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Purification and regeneration of organic solvents: modern approaches and development prospects

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Abstract

Organic solvents are essential across various industrial sectors, including pharmaceuticals, petrochemicals, and polymer manufacturing, but they gradually accumulate contaminants during technological processes. Direct disposal of spent solvents leads to substantial economic losses and environmental degradation through the formation of volatile organic compounds. Consequently, developing efficient purification and regeneration technologies is crucial for sustainable industrial operations. This work reviews key physical, chemical, and combined solvent recovery methods, evaluating their operating principles, benefits, and limitations. Standard techniques such as distillation and rectification enable high-volume processing but demand high energy, whereas membrane separation, extraction, and vacuum technologies offer energy-efficient solutions suitable for azeotropic or heat-sensitive mixtures. Adsorption is particularly effective for removing trace impurities, with increasing emphasis on biomass-derived adsorbents. Special attention is paid to lignin, whose functional group diversity, high porosity, and chemical modifiability enable the creation of low-cost, highly effective, and ecologically safe adsorbents.

Furthermore, integrated processes—such as combining distillation with adsorption or membrane technologies—are increasingly implemented to achieve superior solvent purity while optimizing energy use. Overall, advancing energy-saving technologies and natural adsorbents supports green chemistry principles and promotes sustainable resource reuse.

Keywords: Organic solvents, Regeneration, Purification, Distillation, Membrane technologies, Lignin adsorbents.

Organic solvents are the integral part of chemical, pharmaceutical, petrochemical, dyes and varnishes, polymeric materials production and many other branches of industry. When used, they are getting polluted with various organic and inorganic admixtures, and thereby their efficiency is significantly reduced. Direct disposal of used solvents is associated both with substantial economic losses and environmental pollution, that is why the development of their purification and regeneration technologies is of great importance [1].

In the presented work, we have considered the key methods of organic solvents purification and regeneration, their advantages and restrictions. Distillation, rectification, adsorption, membrane technologies, extraction and other modern approaches have been considered. Special attention has been paid to the use of natural-origin adsorbents, especially lignin in the organic solvents' purification process [2].

Organic solvents are liquid organic compounds used for securing of extraction, purification, synthesis and technological processes related to different substances. Their ability to dissolve diverse organic and inorganic substances stipulates their wide application in the industry and scientific research [3].

As of today, million tons of organic solvents are used every year worldwide.

They become most widely used in pharmaceutical production, organic synthesis process, petroleum (oil) processing, manufacture of polymeric materials, dyes, varnishes, and electronic components.

Acetone, methanol, ethanol, isopropanol, ethyl acetate, toluene, xylene, hexane, chloroform, and dichloromethane are ranked among the most common solutions.

In the course of technological processes, the solvents are gradually polluted by different admixtures, such as reaction by-products, resinous substances, catalyst residuals, water, metal ions and mechanical particles. Use of polluted solvents deteriorates product quality, increases energy consumption and frequently leads to technological process failure [4].

Many organic solvents easily evaporate and form volatile organic compounds, which take part in photochemical smog formation and have a negative effect on human health and ecosystem.

One of the most effective lines of problem solution is a regeneration of organic solvents, which implies their restoration up to such degree, which makes it possible to reuse them in the technological process, reduces the consumption of new solvents, amount of hazardous waste and economic expenses incurred by enterprise.

Over the last two decades a special attention has been paid to development of those technologies, which are featured by low energy consumption, high efficiency and minimum environmental impact]5].

Among these methods the most important ones are membrane separation, use of supercritical fluids, advanced adsorption technologies and application of modified forms of natural adsorbents, including lignin.

Lignin, as one of the basic components of vegetable biomass, has become the subject of special attention over the last years. Its chemical structure, high porosity and diversity of functional groups makes it possible to generate effective, cheap and ecologically safe adsorbents successfully used in purification and regeneration of organic solvents.

Organic solvents are classified by several features according to polarity.

Polar solvents are distinguished by high dielectric constant and they are good solvents for polar substances [6].

Non-polar solvents are used as solvents for fats, oils and other hydrophobic substances.

Chlorinated solvents are distinguished by high dissolving ability, however due to toxicity and environmental impact they require special control.

Classification according to boiling temperature is especially important during distillatory regeneration:

- low-boiling <100°C;
- medium-boiling 100°C-150°C;
- high-boiling >150°C.

Multiple use of solvents gradually deteriorates their quality. In the course of reaction, the by-products, resinous substances, polymers and oxidation products are formed, which reduce solvent purity.

Many organic solvents are hygroscopic and absorb moisture from the air. Water presence is especially problematic in pharmaceutical and high-purity chemical production, since it has an effect on reaction rate and product quality [7].

Solvents can be polluted by inorganic admixtures, which frequently leads to corrosion and reduces service life of processing equipment.

Dust, carbon particles, filter residuals and other solid particles impede technological process and deteriorate solvent quality.

Regeneration of organic solvents is one of the important directions of modern chemical technology [8].

Various physical, chemical and mixed technologies are used for regeneration of organic solvents. Method choice depends on solvent nature, admixture type, their concentration, required purity degree and economic efficiency of the process. Modern enterprises frequently use the combination of several methods, which enables restoration of high quality.

- Distillation and rectification;

Distillation is one of the oldest and widely used methods of organic solvent purification. The method is based on difference between boiling temperature of components entering a mixture. More volatile components evaporate during a process, then become condensed and relatively pure substance (solvent) is obtained [9].

This method is especially effective in case of regeneration of such solvents, which admixtures are featured by different volatility. For instance, it is possible to restore hexane, acetone, ethanol, ethyl acetate and other solvents.

Rectification is an improved version of distillation, during which a multi-stage separation is used. Repeated contact between steam and vapor in the column type rectifier enhances separation efficiency and makes it possible to obtain a high-quality product.

Advantages:

- technology simplicity
- opportunity of processing large volumes of solvents;
- receipt of high-quality product.

Shortcomings:

- high energy consumption;
- opportunity of decomposition of thermally sensitive compounds;
- difficulty of azeotropic mixtures' separation;
- adsorptive purification.

Adsorption is one of the most effective methods for small amount admixture removal from organic solvents. This process is based on substance adsorption on the solid state surface [10].

The following substances are used as adsorbents:

- activated carbon;
- zeolites;
- silicagel;
- aluminium oxide;
- polymeric adsorbents;
- materials prepared on biomass basis.

Activated carbon is widely used due to its large surface and porous structure. It effectively adsorbs nonpolar organic solvents, including hexane, toluene and chlorinated solvents.

In recent years a special attention has been paid to natural adsorbents. Lignin, as a basic polymer of vegetable biomass, consists of functional groups of hydroxide, methoxide and other substances, which participate in organic molecules' binding. Lignin chemical modification enhances its adsorptive capacity and extends its potential for use [11].

Advantages:

- high selectivity;
- low temperature;
- effective removal of small amounts of admixtures;

Restrictions:

- adsorbent saturation;
- necessity of periodical substitution;
- low selectivity of some solvents;
- membrane technologies.

Membranous processes represent the modern energy-efficient technology, which is based on selective transport (transfer) of mixture components through semi-conducting membrane.

The following techniques are used for organic solvent purification: pervaporation, steam-conducting membranes, nano-filtration, and organo-filtration processes.

The key advantage of membrane methods is their low energy consumption compared to distillation. They are especially prospective for azeotropic mixture separation and removal of small amount of water from organic solvents [12].

Disadvantages:

- membrane contamination;
- relatively high initial cost;
- difficulty with membrane selection for particular system.

Extraction method.

Extraction is the method for organic solvent purification, based on different solubility of components entering into the mixture, between two phases immiscible to each other. This method is especially effective, when it is difficult to separate via distillation the admixtures present in the solvent to be processed or their boiling temperature is close to that of basic solvent.

In the extraction process, such solvent is used additionally, which has high selectivity towards specific admixture. Upon completion of the process takes place phase separation and extragent (extraction agent) regeneration if required [9,10].

Extraction is used for: removal of organic acids; separation of polar admixtures; removal of resinous compounds and compounds with high molecular mass.

The method advantages:

- high selectivity;
- it is possible to purify thermally sensitive compounds;
- relatively low temperature regime.

Shortcomings:

- need for additional solvent;
- multiple-stage process;
- necessity of subsequent removal of extragent (extraction agent)
- chemical treatment methods.

In some cases, chemical treatment is necessary for receipt of high-purity organic solvent. This method is used when it is impossible to remove admixtures using physical methods only [11,12].

For removal of water, acids and alkaline admixtures, as well as oxidative admixtures, the following chemical treatment methods are used: cryogenic and vacuum technologies. For regeneration of some high-purity solvents the special technologies, such as vacuum distillation and low-temperature selection are used.

Vacuum distillation makes it possible to reduce boiling temperature and to avoid decomposition of thermally unstable organic compounds.

This method is of great importance for pharmaceutical production, receipt of high-purity reagents and heat-sensitive solvents.

- Combined methods

Modern enterprises increasingly make use of integration of several technologies, since a single method doesn't not always guarantee complete removal of all types of admixtures.

For instance:

Distillation + adsorption.

Separation of basic solution is conducted using distillation, while adsorption removes the rest small amounts of organic admixtures [4].

Membrane technology + distillation

Membrane reduces content of water or specific components, while distillation secures final purification.

Chemical processing + adsorption.

Chemical method, when used, transforms or decomposes complex admixtures, and adsorbent provides final polishing.

Combined processes are especially important for modern green chemistry, since they reduce energy consumption and increases possibility of solvents' reuse [9,12].

Conclusions

Purification and regeneration of organic solvents is an important field of modern chemical technology. Restoration of used solvents reduces both manufacturing expenses and negative environmental impact.

Distillation, rectification, adsorption, membrane and other physical-chemical methods are widely used as of today. Each technology has its own advantages and restrictions, that is why their combination is frequently used for attaining high efficiency.

Application of energy-saving processes and ecologically safe adsorbents, including materials based on biomass, is particularly promising. Development of organic solvent regeneration will promote implementation of green chemistry principles and establishment of sustainable production.

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ორგანული გამხსნელების გასუფთავება და რეგენერაცია: თანამედროვე მიდგომები და განვითარების პერსპექტივები

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რეზიუმე

ორგანული გამხსნელები უმნიშვნელოვანეს როლს ასრულებენ ინდუსტრიის სხვადასხვა სექტორში, მათ შორის ფარმაცევტულ, ნავთობქიმიურ და პოლიმერების წარმოებაში, თუმცა ტექნოლოგიური პროცესების დროს ისინი თანდათან ბინძურდებიან მინარევებით. გამოყენებული გამხსნელების პირდაპირი უტილიზაცია დაკავშირებულია როგორც მნიშვნელოვან ეკონომიკურ დანაკარგებთან, ასევე გარემოს დაბინძურებასთან მრავალი ორგანული ნაერთების წარმოქმნის გზით. შესაბამისად, გაწმენდისა და რეგენერაციის ეფექტური ტექნოლოგიების შემუშავებას დიდი მნიშვნელობა აქვს მდგრადი სამრეწველო საქმიანობისთვის. წინამდებარე ნაშრომში განხილულია გამხსნელების აღდგენის ძირითადი ფიზიკური, ქიმიური და კომბინირებული მეთოდები, მათი მოქმედების პრინციპები, უპირატესობები და შეზღუდვები. სტანდარტული ტექნოლოგიები, როგორებიცაა დისტილაცია და რექტიფიკაცია, იძლევა დიდი მოცულობის გადამუშავების საშუალებას, თუმცა ხასიათდება მაღალი ენერგომოხმარებით; ხოლო მემბრანული სეპარაცია, ექსტრაქცია და ვაკუუმური ტექნოლოგიები ენერგოეფექტურ გადაწყვეტილებებს გვთავაზობენ აზეოტროპული ან

თერმულად მგრძნობიარე ნარევებისთვის. ადსორბცია განსაკუთრებით ეფექტურია მცირე რაოდენობის მინარევების მოსაცილებლად, სადაც სულ უფრო მეტი ყურადღება ეთმობა ბიომასაზე დაფუძნებულ ადსორბენტებს. განსაკუთრებული ყურადღება გამახვილებულია ლიგნინზე, რომლის ფუნქციური ჯგუფების მრავალფეროვნება, მაღალი ფორების არსებობა და ქიმიური მოდიფიცირების შესაძლებლობა იძლევა იაფი, მაღალეფექტური და ეკოლოგიურად უსაფრთხო ადსორბენტების შექმნის საშუალებას. გარდა ამისა, სულ უფრო ხშირად დანერგილია ინტეგრირებული პროცესები - მაგალითად, დისტილაციისა და ადსორბციის ან მემბრანული ტექნოლოგიების კომბინაცია -გამხსნელის მაღალი სიწმინდის მისაღწევად და ენერგიის მოხმარების ოპტიმიზაციისთვის. მთლიანობაში, ენერგოდამზოგავი ტექნოლოგიებისა და ბუნებრივი ადსორბენტების განვითარება ხელს უწყობს „მწვანე ქიმიის“ პრინციპების დანერგვასა და რესურსების მდგრად განმეორებით გამოყენებას.

საკვანძო სიტყვები: *ორგანული გამხსნელები, რეგენერაცია, გაწმენდა, დისტილაცია, მემბრანული ტექნოლოგიები, ლიგნინის ადსორბენტები.*