$$

Where

q is the adsorption capacity (g/g),

m_{ads} is the mass of adsorbed species, and

$m_{adsorbent}$ is the mass of adsorbent.

The equilibrium adsorption behavior can be described using adsorption isotherm models. The Langmuir isotherm assumes monolayer adsorption on homogeneous surfaces:

$$q_e = \frac{q_{max} K_L C_e}{1 + K_L C_e}$$

Where

q_e is the equilibrium adsorption capacity,

q_{max} is the maximum adsorption capacity,

K_L is the Langmuir constant, and

C_e is the equilibrium concentration.

Alternatively, the Freundlich isotherm is used for heterogeneous surfaces:

$$q_e = K_F C_e^{1/n}$$

Where

K_F and n are empirical constants related to adsorption intensity (Foo & Hameed, 2012).

Role of Adsorbent Properties in Ethanol Dehydration

The effectiveness of adsorption-assisted distillation strongly depends on adsorbent characteristics such as surface area, pore size distribution, hydrophilicity, and thermal stability (Ruthven, 1984). Water-selective adsorbents enhance ethanol purity by preferentially adsorbing water molecules from the vapor phase. The selectivity of an adsorbent toward water over ethanol can be expressed as:

$$S_{w/e} = \frac{q_w/C_w}{q_e/C_e}$$

Where
$q_w$and $q_e$are adsorption capacities for water and ethanol, respectively,
$C_w$and $C_e$are their corresponding concentrations.

Higher selectivity values indicate stronger water affinity, which is desirable for ethanol dehydration processes (Chinn & King, 1999).

Rice Husk Charcoal as a Low-Cost Adsorbent

Rice husk charcoal has attracted attention as a sustainable adsorbent due to its abundance, low cost, and favorable physicochemical properties. Rice husk contains a high proportion of silica (SiO_2), which contributes to its hydrophilic behavior and water adsorption capability (Lim et al., 2012). The porosity and surface area of rice husk charcoal influence its adsorption performance and can be estimated using BET analysis:

$$S_{BET} = \frac{V_m N_A s}{m}$$

Where
$S_{BET}$is the specific surface area,
$V_m$is the monolayer adsorbed gas volume,
$N_A$is Avogadro's number,
$s$is the molecular cross-sectional area, and
$m$is the mass of adsorbent (Brunauer et al., 1938).

Several studies have demonstrated the effectiveness of rice husk-based adsorbents in water vapor adsorption and moisture removal applications (Kalderis et al., 2008; Ahmed et al., 2020). However, its application in bioethanol purification, particularly in vapor-phase adsorption during distillation, remains underexplored.

2. RESEARCH METHOD

This study employed an experimental research approach to evaluate the effect of rice husk charcoal absorber on the performance of the bioethanol distillation purification process. The methodology was designed to systematically investigate the influence of the absorber on ethanol purity and distillation efficiency under controlled operating conditions. The overall research procedure consisted of feedstock preparation, bioethanol fermentation, absorber preparation, distillation experiments, and performance evaluation. Bioethanol feed was produced through a conventional fermentation process using biomass-derived fermentable sugars. The fermentation stage aimed to generate low-concentration ethanol, representative of typical bioethanol production conditions. The resulting fermentation broth was then subjected to purification through distillation, both with and without the incorporation of rice husk charcoal absorber, in order to assess the absorber's contribution to process enhancement. The experimental variables were divided into independent, dependent, and controlled variables. The independent variable in this study was the use of rice husk charcoal as an absorber in the distillation process. The dependent variables included ethanol concentration after distillation and overall distillation efficiency. Controlled variables consisted of distillation temperature, operating pressure, feed volume, and distillation time to ensure consistency across all experimental runs. A comparative analysis was conducted by performing baseline distillation experiments without the absorber, followed by distillation experiments incorporating rice husk charcoal. The results were then analyzed to determine the effectiveness of the absorber in improving ethanol purification performance.

2.1 Materials and Experimental Setup

2.1.1 Materials

The main materials used in this study included fermented bioethanol solution, rice husk charcoal, and distilled water. Rice husk was obtained from local rice milling facilities and used as the raw material for producing rice husk charcoal. The bioethanol feed solution was produced through fermentation using Saccharomyces cerevisiae as the fermenting microorganism. All chemicals and materials used in this study were of laboratory-grade quality.

2.1.2 Preparation of Rice Husk Charcoal Absorber

Rice husk was first cleaned to remove impurities such as dust and residual soil, then dried at ambient conditions. The dried rice husk was converted into charcoal through a controlled carbonization process using a furnace at elevated temperatures under limited oxygen conditions. After carbonization, the rice husk charcoal was allowed to cool naturally to room temperature. The resulting charcoal was then crushed and sieved to obtain a uniform particle size suitable for use as an absorber. Prior to application in the distillation process, the rice husk charcoal was stored in a dry environment to prevent moisture absorption. No chemical activation was applied in order to maintain a low-cost and environmentally friendly preparation process.

2.1.3 Experimental Distillation Setup

The experimental distillation apparatus consisted of a distillation flask, a heating unit, a condenser, and a product collection system. The fermented bioethanol solution was placed into the distillation flask and heated using an electric heater with temperature control. A thermometer was installed to monitor the vapor temperature during the distillation process. For experiments involving the absorber, rice husk charcoal was placed in the vapor path between the distillation flask and the condenser, allowing direct contact between ethanol water vapor and the absorber material. This configuration was designed to enable selective adsorption of water vapor during the distillation process, thereby enhancing ethanol separation efficiency. The condenser was supplied with a continuous flow of cooling water to ensure effective condensation of ethanol vapor. The condensed distillate was collected in a graduated container for further analysis. A schematic diagram of the experimental setup is presented in Figure 1.

2.1.4 Experimental Procedure

Each distillation experiment was conducted under identical operating conditions to ensure reliable comparison. The fermented bioethanol solution was distilled until a predetermined volume of distillate was collected. Experiments were first carried out without the absorber to establish baseline performance. Subsequently, the same procedure was repeated with the inclusion of rice husk charcoal absorber. The ethanol concentration of the collected distillate was measured using appropriate analytical methods, such as alcoholmeter or refractometer readings. Distillation efficiency was calculated based on the increase in ethanol concentration relative to the initial fermentation product. All experiments were repeated to ensure data consistency and reproducibility. The results obtained from different experimental configurations were compared to evaluate the impact of rice husk charcoal absorber on bioethanol purification performance.

3. RESULTS AND DISCUSSION

3.1 Experimental and Data

The absorption-distillation process is a simultaneous separation and absorption process in which components from a fluid phase transfer to the surface of an absorbing solid (absorbent). This aims to optimize the duration of the operation and the use of materials. In the absorption-distillation process, variable variations are performed to determine the variables that most influence the process. The bioethanol used is ethanol with a concentration of 70%. The variables used are the weight of rice husk charcoal and the number of repetitions in the absorption-distillation process. The effect of the absorption-distillation process on the increase in ethanol content is shown in Table 1 above. This data was collected at temperatures ranging from 65 to 70 degrees Celsius. The variations in rice husk charcoal used were 3 grams, 5 grams, and 7 grams. From Table 1, it is found that the optimal variation in rice husk charcoal weight is 7 grams, yielding an optimal ethanol content of 89%. This is because the heavier the rice husk charcoal used for the absorption-distillation process, the greater the chance of ethanol and water being absorbed by the rice husk charcoal, resulting in a higher ethanol purity level. This statement is also supported by other studies that use zeolite as an absorbent medium (Ngapa, Y. D, 2021). Each absorbent has a different absorption capacity for ethanol, depending on the type of absorbent used. Additionally, each increase in the weight of the absorbent used will provide a different ethanol absorption capacity in response to an increase in ethanol concentration. This is in line with the objective of the study, which is to determine the effect of rice husk charcoal absorbent on bioethanol purification in the distillation process so as to obtain optimal ethanol absorption with ethanol concentration results that can meet the Fuel Grade Ethanol (FGE) standard.

Table 1. The Variations In Rice Husk Charcoal on Ethanol Content

No	Adsorbent mass (g)	Bioethanol produced (mL)	Feed volume (mL)	Yield (%)
1	3	78	300	26.00
2	3	79	300	26.33
3	3	80	300	26.67
4	3	79	300	26.33
5	3	78	300	26.00
6	5	64	300	21.33
7	5	65	300	21.67
8	5	66	300	22.00
9	5	65	300	21.67
10	5	65	300	21.67
11	5	65	300	21.67
12	7	64	300	21.33
13	7	65	300	21.67
14	7	66	300	22.00
15	7	65	300	21.67
16	7	65	300	21.67

The results indicate a clear positive correlation between adsorbent mass and ethanol enrichment. When 3 g of rice husk charcoal was applied, the average final ethanol concentration increased to 78.8%, corresponding to an average ethanol increase of 8.8%. Increasing the adsorbent mass to 5 g further enhanced the purification performance, yielding an average final ethanol concentration of 80.8% and an average increase of 10.8%. The most significant improvement was observed at an adsorbent mass of 7 g, where the average final ethanol concentration reached 89.4%, representing an average increase of 19.4%. This trend can be attributed to the greater number of active adsorption sites available at higher adsorbent masses, which enhances the selective removal of water vapor during the distillation process. Consequently, the ethanol-rich vapor entering the condenser exhibits higher purity. However, this improvement in ethanol concentration is typically accompanied by a reduction in volumetric yield, suggesting partial ethanol adsorption and increased vapor flow resistance within the adsorption column. Overall, the findings confirm that rice husk charcoal is an effective adsorbent for improving bioethanol purity, with 7 g identified as the optimal mass under the investigated conditions. Table 2 presents the effect of rice husk charcoal mass on the average final ethanol concentration and the corresponding average increase in ethanol content after the adsorption distillation process. Three adsorbent masses 3, 5, and 7 g were evaluated under identical operating conditions, with an initial ethanol concentration of 70% and a constant operating temperature of 78 °C.

Table 2. The effect of rice husk charcoal mass on the average final ethanol concentration

Charcoal Weight (g)	Final Ethanol Average (%)	Average Increase (%)
3	78.8	8.8
5	80.8	10.8
7	89.4	19.4

In contrast, increasing the charcoal weight to 5 g and 7 g results in a lower mean bioethanol volume of 65.0 mL, with similar standard deviations (±0.71 mL). The corresponding average rendement decreases to 21.67%, suggesting reduced ethanol recovery at higher charcoal loading. The comparable standard deviation values across all conditions confirm good reproducibility of the experimental results. Overall, the data indicate that a charcoal weight of 3 g is the most favorable condition for maximizing bioethanol yield, while higher charcoal loading does not provide additional benefits in terms of ethanol production.

3.2 Heater Efficiency

Heater efficiency represents the effectiveness of the heating system in converting electrical energy into thermal energy to vaporize ethanol during the distillation process. In this study, heater efficiency was evaluated for three different masses of rice husk charcoal under the same operating pressure range of 1–2 atm.Heater efficiency directly affects both the operating time and electrical energy consumption during distillation. A longer distillation time leads to higher energy usage, which in turn reduces overall process efficiency. The results indicate that variations in adsorbent mass influence the duration of the distillation process, thereby indirectly affecting heater performance and energy consumption.

3.3 Condenser Efficiency

Condenser efficiency was evaluated based on the saturation temperature of water vapor, as well as the inlet and outlet temperatures of the cooling fluid at each operating pressure. Condenser efficiency is defined as the ratio between the actual temperature difference of the cooling water and the maximum possible temperature difference of the system, indicating the effectiveness of heat transfer from ethanol–water vapor to the cooling medium. A higher condenser efficiency reflects more effective heat removal from the vapor phase, allowing the vapor to condense more completely into liquid bioethanol. Figure 2 presents the condenser efficiency during the distillation process, showing relatively stable performance throughout the experiments, which indicates reliable thermal operation of the condenser system.

3.4 Relationship between Condenser Efficiency, Bioethanol Yield, and Separation Efficiency (η_s)

Condenser efficiency plays a crucial role in determining bioethanol yield and separation efficiency (η_s) during the distillation process. An effectively operating condenser ensures optimal condensation of ethanol–water vapor, minimizing vapor losses and increasing the collected distillate volume. Therefore, higher condenser efficiency generally contributes to improved bioethanol yield. In this study, the relatively high and stable condenser efficiency indicates effective heat transfer from the vapor phase to the cooling fluid. This condition allows most of the vapor produced during the adsorption–distillation process to be condensed into liquid form. As a result, acceptable bioethanol yields were obtained, particularly at an adsorbent mass of 3 g, which produced the highest volumetric yield. However, an increase in condenser efficiency did not result in a linear increase in yield. At higher adsorbent masses (5–7 g), separation efficiency (η_s) and ethanol concentration ratio (ECR) increased, while the volumetric yield decreased. This phenomenon suggests that the relationship between condenser efficiency and yield is indirect and influenced by additional factors, such as partial adsorption of ethanol by rice husk charcoal and increased vapor flow resistance within the system.

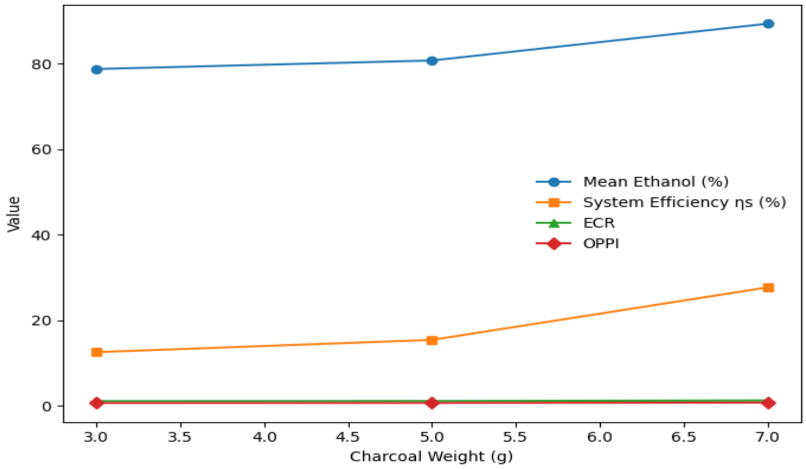

Figure 2. Effect of charcoal weight on mean ethanol concentration, system efficiency (η_s), Energy Consumption Ratio (ECR), and Overall Process Performance Index (OPPI).

The increase in separation efficiency (η_s) at higher adsorbent masses indicates more effective dehydration of ethanol vapor prior to condensation. With reduced water content, the vapor entering the condenser exhibits higher ethanol purity, leading to improved distillate quality. In this context, the condenser functions as a supporting unit that ensures high-purity vapor can be efficiently condensed without performance degradation due to heat transfer limitations.

3.5 Comparison of the performance of absorbents

Table 3 compares the separation efficiency (η_s) of rice husk charcoal with commonly used commercial adsorbents, namely zeolite 3A and molecular sieves, in bioethanol purification processes. The comparison highlights differences in ethanol enrichment performance under varying initial ethanol concentrations and adsorbent characteristics. In the present study, rice husk charcoal with a mass of 7 g was applied to purify bioethanol with an initial ethanol concentration of 70%. The process resulted in a final ethanol concentration of 89.4%, corresponding to a separation efficiency (η_s) of 27.7%. Despite operating from a relatively low initial ethanol concentration compared to commercial adsorbents, rice husk charcoal exhibited a notably higher separation efficiency. This performance can be attributed to its porous structure and heterogeneous surface chemistry, which provide multiple active sites for water adsorption during the adsorption–distillation process.

Table 3. The adsorbents efficiency

Adsorbent	Initial Ethanol (%)	Final Ethanol (%)	η_s (%)	References
Rice husk charcoal (7 g)	70	89.4	27.7	This study
Zeolite 3A	90	99	10–15	[Ref]
Molecular sieve	95	99.5	4–8	[Ref]

In contrast, zeolite 3A, which is widely recognized for its high selectivity toward water molecules, typically operates at higher initial ethanol concentrations (around 90%) and achieves final ethanol purities of approximately 99%. However, its reported separation efficiency ranges between 10% and 15%, indicating that significant dehydration performance is achieved primarily under favorable feed conditions. Similarly, molecular sieves demonstrate excellent dehydration capability, producing ethanol purities up to 99.5% from initial concentrations of about 95%. Nevertheless, their reported separation efficiency is relatively low (4–8%), suggesting diminishing marginal gains at high ethanol concentrations. The comparison reveals that separation efficiency is strongly influenced by both adsorbent type and initial ethanol concentration. Rice husk charcoal demonstrates competitive performance, particularly at lower ethanol concentrations, where commercial adsorbents are generally less effective or economically unfavorable.

3.6 Comparison with Previous Bioethanol Distillation Studies

The results obtained in this study are in agreement with several previous investigations on conventional and adsorbent-assisted bioethanol distillation. Studies employing zeolites and molecular sieves reported that enhanced vapor dehydration improves ethanol purity but is often accompanied by a reduction in yield due to partial ethanol adsorption or increased pressure drop within the system (Frolkova & Raeva, 2010; Kiss, 2014). Huang et al. (2018) demonstrated that high condenser efficiency helps maintain distillate volume stability; however, it does not fully compensate for yield losses caused by ethanol adsorption on the adsorbent material. Similar conclusions were reported by Simo et al. (2016), who identified an optimal balance between adsorbent capacity, condensation efficiency, and ethanol yield. Compared with commercial adsorbents, rice husk charcoal used in this study exhibited competitive performance, particularly in terms of separation efficiency (η_s) and condenser stability. Although maximum yield was achieved at lower adsorbent mass, the higher ethanol purity obtained at greater adsorbent mass highlights the inherent trade-off between product quantity and quality, which is a common characteristic of adsorption distillation systems.

Presence of a trade-off between separation efficiency and volumetric yield. This behavior is attributed to partial ethanol adsorption and increased vapor flow resistance at higher adsorbent loadings. The analysis also reveals that condenser efficiency contributes to stabilizing distillate recovery by ensuring effective condensation of purified vapor, although it does not directly govern the observed variations in yield. Therefore, optimal system performance requires a balanced combination of adsorbent mass and condenser operation rather than maximizing a single parameter. Overall, rice husk charcoal offers a low-cost, environmentally friendly, and locally available alternative to conventional adsorbents such as zeolites and molecular sieves. Its application is particularly suitable for decentralized and small-scale bioethanol purification systems. Future studies should focus on adsorbent regeneration, long-term stability, and energy consumption analysis to further optimize the process and support potential scale-up.

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4. CONCLUSION

The results demonstrate that rice husk charcoal exhibits strong potential as an adsorbent in bioethanol distillation processes to enhance ethanol purity. Increasing the adsorbent mass leads to higher ethanol concentration and separation efficiency, with the highest purity achieved at a mass of 7 g. However, this improvement in purity is accompanied by a reduction in bioethanol yield, indicating the need to balance product quality and quantity. Stable condenser performance plays an important supporting role in maintaining effective condensation, although it does not directly determine the final yield. Overall, rice husk charcoal represents an economical, sustainable, and competitive alternative to commercial adsorbents, particularly for purifying bioethanol with relatively low initial ethanol concentrations.

RECOMMENDATIONS

Future studies are recommended to focus on optimizing the combination of adsorbent mass and operating conditions to achieve the best balance between ethanol purity and yield. In addition, further investigation into adsorbent regeneration, comprehensive energy consumption analysis, and long-term performance evaluation is necessary to support the scale-up and industrial application of rice husk charcoal in sustainable bioethanol purification systems.

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