

The Distillation Imperative in Bioethanol Production: A Review of Technologies, Energy Challenges, and Future Directions for Waste Valorization

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ABSTRACT

The distillation of ethanol is a crucial and energy-demanding process in the bioethanol production chain, significantly affecting the fuel's quality, economic feasibility, and environmental impact. This paper thoroughly analyses the technology environment, energy problems, and future trajectories of distillation in waste-based biorefineries. It elucidates the essential concepts of vapor-liquid equilibrium and the complication posed by the ethanol-water azeotrope, which constrains traditional distillation to about 95.6% purity. This study offers a comparative review of sophisticated separation methods, such as azeotropic distillation and extractive distillation, assessing their effectiveness, energy consumption, and operational complexity in producing fuel-grade ethanol (>99.5%). The study consolidates essential design factors for enhancing distillation systems, including thermodynamic efficiency via heat integration, column configuration, material selection for corrosion resistance, and sophisticated process control. The research indicates that while distillation is crucial to bioethanol purification, its sustainability depends on the incorporation of energy-efficient designs, waste valorisation techniques, and the use of innovative separation media such as ionic liquids. Future initiatives should prioritise process intensification and the synergistic integration of distillation with upstream and downstream activities to improve the overall sustainability of bioethanol production from agricultural waste.

KEYWORD(S): Process Intensification; Waste Valorization; Energy Efficiency; Distillation; Bioethanol.

I. INTRODUCTION

Bioethanol production is a multi-stage biochemical and thermochemical process that transforms biomass into a high-purity liquid fuel suitable for energy applications. The first critical stage is hydrolysis, where the complex lignocellulosic structure of biomass composed primarily of cellulose, hemicellulose, and lignin is broken down into fermentable sugars. This step is essential for converting the otherwise inaccessible polysaccharides in agricultural residues, such as garri processing waste, into simple sugars like glucose and xylose that can be utilized in subsequent steps [1, 2]. Pretreatment methods, including acid hydrolysis and enzymatic approaches, have been optimized to maximize sugar yields from cassava waste, with thermochemical pretreatments showing up to 80% efficiency in sugar recovery [3, 4].

Following hydrolysis, the process advances to the fermentation stage. Here, the released sugars are biologically converted into ethanol by microbial agents, with *Saccharomyces cerevisiae* (baker's yeast) being the most commonly used microorganism due to its high ethanol tolerance and efficiency. Under anaerobic conditions, these microbes metabolize the sugars, typically producing a fermentation broth containing 5–12% ethanol, along with carbon dioxide and minor by-products [5, 6]. Alternative microbes like *Zymomonas mobilis* offer higher productivity, particularly for lignocellulosic feedstocks [2].

The final stage is distillation, which involves the physical separation of ethanol from the fermentation broth to obtain a concentrated, fuel-grade product. This step exploits the difference in boiling points between ethanol (78.3°C) and water (100°C) to isolate the ethanol. Through successive

heating and condensation stages, ethanol is purified to a concentration of 95.5% or higher, suitable for blending with gasoline or use as a standalone biofuel [7, 8]. Distillation is a vital step in the bioethanol production process, involving the thermal separation of ethanol from a fermented broth based on the difference in boiling points. The quality and yield of the final product depend heavily on the design of the distillation unit, the heat exchange efficiency, and process control [9, 6]. Emerging techniques, such as pervaporation and extractive distillation, reduce energy consumption by up to 60% compared to conventional methods [6, 8].

The distillation unit serves as the linchpin in the bioethanol production process, performing the critical function of purifying ethanol to fuel-grade standards. It operates on the principle of fractional distillation, which separates components of a liquid mixture based on their differing boiling points, 78.3°C for ethanol and 100°C for water. This thermal separation technique ensures that ethanol, which forms the lower boiling component, is selectively vaporized and collected from the fermentation broth, typically containing 5–12% ethanol by volume [5].

A standard distillation unit consists of several key components working in concert to optimize separation efficiency. At its core is a vertical shell, which houses the internal structures necessary for enhancing vapor-liquid interaction. Within this column are trays or structured packing materials, such as Raschig rings or sieve trays, designed to maximize surface area and promote intimate contact between ascending vapours and descending liquid condensates. This interaction increases the rectification of ethanol, allowing for more precise separation from water and other impurities [9].

At the base of the column lies the reboiler, a heat exchanger responsible for vaporizing the liquid feed. The generated vapours rise through the column, undergoing multiple stages of partial condensation and enrichment as they ascend. At the top of the unit, a condenser transforms the purified ethanol vapours back into liquid form. A portion of this condensed liquid is directed to a reflux drum, from which it is either collected as the final product or returned to the column as reflux, a mechanism that recycles part of the distillate to enhance separation efficiency and ensure higher ethanol purity. This recycling mechanism significantly sharpens the separation profile and ensures that the ethanol product achieves concentrations of 95.5% or more, suitable for fuel applications [6]. Vacuum

distillation and integration with cogeneration heat further improve efficiency, reducing energy needs and environmental impacts [9, 8].

While much research focuses on feedstock development and fermentation efficiency, the downstream purification process, distillation is a decisive factor for both product quality and overall economic and environmental sustainability. This review aims to consolidate current knowledge on distillation technologies used in bioethanol production, analyze their energy profiles, and discuss future pathways for optimizing this vital step, particularly within the context of waste-based biorefineries.

II. THE REVIEW REPORT

To highlight the work's importance, the review information was culled from a variety of credible literary sources, including books, theses, journal articles, and other publications published between 2000 and 2024. Older publications are cited in special cases, namely formulators of laws and formula. These sources can be found in print at institutional libraries or online. The reviewers then integrated, fine-tuned, and analysed the material.

2.1 The Principles and Technological Landscape of Ethanol Distillation

1. Vapor-Liquid Equilibrium and the Azeotrope

The basis of ethanol-water separation in distillation processes relies on vapor-liquid equilibrium (VLE), which describes the distribution of components between the vapor and liquid phases at equilibrium. Understanding VLE is essential for predicting the behaviour of ethanol-water mixtures under various operating conditions and for designing efficient separation systems [10].

The ethanol-water system exhibits complex behaviour due to the non-ideal interactions between ethanol and water molecules. These interactions lead to deviations from Raoult's law, the formation of azeotropes, and variations in activity coefficients, all of which impact the efficiency of distillation processes [11].

i. Thermodynamic Principles of VLE

Phase Equilibrium and Raoult's Law: Vapor-liquid equilibrium occurs when the rates of vaporization and condensation between the vapor and liquid phases are equal, resulting in constant phase compositions at a given temperature and pressure. In ideal systems, Raoult's law provides a simple description of VLE, where the partial pressure of each component in the vapor phase is proportional to its mole fraction in the liquid phase

and its vapor pressure at the given temperature [10]. For an ideal binary mixture of components A and B, Raoult's law is expressed as:

$$P_A = x_A P_A^*$$

$$P_B = x_B P_B^*$$

Where P_A and P_B are the partial pressures of components A and B in the vapor phase, x_A and x_B are their mole fractions in the liquid phase, and P_A^* and P_B^* are their vapor pressures.

However, ethanol-water mixtures are non-ideal, and Raoult's law fails to accurately describe their behaviour, particularly at higher ethanol concentrations [11]. This deviation necessitates the use of more complex models that account for the non-ideal interactions between ethanol and water molecules.

Activity Coefficients and Non-Ideal Behavior: In non-ideal mixtures like ethanol and water, the activity coefficient (γ) is introduced to account for deviations from ideal behavior. The activity coefficient modifies Raoult's law as follows:

$$P_A = \gamma_A x_A P_A^*$$

$$P_B = \gamma_B x_B P_B^*$$

The activity coefficients γ_A and γ_B reflect the non-ideal interactions between the components in the liquid phase, with values greater than 1 indicating positive deviations (repulsive forces) and values less than 1 indicating negative deviations (attractive forces). In ethanol-water systems, hydrogen bonding between water molecules and the hydroxyl group in ethanol leads to strong attractive forces, particularly at lower ethanol concentrations. This results in significant deviations from Raoult's law [12].

Accurately predicting activity coefficients is crucial for describing VLE in ethanol-water mixtures, and several thermodynamic models have been developed for this purpose. Among these, the Non-Random Two-Liquid (NRTL) model and the Wilson equation are widely used in industrial applications due to their ability to capture the complex interactions in non-ideal systems [13].

ii. VLE of Ethanol-Water Systems

Azeotropic Behavior: One of the most significant challenges in ethanol-water separation is the formation of an azeotrope, a mixture that exhibits a constant boiling point and vapor-liquid composition at equilibrium. In ethanol-water systems, a minimum-boiling azeotrope forms at approximately 95.6% ethanol by volume at atmospheric pressure, limiting the concentration of ethanol that can be achieved by simple distillation [14]. At the azeotropic point, the relative volatility

of ethanol to water is equal to 1, meaning that both components vaporize at the same rate, and further purification of ethanol requires alternative separation techniques, such as azeotropic or extractive distillation [15].

Non-Ideal VLE Models: The accurate prediction of VLE in ethanol-water systems requires thermodynamic models that account for non-ideal behavior. The NRTL model, developed by Renon and Prausnitz [16], is particularly effective for describing the phase behavior of ethanol-water mixtures. This model introduces binary interaction parameters that account for the non-random distribution of molecules in the liquid phase, enabling the calculation of activity coefficients for non-ideal systems [11]. The NRTL equation is given by:

$$\ln(\gamma_i) = x_j^2 \left[\tau_{ji} \left(\frac{G_{ji}}{x_i + x_j G_{ji}} \right)^2 + \tau_{ij} \left(\frac{G_{ij}}{x_j + x_i G_{ij}} \right)^2 \right]$$

Where τ_{ji} and τ_{ij} are binary interaction parameters and G_{ji} and G_{ij} are functions of these parameters.

The Wilson equation, another widely used model, assumes that molecular interactions in the liquid phase depend on the molar volumes of the components and the interaction energies between them. This model is particularly useful for systems where the size difference between molecules plays a significant role in determining VLE behavior [13].

Both the NRTL and Wilson models are implemented in process simulation software such as Aspen Plus, enabling engineers to accurately predict VLE and optimize distillation processes for ethanol-water separation [16].

iii. Industrial Applications of VLE in Ethanol-Water Separation

Distillation and Ethanol Purification: VLE plays a critical role in the design and operation of distillation columns for ethanol-water separation. In conventional distillation, the difference in volatility between ethanol and water is exploited to separate the components, with ethanol being enriched in the vapor phase as the mixture moves up the column [10]. However, due to the formation of an azeotrope, the concentration of ethanol in the distillate is limited to 95.6%, necessitating additional separation techniques to obtain high-purity ethanol.

Azeotropic and Extractive Distillation: Azeotropic distillation involves the introduction of a third component to break the ethanol-water azeotrope and allow further separation. Commonly used entrainers include benzene, cyclohexane, and isopropanol, which form azeotropes with water that are easier to separate from ethanol [17]. Extractive

distillation, on the other hand, involves the use of a solvent that preferentially interacts with water, increasing its relative volatility and facilitating ethanol separation [11].

Simulation and Optimization: Process simulation tools such as Aspen Plus rely on accurate VLE models to simulate ethanol-water separation processes. These tools allow engineers to explore different column configurations, operating conditions, and separation techniques to optimize the efficiency of ethanol purification [16]. By incorporating thermodynamic models such as NRTL and Wilson, these simulations provide valuable insights into the behavior of ethanol-water mixtures and the impact of non-ideal interactions on distillation performance.

2.2 Industrial-Scale Distillation of Bioethanol

The industrial distillation of bioethanol is a complex and energy-intensive process, critical to meeting the global demand for biofuels and industrial-grade ethanol. This process typically takes place in large cylindrical distillation columns or towers, which can range in diameter from approximately 65 centimetres to 16 meters, and in height from 6 to 90 meters or more [18]. In such systems, various product fractions are separated based on their distinct boiling points, with the lightest products exiting from the top and the heaviest from the bottom of the column. The operational complexity is amplified by the presence of minor components, which significantly influence both the design and performance of the distillation system, especially in bioethanol production.

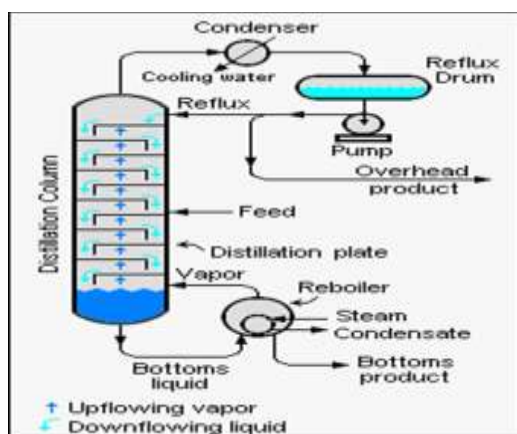


Figure 1: Diagram of a Typical Industrial Distillation Tower

The design of distillation units for bioethanol production is influenced by the need for efficiency in separating ethanol from water and

other impurities. Industrial-scale systems often consist of multiple columns, each serving specific functions in the distillation sequence. For example, Brazilian bioethanol production typically involves two distillation columns. The first column removes light contaminants such as volatile acids, while the second concentrates the ethanol to meet regulatory purity standards [19].

One major design consideration is the handling of minor components such as volatile acids, higher alcohols, and other by-products. These components, though often overlooked in studies, can significantly impact both the operational efficiency and final product purity [20]. For example, volatile acids, such as acetic acid, can accumulate during distillation, leading to increased acidity in the final ethanol product if not properly managed. Furthermore, higher alcohols like isoamyl and butanol are typically removed as side streams during distillation to ensure ethanol purity. Although fusel oil, a by-product of higher alcohols, has limited commercial value, after purification it becomes a valuable commodity for industries such as cosmetics [21].

Additionally, the energy-intensive nature of distillation must be accounted for in the design of bioethanol production facilities. Distillation accounts for a significant portion of total energy consumption in bioethanol production, making energy efficiency a key consideration in the design of distillation units. Simulation-based tools such as Aspen Plus have become indispensable in optimizing these systems. Through simulations, researchers can accurately model the thermodynamics of bioethanol-water mixtures, including the effects of minor components, to optimize operating conditions such as temperature, pressure, and feed composition [22].

Several distillation technologies are employed in industrial bioethanol production, with varying degrees of efficiency and complexity. The most commonly used technologies include conventional distillation, azeotropic distillation, and extractive distillation. Each of these methods presents unique advantages and challenges when applied to bioethanol production. Simulation-based approaches have been instrumental in optimizing the distillation of bioethanol. By incorporating minor components into the models, researchers can more accurately predict the behavior of the distillation system and identify potential inefficiencies. For instance, simulations conducted by Batista et al. [23] demonstrated how minor contaminants affect equipment performance and product purity in a system designed to produce

neutral alcohol for the cosmetics and pharmaceutical industries. Similar studies have validated the performance of continuous distillation systems for spirits and bioethanol production, showing that minor components play a critical role in both product quality and equipment longevity [24].

2.3 Comparison of Distillation Technologies for Bioethanol

Conventional Distillation: Conventional distillation remains the most widely used method for ethanol separation due to its simplicity and well-established technology. It operates based on the relative volatility of ethanol and water, using heat to vaporize ethanol at a lower temperature than water [25]. However, conventional distillation is limited by the ethanol-water azeotrope, which occurs at around 95.6% ethanol by volume. As a result, additional purification methods are required to achieve fuel-grade ethanol (99.5% purity) [17]. Despite its limitations, conventional distillation remains an efficient process for large-scale ethanol production when combined with energy recovery techniques such as heat integration. In this approach, thermal energy from the distillation process is recycled, reducing the overall energy consumption and improving the sustainability of the process [26].

Azeotropic Distillation: Azeotropic distillation is a specialized technique designed to overcome the limitations posed by the ethanol-water azeotrope. In ethanol-water systems, the azeotropic composition, which occurs at approximately 95.6% ethanol by volume, cannot be separated using conventional distillation methods because the vapor and liquid phases have the same composition at the azeotropic point [27]. Azeotropic distillation introduces a third component, referred to as an entrainer, to disrupt this azeotropic behaviour and facilitate further separation. Common entrainers include benzene, cyclohexane, and toluene, although their usage is increasingly scrutinized due to their environmental and health risks, leading to the search for safer, more sustainable alternatives [28].

In industrial bioethanol production, azeotropic distillation is commonly employed when ultra-high purity ethanol is required, such as in pharmaceutical or chemical applications. However, the process is energy-intensive and requires careful

management of the entrainer, as traces of the third component can persist in the final ethanol product. This necessitates additional purification steps to ensure compliance with safety and quality standards [29].

An advanced variant of azeotropic distillation, Batch Extractive Distillation (BED), has proven effective in separating azeotropic and low relative volatility mixtures [29]. This method leverages the intermolecular interactions between the components of the mixture to achieve separation. In general, azeotropes are mixtures that exhibit a higher or lower boiling point than either of their individual components. Due to the constant composition of the liquid and vapor phases at the azeotropic point, traditional distillation methods are ineffective.

Several alternative techniques can be employed to break the azeotropic behaviour. One such approach is extractive distillation, in which a solvent is introduced that preferentially interacts with one component of the mixture. This modifies the relative volatility of the components, enabling the separation via distillation. Another approach is reactive distillation, where a reactive agent is added to selectively react with one component of the mixture, forming a new compound that can be separated by distillation. Finally, the addition of ionic salts can also be used to alter the volatilities of the components, making distillation feasible [29]. Collectively, these methods are often referred to as azeotropic distillation or azeotropic refining.

Extractive Distillation: Extractive distillation involves the use of a solvent that selectively interacts with one of the components in the mixture to alter the relative volatility and enable separation. Unlike azeotropic distillation, the solvent does not form an azeotrope with the mixture, allowing for continuous operation. Common solvents used in extractive distillation of ethanol include glycerol, ethylene glycol, and certain ionic liquids [10].

Extractive distillation is highly effective at breaking the ethanol-water azeotrope and can achieve high ethanol purities with relatively lower energy input compared to azeotropic distillation. The choice of solvent is crucial, as it must be easily separable from the ethanol product, non-toxic, and thermally stable. While extractive distillation offers advantages in terms of energy efficiency, the need for solvent recovery and recycling adds complexity to the process [17].

Table 1: Summary of distillation technology comparison

Distillation Technology	Description/Key Strengths	References
Conventional distillation	<ul style="list-style-type: none"> • Most widely used method; simple and well-established • Efficient for large-scale production, especially with heat integration • Effective for initial separation but limited by the ethanol-water azeotrope (~95.6% purity) 	[17, 25, 26]
Azeotropic distillation	<ul style="list-style-type: none"> • Breaks the azeotrope using an entrainer (e.g., cyclohexane). • Effective for achieving ultra-high purity ethanol for pharmaceutical/chemical use • Batch Extractive Distillation (BED) is an effective advanced variant for complex mixtures 	[27, 28, 29]
Extractive distillation	<ul style="list-style-type: none"> • Uses a solvent (e.g., glycerol, ionic liquids) to alter relative volatility without forming a new azeotrope. • Can achieve high purity with relatively lower energy input than azeotropic distillation • Allows for continuous operation 	[10, 17]

2.4 Limitation of Distillation

Conventional Distillation: Conventional distillation relies on the difference in volatility between components to achieve separation. In the case of ethanol-water mixtures, ethanol is more volatile than water, allowing it to be enriched in the vapor phase during distillation. However, at the azeotropic composition, the relative volatility of ethanol to water becomes 1, meaning that the two components vaporize at the same rate. As a result, conventional distillation cannot achieve ethanol purities beyond 95.6% [25].

This limitation poses a significant challenge in industries that require anhydrous ethanol, such as biofuel production. To overcome this challenge, specialized separation techniques must be employed to break the azeotrope and achieve higher ethanol concentrations.

Azeotropic Distillation: Azeotropic distillation is one method used to break the ethanol-water azeotrope. In this process, an entrainer, or third component, is added to the system to alter the relative volatility of ethanol and water. The entrainer forms a new azeotrope with one of the components, usually water, that has a lower boiling point than the ethanol-water azeotrope [27].

For example, benzene and cyclohexane are commonly used as entrainers in industrial azeotropic distillation processes. These entrainers form azeotropes with water, allowing ethanol to be separated in a subsequent distillation step. However, the use of certain entrainers, such as benzene, raises environmental and health concerns, prompting the search for safer and more sustainable alternatives [17].

Extractive Distillation: Extractive distillation is another technique for overcoming azeotropic limitations. In this method, a solvent is added that selectively interacts with one of the components, typically water, to enhance its volatility relative to ethanol. Unlike azeotropic distillation, the solvent does not form an azeotrope with the components, allowing for a continuous separation process [10]. Common solvents used in extractive distillation for ethanol-water separation include glycerol, ethylene glycol, and certain ionic liquids. The choice of solvent is critical for the success of the process, as it must effectively alter the relative volatility of the azeotropic mixture while being easily separable from the ethanol product [25].

Table 2: Summary of limitations of distillation technologies

Distillation Technology	Description	Limitation	References
Conventional distillation	Separates components based on differences in volatility	Cannot purify beyond 95.6% ethanol due to the azeotrope (relative volatility = 1)	[25]
Azeotropic distillation	Uses an entrainer to form a new, lower-boiling azeotrope with water	Entrainers like benzene pose health/environmental risks; process is complex	[17, 27]
Extractive distillation	Uses a solvent to selectively increase water's volatility, with no new azeotrope formed.	Solvent must be carefully selected and recovered, making the process energy-intensive	[10, 25]

2.5 Design Considerations to Offset Challenges

1. Thermodynamic Efficiency and Heat Integration

Thermodynamic efficiency is a key consideration in the design of bioethanol distillation units. The separation of ethanol from water requires significant energy input due to the close boiling points of the two components. To optimize efficiency, industrial-scale distillation units often employ heat integration strategies, such as using multiple-effect distillation or employing vapor recompression technologies [30]. Multiple-effect distillation involves using the latent heat of vaporization from one stage to drive the next stage, reducing the overall energy consumption. Vapor recompression systems recover heat from the overhead vapor, compress it, and return it to the distillation column, further lowering energy demands [28].

2. Column Design and Configuration

The design of the distillation column plays a critical role in determining the separation efficiency and energy consumption of the process. Key design parameters include the number of theoretical stages, column diameter, tray or packing design, and reflux ratio. The number of stages is directly related to the separation efficiency, with more stages allowing for better ethanol purity but increasing the size and cost of the column. Column packing is often preferred over trays in bioethanol distillation due to its lower pressure drop and improved mass transfer efficiency [25].

Another design consideration is the column configuration. Industrial bioethanol distillation units typically employ a series of distillation columns, with the first column performing a rough separation and subsequent columns providing further purification. For instance, the first column (beer still) separates

ethanol from the fermentation broth, while a rectifying column refines the ethanol to achieve higher purities [28]. This multi-column approach allows for better process control and heat recovery.

3. Material Selection and Corrosion Resistance

Given the acidic nature of the fermentation broth and the presence of by-products such as acetic acid, formic acid, and higher alcohols, the materials used in the construction of distillation units must be corrosion-resistant. Stainless steel, particularly 316L grade, is commonly used due to its high resistance to corrosion and its ability to maintain structural integrity at elevated temperatures. In cases where higher concentrations of acids are expected, more corrosion-resistant alloys such as Hastelloy may be required [31].

4. Process Control and Automation

Distillation units for bioethanol production must be designed with robust process control systems to maintain optimal operation and product quality. Key process variables include temperature, pressure, reflux ratio, and feed flow rate. Advanced process control strategies, such as model predictive control (MPC), can be used to optimize these variables in real-time, ensuring consistent ethanol purity while minimizing energy consumption [32]. Automation also enhances safety by allowing for continuous monitoring and adjustment of operating conditions, reducing the risk of equipment failure or process deviations.

5. Environmental and Safety Considerations

Industrial distillation of bioethanol generates a significant amount of wastewater and volatile organic compounds (VOCs). Therefore, the design of bioethanol distillation units must incorporate systems for waste management and

emissions control. Wastewater treatment technologies, such as anaerobic digestion, can be used to treat effluent streams, while VOCs can be captured using scrubbers or activated carbon filters [33]. In terms of safety, ethanol distillation involves the handling of flammable liquids at high temperatures, necessitating the use of explosion-proof equipment and rigorous safety protocols.

III. CONCLUSION

Distillation is the fundamental process in bioethanol production, acting as the crucial step to convert a dilute fermentation broth into a high-purity, fuel-grade product. This review has clarified the intricate interaction of thermodynamic concepts, especially vapor-liquid equilibrium and azeotropic behaviour, that regulate the separation process and establish its technical constraints. Conventional distillation effectively provides initial enrichment; however, its restriction at the ethanol-water azeotrope requires the use of advanced methods such extractive and azeotropic distillation to get the anhydrous ethanol necessary for blending.

The comparative examination of these methods indicates a significant trade-off among purity, energy consumption, and process complexity. The substantial energy requirements of distillation highlight the need for novel design solutions focused on thermodynamic efficiency. Methods such as multiple-effect distillation, vapour recompression, and advanced heat integration are essential for minimising environmental and economic expenses. Moreover, a resilient design including corrosion-resistant materials, optimised column layout, and sophisticated process control is crucial for guaranteeing operational life, safety, and uniform product quality.

The future of distillation in bioethanol production is centred on process intensification and intelligent integration. The investigation of environmentally friendly entrainers, the use of innovative solvents such as ionic liquids in extractive distillation, and the integration of distillation with membrane technologies provide interesting avenues to overcome the energy barrier. For waste-based biorefineries to achieve true sustainability, the distillation unit must be regarded as an integral part of a broader system, where waste heat is recovered and by-products are valorised, thus fostering a circular and economically viable bioeconomy.

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