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ECO-FRIENDLY SOLVENT RECOVERY: CUTTING-EDGE TECHNIQUES FOR ACETONITRILE AND GREEN CHEMISTRY

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Abstract

This review article explores innovative methods and recent advancements in the reclamation of organic solvents from reaction media, underscoring the principles of green chemistry and the goal of achieving a zero-waste synthesis chain. Effective solvent recovery and waste management are critical for sustainable industrial practices. Acetonitrile, in particular, is a vital solvent in the pharmaceutical and fine chemical industries due to its high polarity and stability. Efficient recovery of acetonitrile is essential to mitigate environmental impacts and reduce costs. This review examines various techniques dedicated to acetonitrile recovery, including pressure-swing, batch, and heterogeneous distillation, as well as advanced separation technologies like ionic liquids and phase equilibrium studies. A comparison of these techniques is presented, highlighting their effectiveness and optimization in solvent recovery. Environmental impacts and sustainability are addressed through comprehensive life cycle assessments and green chemistry practices, providing insights into current trends and innovations in solvent recovery for enhanced sustainability and economic efficiency.

***Keywords*:** Solvent recovery, Acetonitile, Green Chemistry, Extractive Distillation, Pharmaceutical Solvent Management, Sustainable Chemical Processes.

Introduction

Green chemistry aims to design products and processes that minimize or eliminate hazardous substances, reducing chemical-related impacts on human health and the environment. Key principles include using renewable feedstocks, designing safer chemicals, and implementing energy-efficient processes [1,2].

A critical aspect of green chemistry is solvent and waste management [3]. Solvents are essential in chemical manufacturing, particularly in the pharmaceutical and fine chemical industries, facilitating various reactions and purification processes. However, organic solvents pose significant environmental and health risks due to their volatility, toxicity, and flammability. Efficient solvent management practices are crucial to mitigate these risks and enhance sustainability [4].

Solvent recovery and recycling reduce the environmental footprint of chemical industries by decreasing the demand for fresh solvent production, conserving resources, and reducing emissions associated with solvent disposal [5].

In the pharmaceutical industry, solvents constitute a significant portion of overall mass and energy consumption. Solvent use accounts for approximately 60% of the energy used in producing active pharmaceutical ingredients (APIs) and contributes to 50% of total greenhouse gas emissions. Therefore, optimizing solvent selection and recovery processes is crucial for reducing the environmental impact of pharmaceutical manufacturing [6].

Life Cycle Assessment (LCA) plays a vital role in solvent and waste management by providing a comprehensive analysis of environmental impacts across the lifecycle of solvents. This approach helps industries identify critical stages where improvements can be made to enhance sustainability [7]. GSK's Solvent Selection Guide (SSG) incorporates LCA data to rank solvents based on their environmental performance, facilitating informed decision-making in solvent selection and use [8].

The LCA module in GSK's SSG highlights the significance of solvent recovery and recycling in reducing lifecycle impacts. Solvent recovery technologies such as distillation, membrane separation, and adsorption are essential for minimizing waste and conserving resources [9]. These techniques not only lower greenhouse gas emissions but also decrease the energy required for solvent production.

The integration of LCA into solvent management practices helps industries adopt greener processes, aligning with the principles of green chemistry. By prioritizing solvent recovery and recycling, companies can reduce their environmental footprint, enhance resource efficiency, and promote sustainable industrial practices [10]. This comprehensive approach ensures that solvent use is optimized, and environmental impacts are minimized throughout the lifecycle.

Solvent recovery in the pharmaceutical and chemical industries employs various techniques, including distillation, membrane separation, and adsorption. Pressure-swing distillation leverages pressure changes to separate azeotropic mixtures efficiently. Membrane technologies, like pervaporation and ultrafiltration, offer energy savings and high selectivity. Adsorption processes, utilizing materials such as activated carbon, facilitate the recovery of solvents from complex waste streams. Finding the correct technique for efficient recovery is crucial due to its significant economic and environmental impact. Effective solvent recovery reduces waste, lowers production costs, and minimizes the ecological footprint of industrial processes [5].

Conflict Setting

The development of effective solvent recovery methods faces several key conflicts, primarily between economic viability, environmental sustainability, and technological efficiency. One of the major challenges is balancing the cost of implementing advanced recovery techniques with their long-term economic benefits. While methods like pressure-swing distillation and extractive distillation offer high efficiency and purity, their initial setup and operational costs can be prohibitive for some industries.

Another significant conflict lies in the environmental impact versus the practicality of recovery methods. Techniques that are environmentally friendly, such as the use of ionic liquids or low transition temperature mixtures, often require complex setups and can be difficult to scale up for industrial use. This creates a tension between adopting greener methods and maintaining industrial feasibility and productivity.

Additionally, there is a conflict between the thoroughness of solvent recovery and the residual waste management. High-efficiency recovery processes can often result in complex waste streams that require further treatment, adding another layer of cost and environmental consideration. This raises the issue of finding a balance between recovering as much solvent as possible and dealing with the subsequent waste in a sustainable manner.

Lastly, the pharmaceutical and fine chemical industries face specific conflicts related to regulatory standards and the need for high-purity solvents. The stringent purity requirements for solvents like acetonitrile necessitate advanced recovery methods that are both cost-effective and capable of achieving the desired purity levels. This adds pressure to continuously innovate and optimize recovery processes to meet regulatory and quality standards while also being economically and environmentally sustainable.

Research Results

Over the decades, various research groups and industries have continually focused on waste management and solvent recovery issues. These efforts have led to the development of new, modern, and effective approaches for solvent recovery. By advancing these technologies, these groups aim to enhance the efficiency of solvent recovery processes, reduce environmental impact, and improve the sustainability of industrial operations. The ongoing research and innovation in this field highlight the commitment to addressing the challenges associated with solvent use and waste generation.

In the early 90s, Malone et al. considered various methods for breaking azeotropes using batch distillation. Their research focused on employing homogeneous entrainers in both conventional and inverted batch columns to break azeotropes. The group aimed to determine the feasibility of separating azeotropic mixtures into pure components by analyzing batch distillation regions and selecting appropriate entrainers [11]. Dussel et al. investigated the separation of azeotropic mixtures using batch distillation with an entrainer. Their research categorized the processes into three classes: single distillation field processes, two distillation field processes, and hybrid processes that combine distillation with other unit operations. The primary focus was on optimizing entrainer selection to enhance the effectiveness of separating azeotropic mixtures [12]. Rodriguez-Donis et al. have made significant contributions to the development of various purification techniques in batch distillation processes. Their research encompasses both homogeneous and heterogeneous batch distillation, utilizing different types of entrainers to break azeotropes and close-boiling-temperature mixtures. They developed comprehensive guidelines for selecting suitable entrainers and explored the advantages of using partially miscible entrainers in heterogeneous distillation to increase design alternatives and simplify distillation sequences. Their work also highlighted the importance of considering distillation boundary curvature and the need for multiple batch distillation configurations.

Overall, their contributions have provided valuable insights and advanced the field of solvent recovery and purification [13-16].

Modla et al. and Luyben et al. both explored pressure-swing distillation (PSD) but with distinct focuses and contributions. Modla et al. optimized PSD and extractive distillation processes using a genetic algorithm to handle wastewaters containing acetone and methanol. Their research aimed to compare the economic efficiency of different scenarios, highlighting the importance of water content and demonstrating the slight advantage of extractive distillation over PSD in terms of total annual costs when heat integration is considered [17]. On the other hand, Luyben et al. focused on the fundamental aspects of PSD for both minimum- and maximum-boiling azeotropes. Their work provided a detailed analysis of energy consumption and pressure sensitivity, showing that there is minimal difference between the two systems regarding energy efficiency despite initial assumptions favoring maximum-boiling systems [18].

In their comprehensive study, Reddy et al. have highlighted the significant potential of ionic liquids as alternative solvents in industrial separation processes. These "green designer solvents" offer unique physicochemical properties such as negligible vapor pressure and high thermal stability, making them ideal for replacing conventional solvents in processes like liquid-liquid extraction and distillation. Their application can significantly reduce the environmental impact associated with traditional solvents, providing a more sustainable approach to solvent recovery and waste management in the chemical industry. By leveraging ionic liquids, industries can achieve more efficient and environmentally friendly separation processes [19].

The search for efficient solvent and waste management techniques continues to be a significant focus in research and industry. Recently, Valentini and Vaccaro (2020) discussed the utilization of azeotropes as a powerful tool for waste minimization in chemical processes, highlighting their role in recycling and reducing solvent usage [20]. Similarly, Naskar, Beckham, and coworkers (2019) proposed an integrated synthesis for the biomass-based production of acrylonitrile, emphasizing the environmental benefits and reduced operational costs achieved by avoiding additional purification steps [21]. These studies underscore the ongoing efforts to develop innovative and sustainable solvent recovery methods.

Acetonitrile (MeCN) is a core solvent in the chemical industries, particularly the pharmaceutical industry, where the global demand accounts for over 70% of the total market. The high popularity of MeCN is due to its excellent solvation ability with respect to a wide range of polar and nonpolar solutes, and favorable properties such as low freezing and boiling points, low viscosity, and relatively low toxicity. These properties make MeCN a versatile solvent used extensively in various applications.

In the pharmaceutical industry, MeCN is crucial for two major uses: (a) laboratory use, particularly as a mobile phase in liquid chromatography analytical techniques such as high-performance liquid chromatography (HPLC), and (b) as an industrial process solvent, for example, in the manufacturing of antibiotics. Due to the need for very high purity solvents in analytical techniques, laboratories tend to use “Analar” grade MeCN, while industrial applications favor “technical grade” MeCN due to its lower cost. In both cases, the solvent is highly refined in terms of purity, typically >99.9% for Analar and >99.5% for technical grade.

The volatility in acetonitrile supply in recent years, coupled with its relatively poor environmental profile, has presented significant challenges to its use in manufacturing processes and laboratories. Issues associated with the MeCN supply position were raised as a major concern during the period 2008 to 2009, when the supply of MeCN was reduced significantly, probably by at least 50%, due to a limited demand for acrylonitrile (its primary production source) resulting from the global economic downturn. This shortfall led to drastic measures within the pharmaceutical industry, such as stringent stock control, prioritization of use, and sourcing solvents from intermediate suppliers, to mitigate supply problems.

Given these challenges, the pharmaceutical industry faces a major incentive to develop new, more sustainable approaches to MeCN use. Efficient recovery and recycling of MeCN are crucial for reducing environmental impact and maintaining a steady supply. Techniques such as azeotropic distillation, hybrid pervaporation-distillation units, and the use of ionic liquids as azeotrope breakers are being explored to enhance the recovery and recycling of MeCN from aqueous waste streams, ensuring its sustainable use in the industry [22].

Sharma et al. investigated the use of low transition temperature mixtures (LTTMs) as versatile alternatives to ionic liquids for extractive distillation, specifically targeting the separation of acetonitrile (ACN) and water azeotropic mixtures. They synthesized a LTTM from glycolic acid and choline chloride in a 3:1 molar ratio (GC3:1) and conducted isobaric vapor−liquid equilibrium (VLE) studies at atmospheric pressure for both pseudobinary and pseudoternary systems containing ACN, water, and GC3:1. The thermodynamic modeling of these systems was performed using the nonrandom two-liquid (NRTL) model, and experimental data were found to align well with predicted values. The study concluded that GC3:1 effectively eliminated the ACN + water azeotrope by manipulating the relative volatility of the mixture, demonstrating its potential as an efficient entrainer for extractive distillation [23]. Li et al. developed new extractive distillation configurations using low transition temperature mixtures (LTTMs) as entrainers for the separation of acetonitrile-water mixtures. They focused on comparing two extractive distillation processes: the extractive distillation column (ED) and the extraction dividing wall column (EDW), using LTTMs like choline chloride/glycolic acid (GC3:1) and choline chloride/ethylene glycol (EC2:1). Their sensitivity analysis and economic evaluation demonstrated that both configurations were effective in minimizing energy consumption and maximizing the purity of acetonitrile and water, highlighting the potential of LTTMs in enhancing the efficiency and sustainability of extractive distillation processes [24]. Sazonova et al. applied extractive distillation for the removal of acetonitrile from water solutions, aiming to validate a thermodynamic criterion based on excess Gibbs energy for entrainer selection. They simulated and analyzed the extractive distillation process with various entrainers, including dimethyl sulfoxide (DMSO), 1,2-ethanediol, and glycerol. Their results indicated that glycerol was the most energetically and ecologically suitable entrainer, offering advantages such as lower energy consumption, reduced reflux ratios, and fewer theoretical stages required for both extractive and regeneration columns [22]. Yu et al. developed an energy-efficient extraction-distillation process to separate diluted azeotropic acetonitrile-water mixtures. They proposed using n-propyl chloride as an efficient solvent for extracting acetonitrile into the extract phase while leaving water in the raffinate phase. This method, validated by ternary liquid-liquid

equilibrium experiments, demonstrated significant savings in steam cost (40.3%) and total annual cost (34.7%) compared to conventional three-column extractive distillation systems. The innovative approach focused on minimizing reboiler duty, thus enhancing economic and energy efficiency in acetonitrile dehydration processes [25]. You et al. presented a multi-objective optimization of the extractive distillation process for acetonitrile-water separation with ethylene glycol. The study considered various factors, including operating pressure, entrainer recycle, and preconcentration column design. Their aim was to reduce total annual costs and energy consumption while maintaining high separation efficiency [26].

To summarize Efficient entrainer selection is crucial for the success of extractive distillation processes. The choice of entrainer significantly affects the energy consumption, process efficiency, and environmental impact. Low transition temperature mixtures (LTTMs) have emerged as valuable alternatives to traditional solvents. These green solvents, such as choline chloride-based mixtures, offer advantages like low toxicity, biodegradability, and the ability to enhance separation efficiency.

LTTMs like choline chloride/ethylene glycol (EC2:1) and choline chloride/glycolic acid (GC3:1) have shown promise in extractive distillation for acetonitrile-water separation. Their use reduces energy consumption and enhances the purity of recovered solvents, making them suitable for sustainable industrial applications. The growing interest in LTTMs underscores the importance of developing eco-friendly and efficient entrainers for solvent recovery processes.

Pressure Swing Distillation (PSD) is an advanced separation technique used for separating azeotropic mixtures, where conventional distillation methods fail due to the formation of constant boiling mixtures. PSD exploits the fact that the composition of azeotropes varies with pressure. By alternating the pressure between two distillation columns, the azeotrope can be shifted and separated effectively. This method is particularly advantageous for separating mixtures with close boiling points or azeotropic behavior, such as the acetonitrile-water mixture.

Li et al. simulated and optimized the separation of acetonitrile-water mixtures using pressure swing distillation (PSD) through Aspen Plus software. They determined the optimal pressures for low and high-pressure columns (1 and 4 atm, respectively) and implemented full-heat integration to achieve significant cost reductions. This method, validated by phase diagram analysis, resulted in a 32.39% reduction in total annual cost compared to conventional PSD without heat integration. The innovative approach focused on maximizing energy efficiency and reducing operational costs, providing a more economical solution for separating azeotropic mixtures [27]. Tripodi et al. compared pressure swing distillation (PSD) and extractive distillation for recovering acetonitrile from ethanol ammoxidation. The PSD method, optimized at 10 bar, achieved higher acetonitrile recovery (95.5%) and purity (>99.9%) compared to extractive distillation using dichloromethane as an entrainer, which had a 92.1% recovery. Economic analysis showed that PSD had lower installation and operating costs. The study concluded that PSD is more efficient and cost-effective, with enhanced energy integration options, making it the preferred method for acetonitrile purification [28]. Both studies highlight the efficiency and economic advantages of Pressure Swing Distillation (PSD) for separating acetonitrile from complex mixtures. Li et al. focused

on optimizing the process using Aspen Plus software to achieve significant cost savings and energy efficiency. In contrast, Tripodi et al. provided a comparative analysis between PSD and extractive distillation, demonstrating that PSD offers higher recovery and purity levels with lower costs. Both studies conclude that PSD is a superior method for acetonitrile purification, emphasizing its practicality and cost-effectiveness in industrial applications.

Simulation and modeling can be effectively implemented in solvent recovery process development. Tasleem and Bomma conducted simulation studies using Aspen Plus to recover acetonitrile from aqueous waste in pharmaceutical processes. They used two sequential distillation columns: the first to produce an azeotropic distillate and the second, after mixing with fresh acetonitrile, to achieve 99.9% purity. The optimized process achieved a 60.4% recovery rate of high-purity acetonitrile. The study highlights the effectiveness of this method in overcoming azeotropic limitations and achieving high recovery and purity rates [29].

Stepnowski et al. developed a comprehensive recycling methodology for chromatographic solvent waste, focusing on methanol and acetonitrile recovery. The system involves waste collection, distillation using a batch distillation setup, and biodegradation of residues. The recovered solvents achieved high purity levels suitable for reuse, and the system demonstrated significant environmental and economic benefits when implemented in academic institutions [30]. Zhang et al. investigated the separation of acetonitrile and methanol azeotropic mixtures using imidazolium-based ionic liquids as entrainers. The study measured isobaric vapor-liquid equilibrium data and found that these ionic liquids effectively increased the relative volatility of acetonitrile to methanol, eliminating the azeotropic point. Among the tested ILs, [BMIM][OAc] showed the most significant salting-out effect, and the separation performance was correlated using the nonrandom two-liquid (NRTL) model [31]. Wang et al. studied the design optimization and the effects of operating pressure in the separation of acetonitrile/methanol/water mixtures using ternary extractive distillation. They proposed a novel sequential iterative optimization methodology to evaluate the process under different pressures. The study found that optimal pressures for the first and third columns are related to the cooling water and chiller water, respectively, while the second column's pressure is influenced by preheating. The optimized process resulted in 60.1% energy cost savings and 47.0% total annual cost savings compared to operating at atmospheric pressure. This methodology offers an efficient and systematic approach to process optimization, highlighting significant cost and energy savings [32]. The three studies collectively advance the recovery and separation processes of acetonitrile and methanol. Stepnowski et al. provided a practical and environmentally beneficial recycling method suitable for academic settings. Zhang et al. contributed by introducing ionic liquids to eliminate azeotropic points, enhancing separation efficiency. Wang et al. presented an optimized ternary extractive distillation method, achieving significant cost and energy savings. Together, these works offer innovative solutions for efficient and sustainable solvent recovery in various applications.

Experimental procedure

In our laboratory, we focus on Atom Transfer Radical Reactions (ATRR) involving different terpenes and trichloroacetonitrile derivatives. Acetonitrile is a critical solvent in our work, utilized both as a reaction medium and for High-Performance Liquid Chromatography

(HPLC) analysis. One of our primary objectives is to develop waste-free synthetic processes, making the recovery of acetonitrile a priority. Based on extensive literature investigations, we consider extractive distillation a valuable, cost-efficient, and practical methodology for the purification of acetonitrile. Consequently, we employed extractive distillation to test its efficacy in purifying acetonitrile from waste streams.

We implemented the methodology of extractive distillation to recover acetonitrile from a 10% aqueous waste solution. In this process, 1 liter of butyl acetate was added to 1 liter of a 10% acetonitrile aqueous waste solution. The mixture was allowed to stand until phase separation was observed. The butyl acetate layer, now containing the acetonitrile, was carefully isolated and subjected to distillation. This procedure yielded 80 mL of acetonitrile with a purity of 99%, representing an 80% recovery yield.

The extractive distillation process demonstrated effective separation and purification of acetonitrile from aqueous waste. The phase separation step facilitated the isolation of acetonitrile in the butyl acetate layer, and the subsequent distillation provided high-purity solvent. The results indicate that extractive distillation is a viable and efficient method for acetonitrile recovery in our laboratory settings.

The findings align with our goal of developing waste-free synthesis methodologies, proving that extractive distillation is not only practical but also cost-efficient for solvent recovery. This method significantly reduces solvent waste and supports sustainable laboratory practices, reinforcing the importance of solvent recovery in modern synthetic chemistry.

Conclusion

This review explores innovative methods and recent advancements in the reclamation of organic solvents from reaction media, emphasizing the principles of green chemistry and the pursuit of a zero-waste synthesis chain. Effective solvent recovery is essential for sustainable industrial practices, particularly in the pharmaceutical and fine chemical industries. Acetonitrile, a vital solvent in these industries, requires efficient recovery methods to mitigate environmental impacts and reduce costs. Various techniques for acetonitrile recovery are examined, including pressure-swing, batch, and heterogeneous distillation, as well as advanced separation technologies like ionic liquids and phase equilibrium studies. The comparison of these techniques highlights their effectiveness and optimization in solvent recovery, with a focus on environmental impacts and sustainability through comprehensive life cycle assessments and green chemistry practices.

In our laboratory, we applied extractive distillation to recover acetonitrile from a 10% aqueous waste solution, achieving an 80% recovery yield with 99% purity. This process demonstrated effective separation and purification, proving to be a viable and cost-efficient method for acetonitrile recovery. Our findings support the implementation of extractive distillation as a practical approach to solvent recovery, significantly reducing solvent waste and supporting sustainable laboratory practices.

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ԼՈՒԾԻՉԻ ՎԵՐԱԿԱՆԳՆՄԱՆ ԲՆԱՊՀՊԱՆԱԿԱՆ ԵՂԱՆԱԿՆԵՐԸ. ԿԱՆԱՉ ՔԻՄԻԱՅԻ ԼԱՎԱԳՈՒՅՆ ՊՐԱԿՏԻԿԱՆԵՐԸ ԱՑԵՏՈՆԻՏՐԻԼԻ ՀԱՄԱՐ

Վ.Ա. Սարգսյան
Երևանի պետական համալսարան

Հոդվածում ուսումնասիրվում է ռեակցիոն միջավայրերից լուծիչների վերականգնման նորարարական մեթոդները և վերջին ձեռքբերումները՝ ընդգծելով կանաչ քիմիայի սկզբունքները և զրոյական թափոնների սինթեզի շղթա ստեղծելու նպատակահարմարությունը: Լուծիչների արդյունավետ վերականգնումը և թափոնների կառավարումը կարևոր նշանակություն ունեն կայուն արդյունաբերական պրակտիկայի համար: Հատկապես ացետոնիտրիլը կարևոր լուծիչ է դեղագործական և նուրբ քիմիական արդյունաբերության մեջ՝ շնորհիվ իր բարձր բևեռականության և կայունության: Ացետոնիտրիլի արդյունավետ վերականգնումն անհրաժեշտ է շրջակա միջավայրի վրա ազդեցությունները մեղմելու և ծախսերը նվազեցնելու տեսանկյուններից: Քննարկվում է ացետոնիտրիլի վերականգնմանն ուղղորդված մի շարք եղանակներ, ներառյալ ճնշման փոփոխմամբ թորումը, մասնակի ռեկտիֆիկացիան և հետերոֆազ թորումը, ինչպես նաև տարանջատման առաջադեմ տեխնոլոգիաները, ինչպիսիք են իոնային հեղուկները և փուլային հավասարակշռության ուսումնասիրությունները: Ներկայացված է նշված մեթոդների համեմատությունը՝ ընդգծելով դրանց արդյունավետությունն ու լավարկումը լուծիչների վերականգնման հարցում: Շրջակա միջավայրի վրա ազդեցությունների և կայունության տեսանկյունից իրականացված է կյանքի ցիկլի համապարփակ գնահատումների և կանաչ քիմիայի գործնական միջոցներով՝ ապահովելով լուծիչների վերականգնման ընթացիկ միտումների և

նորարարությունների շրջանակը՝ կայունությունը և արդյունավետությունը բարելավելու նպատակով:

Բանալի բառեր. լուծիչների վերականգնում, ացետոնիտրիլ, կանաչ քիմիա, էքստրակցիոն թորում, դեղագործական լուծիչների կառավարում, կայուն քիմիական պրոցեսներ

ЭКОЛОГИЧЕСКИ ЧИСТОЕ ВОССТАНОВЛЕНИЕ РАСТВОРИТЕЛЕЙ: ПЕРЕДОВЫЕ МЕТОДЫ ДЛЯ АЦЕТОНИТРИЛА И ЗЕЛЕНОЙ ХИМИИ

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Данная обзорная статья исследует инновационные методы и последние достижения в области восстановления органических растворителей из реакционных сред, подчеркивая принципы зеленой химии и цель достижения цепочки синтеза без отходов. Эффективное восстановление растворителей и управление отходами критически важны для устойчивых промышленных практик. Ацетонитрил, в частности, является важным растворителем в фармацевтической и тонкой химической промышленности благодаря своей высокой полярности и стабильности. Эффективное восстановление ацетонитрила необходимо для смягчения экологических воздействий и снижения затрат. В данном обзоре рассматриваются различные методы, посвященные восстановлению ацетонитрила, включая дистилляцию с изменением давления, партионную и гетерогенную дистилляцию, а также передовые технологии разделения, такие как ионные жидкости и исследования фазового равновесия. Представлено сравнение этих методов, подчеркивающее их эффективность и оптимизацию в восстановлении растворителей. Экологические воздействия и устойчивость рассматриваются через комплексные оценки жизненного цикла и практики зеленой химии, предоставляя понимание текущих тенденций и инноваций в восстановлении растворителей для повышения устойчивости и экономической эффективности.

Ключевые слова: восстановление растворителей, ацетонитрил, зеленая химия, экстрактивная дистилляция, управление фармацевтическими растворителями, устойчивые химические процессы.

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