Driving the innovation
SUNRESIN

Polymeric Adsorbents

Resin Technologies and Systems for Pharma, Food, Chemical and Waste Water Applications

SEPLITE SEPSOLUT

About Sunresin

- Market Value: **$4 Billion**

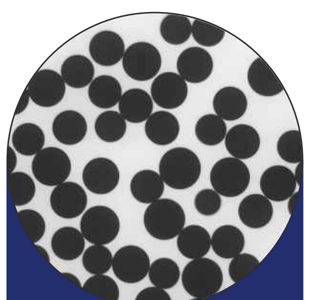
  We're Asia's largest manufacturer of ion exchange and adsorbent resins and an A-listed company in China, employing over 1400 people worldwide.

- Driven by **Innovation**

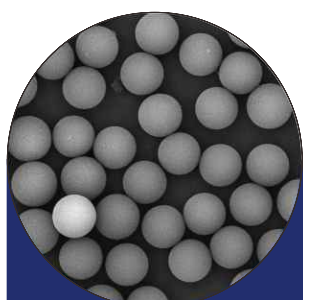
  With 30% of our workforce dedicated to R&D, we lead the way in developing cutting-edge solutions for the most complex challenges.

- **Top 3** in the world

  An internationally-recognized innovation leader in separation, purification and extraction technologies for highly-regulated global industries.



Solid Phase Synthesis resins



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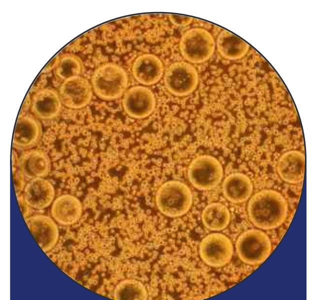

Microcarriers cell culture

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Adsorption, Extraction, and Purification Technologies

Ion exchange resin and polymeric adsorbents are well established products for purification and separation technologies. The significance of adsorption, extraction, and purification technologies cannot be overstated as they are the core steps in a myriad of applications, ranging from pharmaceuticals to food processing, and from environmental conservation to chemical processing. At Sunresin, we are not just participants in the field of adsorption; but we are an innovation company at the forefront of resin technology. We are committed to research and development, as we understand that the complexities of modern purification require unique products and solutions.

This brochure explores the world of adsorption, and the pivotal role played by polymeric adsorbents, highlighting their industrial applications and the groundbreaking work of Sunresin in this field.

Adsorption is a surface-based process where molecules from a liquid or gas phase adhere to a solid surface, the adsorbent, via a combination of hydrophobic (water hating) and/or hydrophilic (water loving) interactions. Activated carbon is the archetype of adsorbents and well established for more than 2000 years (e.g. wine production and water purification). Polymeric ion exchange resins of high capacities have been introduced in the mid of the twentieth century. Since then, many special resins and applications have been developed. Adsorbents have been commercialized in the early 1970s to improve the purity of new food applications. Today polymeric adsorbents are used in extraction processes to separate specific substances from a complex mixture and is widely used in food processing, such as the isolation of flavours and nutritional components, as well as the extraction of impurities. While the pore structure and surface chemistry of activated carbon can depend on the location and type of raw material, synthetic adsorbents allow to design the adsorbents with defined producible pore structure, hydrophobicity, particle size and surface modifications e.g. to allow for chemisorption of CO_2 as an important and emerging application (direct air capture).

• Introduction to Adsorption

Adsorption is a process where molecules from a fluid (liquid or gas) adhere to the surface of a solid (adsorbent), forming a single or multilayer adhesion onto the surface of the adsorbent. In the following section, the principles of adsorption are briefly discussed to support the selection of polymeric adsorbents for certain applications. Adsorption processes are driven by the different resin properties within these applications. The most important apparent property might be specific adsorption capacity but kinetics, pressure drop, yield, and productivity play an important role as well.

• Fundamental Principles

In general adsorption can be categorized into physical adsorption (physisorption) and chemical adsorption (chemisorption). Physisorption is induced by bonding forces based on surface energy. These bonding forces are hydrophobic, ionic, hydrogen bonds, and van der Waals forces. They vary in the kind of interaction and the binding forces but typically are below 100 kJ/mol, allowing for the reuse of the adsorbent. Chemisorption is a process of different binding forces, which exceeds 200 kJ/mol by forming covalent bonds, making the reuse of the resin a challenging step. Molecules will typically leave the fluid phase to bond with the adsorbent surface based on its solubility or selectivity towards the polymeric resin backbone. Elution is then performed by reversing the process where the molecules will be more miscible in the new fluid phase, such as the use of alcohols or extreme pH changing the miscibility.

Polymeric Adsorbents consist of different polymeric backbones and hence different hydrophobicities. The adsorbents are highly crosslinked to produce a very porous matrix with a significant surface area (equivalent to the area of multiple tennis courts per dry gram of resin). Adsorbents are defined by the following:

- resin backbone
- high surface area (expressed in m^2/dry gram)
- controlled pore size (expressed in nm or Angstrom, Å) or pore volume (expressed in ml/dry gram)
- Resin bead size (expressed in μm)

• Resin Backbone

One of the most common polymeric adsorbents is produced as a copolymer of styrene and divinylbenzene (DVB). The composition can vary and hence several properties of such adsorbents can be modified, Figure 1.

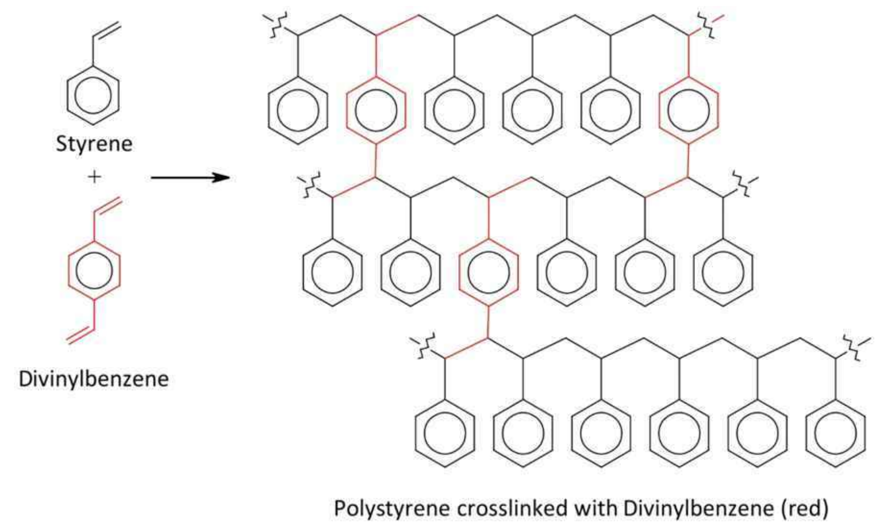


Figure 1. Styrene Crosslinked with Divinylbenzene

Styrenic adsorbents are hydrophobic in nature and so they adsorb non-polar or hydrophobic molecules. Typically, these hydrophobic species show a limited solubility in polar solvents such as water. More polar polymeric adsorbents, such as acrylic adsorbents, can also be used in non-polar solvents where they can show stronger hydrophilic interaction with the more hydrophilic molecules. With polar adsorbents (like polymethylmethacrylate PMMA), weaker solvents can be used to regenerate and elute since they have limited hydrophobic behaviour, Figure 2. Therefore, savings in elution and regeneration can be achieved with PMMA when compared to the non-polar adsorbents. PMMA is typically the first-choice adsorbent when extracting highly hydrophobic molecules that would be too challenging to extract out of a styrenic adsorbents (such as the extraction of highly non-polar molecules).

Figure 2. Structure of methacrylic polymer.

A third type of adsorbent that is offered by Sunresin is the brominated styrenic adsorbent. The bromine is added as a highly electronegative halogen that will increase the hydrophobicity of the resin backbone(Figure 3). This implies that the brominated styrenic resin will be more hydrophobic than the standard styrenic adsorbents. The brominated styrenic is so hydrophobic that it leads to multilayer adsorption and therefore more capacity for extracted molecules. Since it is highly hydrophobic, it could be challenging to regenerate. Therefore, its applications are limited to molecules that show small hydrophobic behaviour like polyphenols and similar highly water miscible compounds.

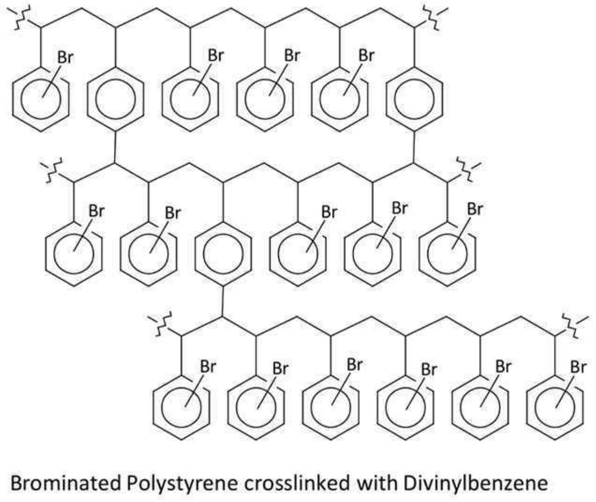


Figure 3. Structure of Brominated Polymer.

These adsorbent matrices are compared to a solvent/solvent extraction. Hence, the resin is a solid phase medium to replace the solvent-solvent purification work reducing the necessity of using a large amount of hazardous and flammable chemicals. The adsorbent will also allow the separation of more than 2 molecules from each other while the solvent/solvent extraction is limited to a binary separation.

• Surface Area

Polymeric adsorbents have a highly porous structure promoting a high surface area. The BET Method, using nitrogen adsorption, is commonly applied to measure the surface area of adsorbents in m^2/dry gram. It is important to note that over 95% of the adsorbent surface area lies inside the beads hidden within its porous structure. As long as the molecules being extracted can enter the pores and access the hidden surface area, a high surface area can lead to higher adsorption capacity (Figure 5.).

• Pore Size

The pore size is classified (by IUPAC) as described in Table 1.

Table 1. Pore Size Classification

Product name	Angström [Å]	Nanometer [nm]
Micropores	< 20	< 2
Mesopores	20-500	2-50
Macropores	> 500	> 50

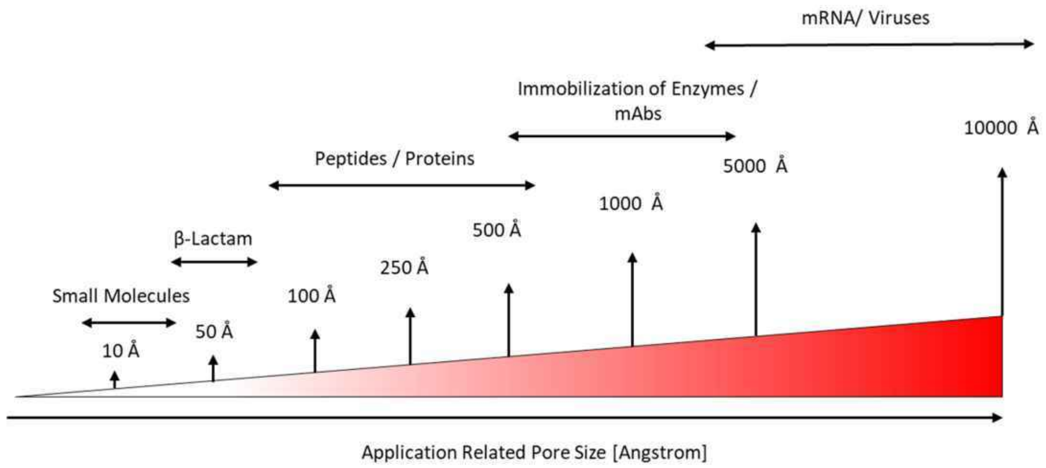
Polymeric adsorbents feature a variety of pore sizes with a unique pore size distribution. Fractions of the space inside the polymeric beads are occupied by different pores ranging from very small (micropores), to medium (mesopores), to large (macropores, see Table 1), each occupying different amount of space within the adsorbent bead.

The size of these pores is crucial because it influences how much of a substance the adsorbent can hold (its capacity) and how quickly it can capture that substance (kinetics). This relationship between pore size, capacity, and kinetics of adsorption is complex because it depends on how easily molecules can move through the pores, a concept known as pore diffusion.

Pore sizes are measured in relation to the volume they occupy, which helps to understand the distribution of different-sized pores within the material. This measurement is key for determining the material's effective surface area, which is the area available for trapping or interacting with the target molecules to be adsorbed.

The specific sizes of these pores also dictate the applications for which the resin is suited. For example, certain pore sizes may be more effective for capturing specific molecules, influencing where and how the adsorbent can be used. This size of different adsorbates is illustrated in Figure 4.

Figure 4. Applications of adsorbents for different types of molecules.



• Pore Volume

The pore volume, typically measured by mercury intrusion, is another important characteristic of polymeric adsorbents and correlates with kinetic, capacity and selectivity since it ties porosity to the surface area. Pore volume can reflect the capacity of a resin for larger molecules (larger than ~400 g/mol) since it represents the volume of the pores that are significant in size.

The set of characteristics of pore size, pore volume and surface area influence the selectivity of polymeric adsorbents on a physical level. For example, molecules and biomolecules vary in size and large molecules can be excluded from diffusion into the polymeric adsorbent only by selecting appropriate adsorbent pore sizes to force separation - called “size exclusion”.

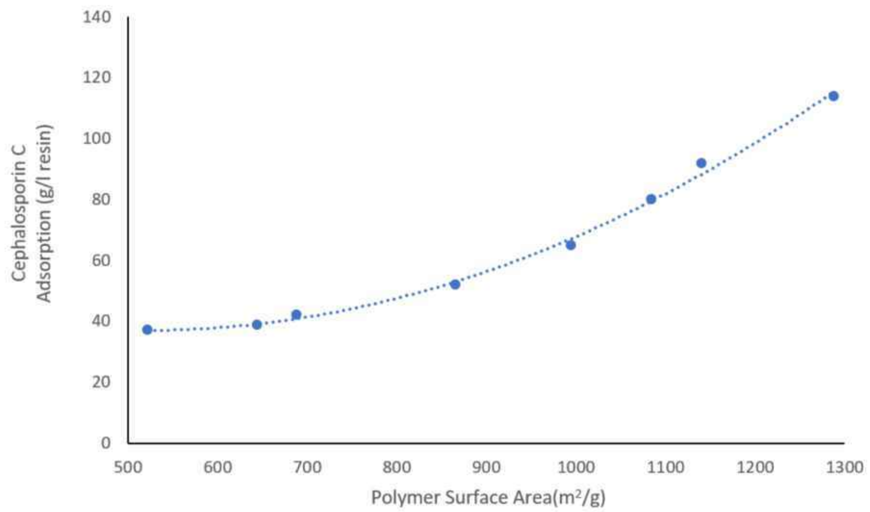


Figure 5. Adsorption isotherm of a Solution of Cephalosporin C (1% w/v Solution) vs. Surface Area (e.g. CT10 (>1200m²/g), LXA8302 (>1100 m²/g) and LXA84 (>700 m²/g)).

• Principle of Adsorption

As a general principle, adsorption often follows the “like attracts like” principle.
Polymeric adsorbents can be classified in base of their affinity towards molecules:

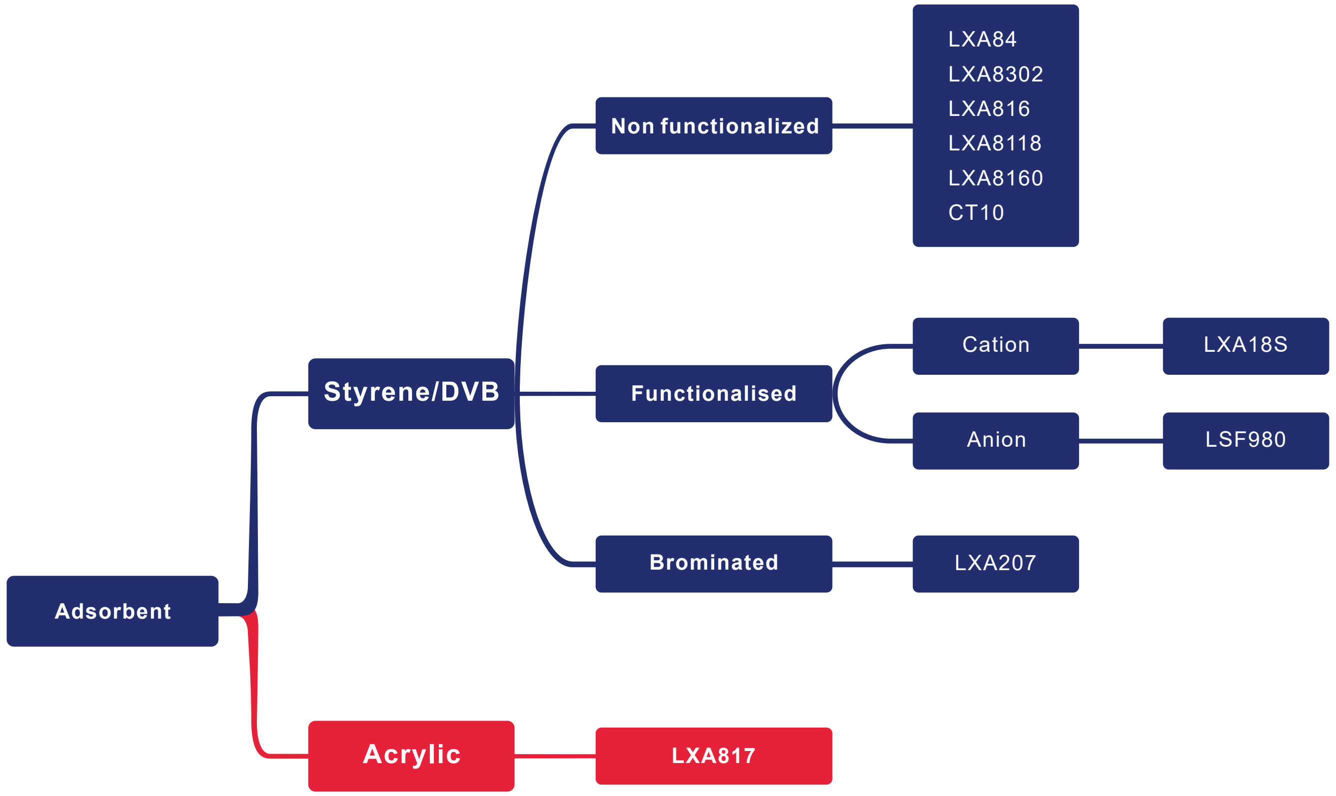
- polar backbone, more hydrophilic (in general acrylic backbone)
- apolar backbone, more hydrophobic (in general aromatic based on styrene/divinylbenzene), (aromatic like aromatic in the so-called π – π interaction).

As the adsorbed species are frequently the target compound (for example if extracted from a complex mixture) the elution of the target compound is important as well and hence the “strongest” (best capacity) adsorber for a compound might not be the best for the process during elution. Please refer to the section “Elution and Regeneration” for more information on elution. It is important to use these resins reversibly to extend its life for the specific application by limiting the build-up of fouling and reducing yields.

Similarly, aliphatic compounds are attracted to aliphatic adsorbent (like PMMA) while aromatic compounds are attracted to aromatic adsorbent (like polystyrenic-DVB resins) via π-π interaction of the aryl-aryl chemistry.

The resin selection guide will present different strategies on choosing the right adsorbent for specific applications.

Adsorbent Selection Guide



Polymer Backbone	Resin	Surface Modification	Specific Gravity	Porosity	Surface area (m^2/g)	Application
Styrene/DVB (Aromatic Resins)	CT10	Non-ionic	1.02 to 1.04	Small	≥1200	Widest applications in the industry for general adsorption
	LXA8302				≥1100	
	LXA84				≥700	
	LXA816			Medium	≥900	
	LXA8118			Large	≥700	
	LXA8160				≥800	
Polyacrylic (Aliphatic Resins)	LXA817	Non-ionic	1.07 to 1.10	Medium	≥400	For highly hydrophobic molecules for easier regeneration
Brominated Styrene/DVB	Lx207	Non-ionic	1.17 to 1.27			Expanded beds and low hydrophobic molecule extraction
Styrene/DVB Functionalized	LSF980	Tertiary amine (weak base)	1.03 to 1.06	Small	≥1000	For hydrophobic molecules with ionic properties (ionic surface to be used for attraction or repulsion mode)
	LXA18S	Sulfonated (strong cation)	1.15 to 1.25	Small	≥250	

Table 2. Adsorbent Characteristics

As mentioned previously, the hydrophobicity of the adsorbent is based on the backbone as well as the surface area (where higher surface area of the same matrix are offers more hydrophobicity). Therefore, one can choose the appropriate hydrophobic resin based on the below order of hydrophobicity:

LX207 > CT10 > LXA816 > LXA8118 > LXA817

Considerations for Optimal Resin Selection

The adsorbent characteristics help in the selection process of the correct adsorbents for specific applications. While there is a lot of published examples, this selection guide can help with new separations or to optimize existing processes. The adsorption efficiency needs a deeper understanding of the resin chemistry that influences the adsorption and desorption performance options, such as its ability to change hydrophobic behaviour based on pH and salt concentration.

The molecule-adsorbent interaction is dependent on the solvent characteristics as well as chemical interactions that can take place on the polymeric backbone or functional groups on the resin surface. Solvents can be polar, non-polar, protic, non-protic, or the combinations of these characteristics. Understanding the mechanisms influencing adsorption and desorption provides insights into picking the correct polymeric adsorbents. As a rule of thumb adsorption follows “like attracts like” hence a hydrophobic molecule will interact with a hydrophobic surface. When significant molecules are absorbed onto the adsorbent surface, a displacement can start occurring with the most hydrophobic molecules substituting for the less hydrophobic molecules.

Molecules which are ionic will be attracted towards ionic functional groups on the resins such as the use of ion exchange resins. Functional groups within a molecule such as alcohol, amine, carbonyl, etc. can undergo hydrogen bonding.

Adsorption and desorption are occurring simultaneously, and for an efficient adsorption process the desorption must be lower compared to the adsorption. The solubility of a molecule in the feed is a critical consideration. One example, glycol is fully miscible in water allowing hydrogen-oxygen bonding and hence the tendency towards the surface of a non-polar adsorbent is quite low in comparison to the desorption. Compounds with limited solubility will be better attracted by hydrophobic surfaces provided by polymeric adsorbents allowing for an efficient removal process. Hydrophobic molecules containing aromatic rings, or long chain non-polar aliphatic chain, are good examples for molecules being adsorbed by hydrophobic adsorbers e.g. Phenol, Polyphenols, Vanilla etc., Figure 6. Polystyrene divinyl benzene adsorbents will typically show better affinity towards molecules with benzene rings via π-π interaction of the aromatic rings.

One can decrease the hydrophobic interaction by increasing the alcohol concentration in the feed or increasing the hydrophilicity of the molecule via pH adjustment (e.g. pH adjustment to protonate the amines or ionize the molecule). Also, one can increase the hydrophobic interact by increasing the salt concentration in the feed or increasing the hydrophobicity of the molecule via pH adjustment (e.g. pH adjustment to deprotonate the amines or reduce the ionization of the molecule).

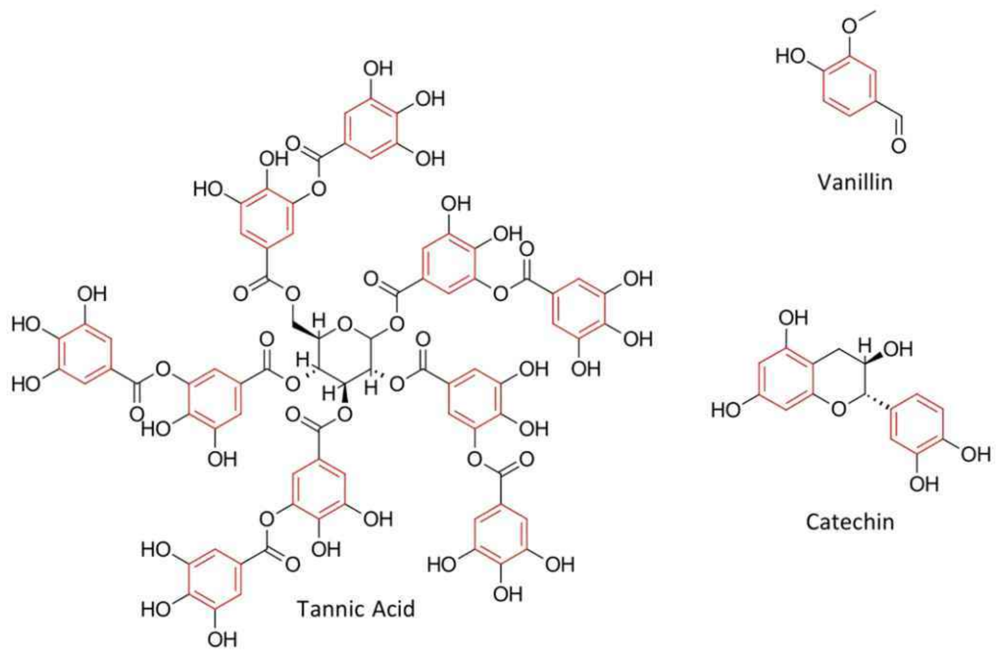


Figure 6. Structures of hydrophobic compounds, with aromatic rings inducing hydrophobic attraction shown in red.

Another important characteristic for choosing adsorbents is the selectivity over capacity. As the adsorption is always in competition with desorption the selectivity can be utilized by selecting a less hydrophobic methacrylic adsorbent (e.g. LXA817) vs more hydrophobic styrenic adsorbent such as LXA84 and brominated styrenic adsorbent such as LX207. The selectivity for various anthocyanins and flavonoids can be seen in Figure 7 with the chemical structure of Flavone and Cyanidin.

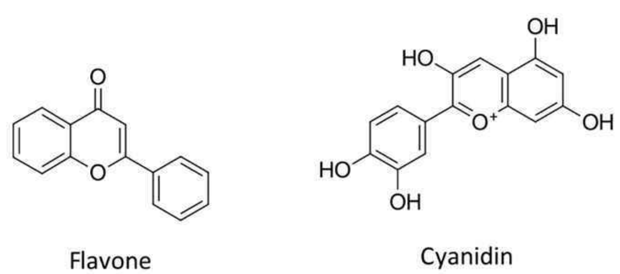
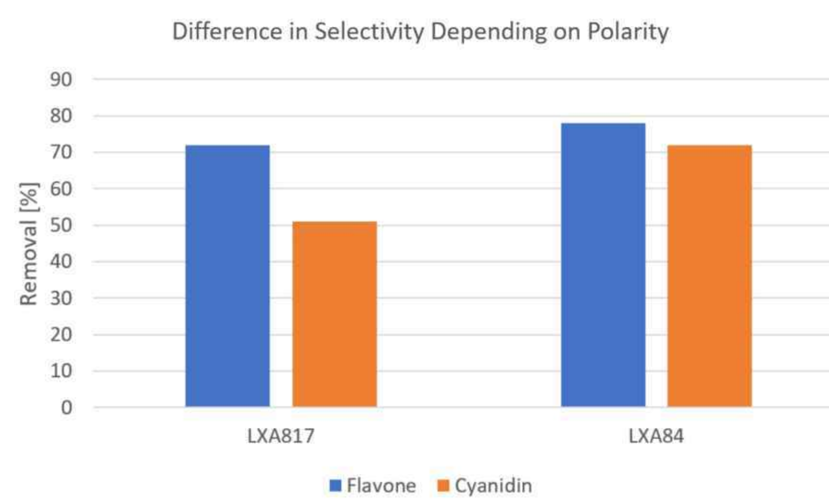


Figure 7. Chemical structure of Flavone and Cyanidin

As the polarity is more pronounced in the Cyanidin, due to more oxygen present, the selectivity towards the adsorbents is less. Hence Flavone will be adsorbed to a higher extent vs Cyanidin:



Selectivity is better on polar adsorbents such as LXA817

Non-polar adsorbent show high capacity but poor selectivity as seen with LXA84

The solubility and hence the desorption of Cyanidin in the aqueous solvent (water) is higher compared to Flavone leading to the difference in selectivity. This selectivity effect will be less pronounced if a strong hydrophobic adsorber is used such as nonpolar adsorbent.

Elution and Regeneration

General Considerations

Elution and regeneration of adsorbents follow the same principles as the adsorption in reverse. The driving forces for adsorption now needs to be weakened by applying the appropriate solvent. Seplite polymeric adsorbents vary in their hydrophobicity by their polymeric backbone. Chemical (e.g. solvents, caustic) as well as thermal (low pressure steam) methods can be applied to elute or regenerate the adsorbents. In case of functionalized adsorbents such as weak basic LSF980 or strong acid LXA18S a chemical regeneration is more applicable. The target of the elution is to extract the desired adsorbed compounds or impurities and return the adsorbent to its original states.

Temperature increase can be effective to weaken the binding forces as temperature nears the volatility of the absorbed compounds. While adsorption can increase with temperature, desorption will increase more significantly with temperature enhanced by the volatility of the absorbed molecules and aided by the use of vacuum. Therefore, thermal regeneration with low pressure steam is applied when dealing with volatile small molecules such as VOC.

Thermal regeneration is not used for larger molecules which necessitates chemical regeneration. Where temperature cannot be applied to elute the products, as the resin can be sensitive to thermal degradation at temperatures higher than 150°C (maximum thermal stability of a polymeric adsorbent in air), elution can be achieved by using the appropriate solvent. If the hydrophobic molecule has been adsorbed from a water phase, a solvent, with stronger solubility effect toward the molecule, can be applied such as acetone or alcohol. In some cases, elution can be achieved by specific solvent/water mixtures. The same concept applies in reversed phase chromatography (small bead adsorbents) where solvent mixtures are also widely applied as gradient or step wise.

Another desorption principle is changing the ionic state of an adsorbed compound. E.g. Phenol can be adsorbed from water easily at a pH where the phenol has no charge (Figure 8). The pKa of Phenol, a weakly acidic compound, is 9.89 (if the pH is 9.89 50% of the Phenol is present as an ion) and elution can be achieved by applying pH conditions at pH>11 where most of the phenols are ionized into their phenolate salt form.

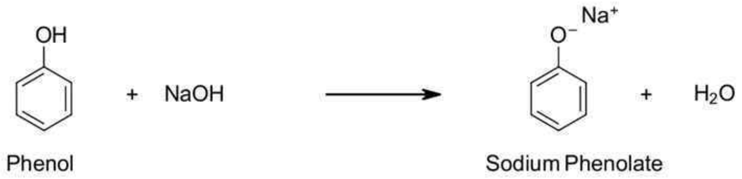


Figure 8. Formation of phenolate

Phenolate is more hydrophilic and hence the hydrophobic interaction is disrupted with pH change. This concept is also applied if adsorbed organic species are oxidized by dilute hydrogen peroxide or nitric acid. The oxidizing method is used in processes where flammable solvents cannot be used such as in debittering citrus juice applications. The oxidized species, present as weak acids, are water soluble and can easily be removed via softer regeneration.

Another example of molecules with properties depending on the pH are the aromatic amino acids. If the pH is equal to the isoelectric point (pI) the amino acid has a net zero charge. The carboxylic acid group is in its carboxylate salt state if the pH is above its pI value. The amine group will get more protonated (positively charged and carboxylic acid neutralized when the pH is below the pI (Figure 9).

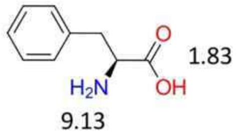


Figure 9. Phenylalanine and the pKa values

Adsorption is performed at the isoelectric point and desorption is possible by shifting the pH ±2 above or below the isoelectric point.

Although the polymeric adsorbents are chemically stable against other organic solvents such as benzene or toluene (adsorbents will extract such hydrophobic non-polar solvents), alcohols or acetone are the main solvents used in desorption processes.

Typical eluents and mixtures used for elution of adsorbed products are shown in Figure 10 and Figure 11.

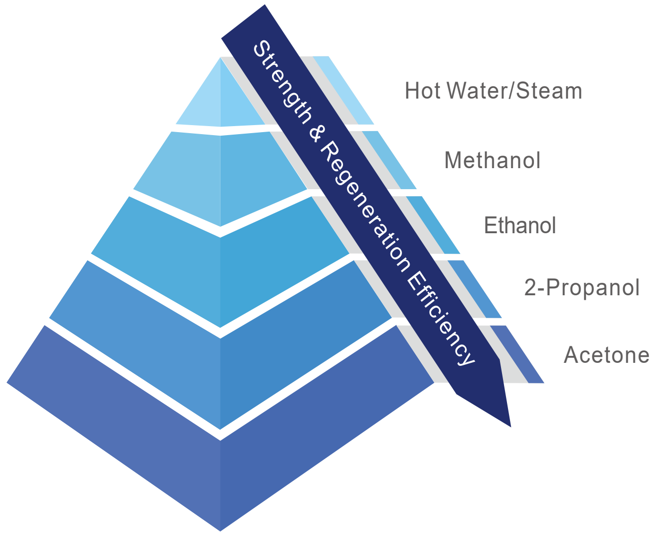


Figure 10. Strength and Regeneration efficiency of some organic solvents.

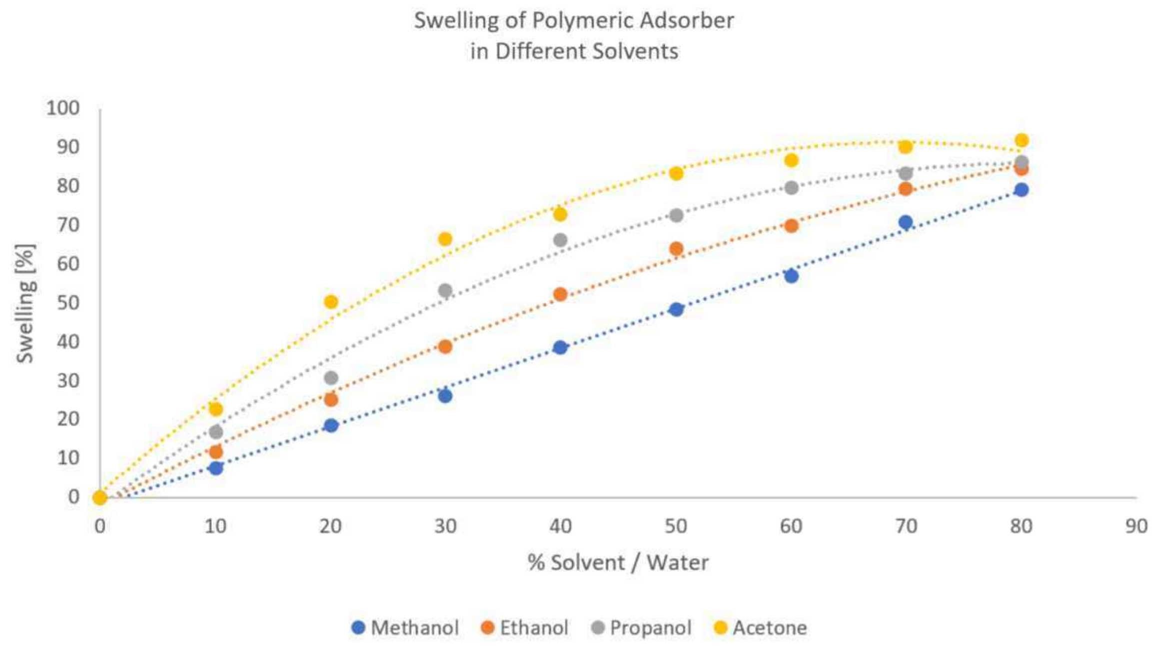


Figure 11. Hydration or elution strength of various alcohols and acetone on a polystyrene adsorbent.

Figure 11 demonstrates how the adsorbent is losing its hydrophobic behavior when alcohols or aceteone are used in elution, The resin swelling (taking on more water) provides important information if the alcohol is better used to elute two closely-related molecules (i.e. using the linear swelling obtained by methanol) or to regenerate the resin completely (i.e. using the highly polar acetone as a solvent).

The high chemical and physical stability of polymeric adsorbents allow for a variety of conditions for elution and cleaning and the presented methods shall be considered as guidelines.

Table 3. Loading, elution and regeneration conditions for adsorbents.

Step	Typical Volumes	Typical Flow Rate	Remarks
Backwash	Varies	Varies	Removal of fines and debris, air, dirt etc. bed expansion up to 75% or more possible
Conditioning (e.g. with solvent)	5 BV	2-3 BV/h	Hydration of surface, removal of air etc.
Rinsing	3 BV	2-3 BV/h	Remove feed, solvents, buffers
Loading	Depends on application	2-5 BV/h	Capacity depends on design and breakthrough limit
Wash	1 BV	2-3 BV/h	“Sweetening Off” – displace feed
Elution	Varies with Application	2 BV/h	Desorption
Cleaning/Regeneration	3-5 BV	2 BV/h	Regularly applied as needed
Final Rinse	2-5 BV	2-3 BV/h	e.g. until pH is neutral

As general considerations for an elution/regeneration process the following steps are typically applied. A min. 50cm bed depth is required for process operation. Max. 3m to avoid resin compression

1. Displacement of Residual Liquid with Original Carrier Fluid (e.g. water)

Often called “sweetening off” the displacement of residual liquid prior to desorption is applied to avoid mixing the eluted target molecules with the feed contaminants Flow rate is typically 1-3 BV/h for about 1-2 hours.

2. Elution/Regeneration

Appropriate amount and concentration of regenerant is applied at a controlled flow rate of 1-2 BV/h for up to 1,5h. Upflow regeneration is typically preferred as not to push the highly hydrophobic molecules through the entire column bed.

3. Backwash

A backwash is applied to achieve a bed expansion of 30% or more) to remove fines, particles and broken beads. The backwash will also avoid channelling and subsequently avoid performance loss during the service and regeneration, via stratifying the resin bed.

If the adsorbed molecule is the product of interest, the elution should be performed carefully to achieve the product in the desired purity. A backwash would be applied after the elution has been completed. If the process is e.g. removal off off-flavours such as debittering of orange juice the backwash can be applied in advance of the desorption step. Note that oils can foul an adsorbent reducing its specific gravity. Therefore, fouled adsorbents will tend to float or settle on the top of the resin bed during backwashing.

As the adsorbents swell when the mobile phases are changed and to avoid damaging equipment, the solvent can be applied in upflow direction to allow sufficient expansion. Swelling of the adsorbents, indicating the resin is taking in more water therefore becoming less hydrophobic, can support release of adsorbed molecules. In addition, the pore structure becomes more open, and desorption is enhanced .The performance of a complete cycle of adsorption and desorption may vary over the initial cycles and hence a stable performance will be achieved after several cycles such as 3-5 cycles.

Some applications may also require a regular stronger cleaning procedure to restore the original adsorption capacity as pores can get blocked by fouling as seen in the example table below.

Method	Specific Surface Area
New Adsorbent	720 m²/g
Used Adsorbent	100 m²/g
Cleaned with Methanol	250 m²/g
Cleaned with Isopropanol	400 m²/g
Cleaned with Isopropanol + 4% NaOH	575 m²/g

Table 4. Recovery of surface area based on different regeneration methods.

Regeneration example:

1.Resin Adsorption Process:

- Feed the solution into the resin column in a forward direction at a flow rate of 1–3 BV/h (BV refers to resin bed volume).
- Collect instantaneous volume samples from the outlet every 2 BV and test the butyl peroxide content.
- Stop adsorption when the content exceeds the required specification.

2.Resin Regeneration:

a. Nitrogen Pressure Displacement:

- Use nitrogen gas (<0.1 MPa) to displace the solution from the resin column in a forward direction.
- Collect the displaced solution into the raw material tank for re-adsorption.
- Perform nitrogen purging for 10–20 minutes (until no liquid exits).

b. Steam Regeneration:

- Use steam (0.1 MPa) to regenerate the resin in a forward direction.
- The effluent is cooled through a heat exchanger and collected into the desorption liquid tank.
- The steam regeneration time is 60–100 minutes (regeneration time = time for steam to exit the bottom of the resin column × 2.5).

c. Cooling with Qualified Liquid:

- Use qualified liquid (post-adsorption solution) to cool the resin column in a reverse direction.
- The outlet is returned to the qualified liquid tank after passing through a heat exchanger.
- Cooling time is 60 minutes (until the resin column temperature drops to ambient temperature).
- The resin regeneration process is complete, and the resin can be immediately used for the adsorption stage.

Separation Efficiency Control of Bead Particle Size

The separation of closely related molecules is a common application in chromatography where the solute is retained by a stationary phase. The particle size in analytical applications, such as high-performance liquid chromatography (HPLC) will be 5 µm or less and as scale increases to industrial processes, the particle size can increase to allow e.g. lower pressure drop across the resin bed. The typical adsorbent bead size in industrial applications in bind and elute application is 300 to 1200 µm. A better separation in applications can be achieved by smaller particles sizes with controlled particle size distribution, see Table 3.

Table 5. Seplife resins for RP chromatography and adsorption.

Product	Matrix	Particle Size (µm)	Pore size: (Å)
Seplife® RP LX-21SS(L)	Polystyrene/DVB	100-300	300
Seplife® RP LX-21SS(M)	Polystyrene/DVB	50-100	300
Seplife® RP LX-21SS(S)	Polystyrene/DVB	30-50	300
LXMS-10	Polystyrene/DVB	10±1.0	150-300
LXMS-15	Polystyrene/DVB	15±1.5	150-300
LXMS-30	Polystyrene/DVB	30±3.0	150-300

Sunresin offers a wide range of chromatography grade resins. For process optimization the cost of such resins needs to be taken into considerations as the costs will increase with smaller particle size. Systems can be designed as batch or as continuous. Sunresin offers simulated moving beds (SMB) design and equipment for efficient separation processes.

It is important to note that salt can increase the hydrophobic attraction between molecules and the polymeric adsorbent. Therefore, salts cannot be used as a regenerant or an eluant. But salts can be used to increase the adsorption capacity of the polymeric adsorbent and add some selectivity criteria without the necessity to using more hydrophobic resins such as Lx207.

Food Industry:

The food industry extensively utilizes adsorption technology for extracting natural sweeteners like Stevia, as well as flavors and natural color bodies. This ensures that food products are not only taste appealing but also safe for consumption.

Nutraceuticals:

In the nutraceutical industry, polymeric adsorbents are crucial for efficiently extracting and purifying a wide range of beneficial compounds, from antioxidants and natural sweeteners to essential amino acids and herbal extracts, enhancing health and well-being.

Pharmaceutical Industry:

In the pharmaceutical sector, adsorption is a key technique for extracting life-saving compounds such as Heparin or Taxol. These compounds, critical for various treatments, require precise and efficient extraction methods to ensure their efficacy and safety.

Medical Devices and Diagnostics:

Polymeric adsorbents play a transformative role in critical care, enhancing plasma detoxification for acute liver or renal failure and sepsis management, and improving diagnostic accuracy by effectively removing interfering substances in blood tests.

Chemical Industry:

In the realm of chemical industry, polymeric adsorbents are key for the purification of raw materials, intermediates and final products. They are extensively used in separation of products and removal of impurities, playing a crucial role in enhancing the quality of fine and specialty chemicals. Applications are countless and includes the petrochemical sector, polymer production (e.g. purifying monomers and solvents) and ensuring protection of the environment, where polymeric adsorbents are employed in treating industrial effluents and emissions, significantly reducing the environmental impact of chemical processes.

Application Guide

The realm of natural extracts is a complex one, where the science and process technology of adsorption play a pivotal role. These extracts, derived from plants or fermentation broths, and other natural sources, present a unique challenge due to their complex composition and the nuances they interact with various adsorbents. As we delve into the diverse applications of adsorption technology, its significance in the extraction and purification of a myriad of natural compounds becomes increasingly evident.

- **Applications in Various Industries**

While these compounds have traditionally been sourced directly from nature, the growing demand for natural products has led to the emergence of biosynthesis and fermentation broths as a vital source. This shift is particularly notable in the context of:

1. Meeting Global Demand:

- Biosynthesis and fermentation broths are increasingly important in fulfilling the global demand for natural products, offering a sustainable and scalable alternative to traditional nature-based methods.

2. Complexity in Downstream Processing:

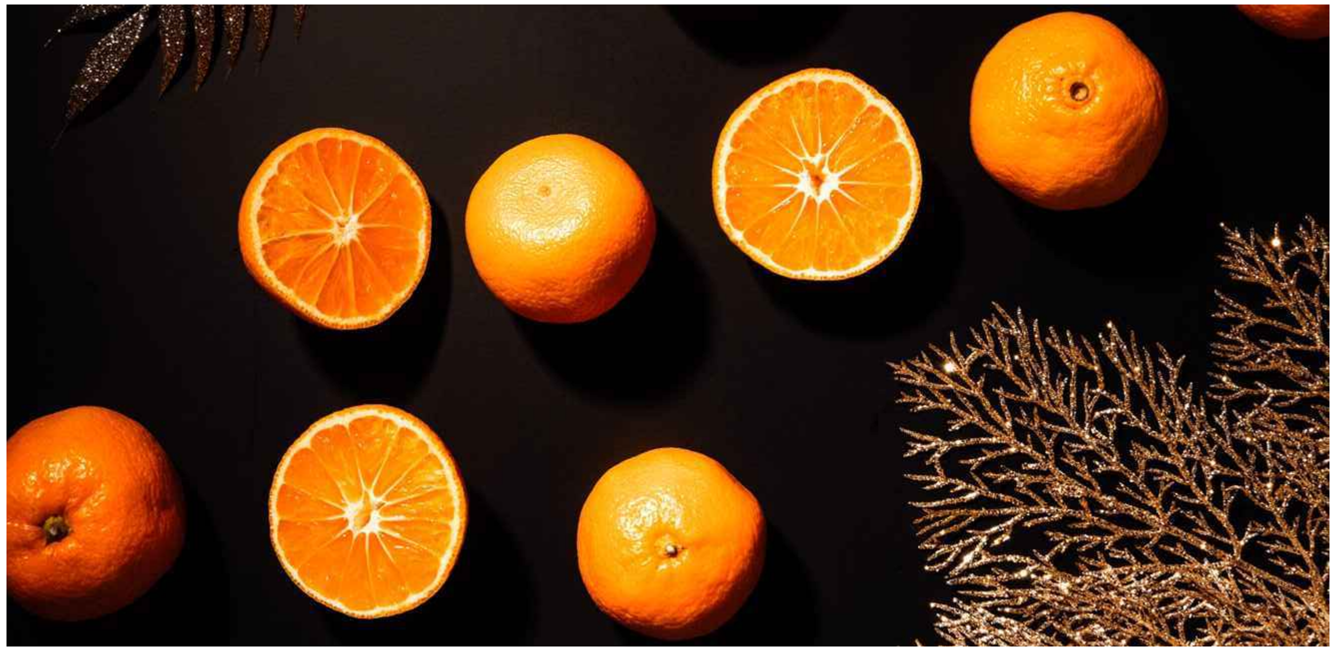
- The downstream processing of products like fermentation broths mirrors the complexity found in the extraction from natural raw materials. This highlights the need for sophisticated adsorption techniques capable of handling diverse and intricate mixtures.

Food and Beverage Applications

In the dynamic and evolving world of food and beverage processing, the application of polymeric adsorbents has emerged as a transformative technology. These adsorbents play a crucial role in refining and purifying a wide array of products, ensuring both quality and safety for consumers. Polymeric adsorbents in the food and beverage industry are applied to for enhancing flavours, removing unwanted components, and ensuring compliance with health standards.

• **Debittering Citrus Juices:**

Bitterness in citrus juices, primarily caused by limonoids and flavonoids like limonin and naringin, can significantly affect the taste and consumer appeal. Polymeric adsorbents are employed to selectively remove these bitter compounds, thereby improving the sensory quality of the juice without altering its natural flavour profile.



• **Patulin Removal in Fruit Juices:**

Patulin, a mycotoxin produced by certain fungi, poses a significant health risk, especially in apple and pear juices. The removal of patulin is critical to meet health standards set by global health authorities. Polymeric adsorbents effectively eliminate patulin, ensuring the safety and compliance of fruit juices with regulatory limits.

• **Color and Impurity Removal:**

In various food and beverage products, the removal of unwanted color and impurities is essential for both aesthetic appeal and quality. Polymeric adsorbents are adept at removing hydrophobic organic compounds, thus enhancing the clarity and purity of these products.

• **Pesticide Removal:**

With growing concerns over pesticide residues in foods and beverages, the role of polymeric adsorbents in removing these harmful substances is increasingly vital. Their ability to selectively adsorb pesticide residues ensures the safety and quality of the final products.

- **Specialized Applications:**

  The use of polymeric adsorbents in the food and beverage industry represents a significant step forward in processing technology. By enhancing flavour profiles, removing toxins and impurities, and ensuring product safety, these adsorbents are integral to delivering high-quality products to consumers as shown in Table 5. As the industry continues to evolve, the role of polymeric adsorbents in meeting the complex demands of food and beverage processing will undoubtedly expand, driving innovation and excellence in this sector.

Table 6. Typical resins used for natural extract applications.

Compound	Application	Process Step	Resin
Color Removal			Various, LSF975, LSF980, LXA8118
Limonin	Bitterness Removal from Orange Juice		LXA817, LXA816
Naringin	Removal from Grapefruit juice		LXA816, LXA817
Patulin	Removal from Apple Juice		LXA816, LSF980
Pesticides Removal	Atrazin, Benazolin, Bentazone, Imazapyr		CT10
Wine Must	Extraction		LX207

Regeneration of the adsorbents on these industries where impurities are being removed typically use caustic rather than alcohols as they are not set-up for flammable proof systems. Dilute peroxides can be used to aid in the regeneration in addition to dilute acids (phosphoric or citric) at the end of the regeneration process to neutralize the pockets of caustics trapped in the resin bed.

Nutraceutical Applications

- **Phenolic and Polyphenolic Compounds: Antioxidants in Nature**

  Phenolic and polyphenolic substances, such **as flavonoids, catechins, and anthocyanins,** are celebrated for their potent antioxidant properties. Predominantly found in fruits, vegetables, tea, and wine, they are pivotal in combating oxidative stress and inflammation, contributing to improved cardiovascular health, enhanced brain function, and potentially reducing cancer risks.

- **Applications in Food and Beverage Industry**

  These compounds significantly influence the food and beverage industry by enhancing sensory attributes like color, taste, and aroma. Natural sweeteners like Stevia have transformed the sweetener industry by offering healthful, low-calorie alternatives to sugar.

• **Pharmaceutical Applications: Alkaloids and Glycoalkaloids**

In pharmaceuticals, alkaloids (from plants like poppy and belladonna) and glycoalkaloids serve medicinal purposes, ranging from pain relief to anti-cancer effects, and even agricultural applications due to their pesticidal properties.

• **Amino Acids and Peptides: Building Blocks of Life**

Amino acids, essential for muscle repair and neurotransmitter function, along with peptides known for anti-aging properties in skincare, are fundamental to human health.

• **Carotenoids and Astaxanthins in Health and Beauty**

Carotenoids and astaxanthins, with their vibrant colors and antioxidant capabilities, are crucial for health and widely used in the cosmetic industry for skin health and UV protection.

• **Nutraceuticals: Enhancing Well-being**

Substances like chondroitin and isoflavones in the field of nutraceuticals exemplify how natural extracts can enhance well-being, treating conditions like osteoarthritis and aiding in menopause management.

- **Herbal Extracts: Traditional and Modern Therapeutics**

  Herbal extracts, rich in phytochemicals, have been integral in both traditional and modern therapeutic practices, treating a range of ailments and supporting complex treatment regimens.

- **Cannabidiol (CBD): Therapeutic Potential**

  CBD, known for its therapeutic benefits ranging from epilepsy relief to chronic pain management, faces unique extraction and purification challenges due to its molecular similarity to THC.

- **Refining Amino Acids and Other Compounds**

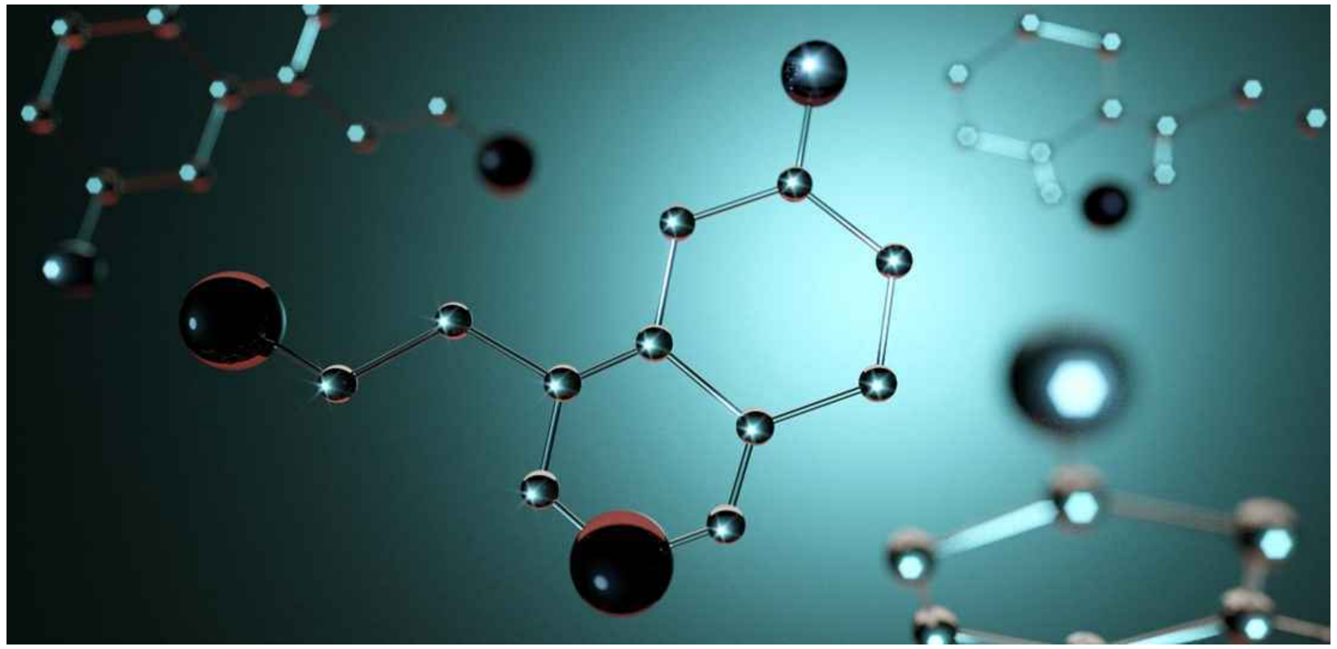
  The purification of amino acids, focusing on nonpolar side chains and specific isoelectric points, utilizes synthetic adsorbents and ion exchange resins. Polymeric adsorbents also refine compounds like curcumin, HMF, lactose, and play a role in wine must processing.

- **Biosynthesis of complex molecules: Advancing Medical Science**

  The synthesis of complex molecules like Taxol and heparin marks significant advancements in medical science. However, their extraction and purification demand sophisticated techniques, where polymeric adsorbents ensure the purity and integrity of these valuable substances.

  In the evolving landscape of biosynthesis, the role of these compounds has expanded further. The ability to synthesize complex molecules like Taxol, a potent anti-cancer agent, or to harness the power of heparin, an anticoagulant, through biotechnological means, marks a significant advancement in medical science.

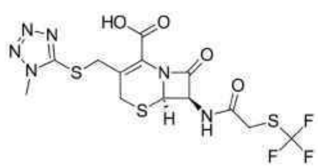
  The extraction and purification of these compounds, however, present unique challenges. The complexity of their natural matrices demands sophisticated and selective extraction techniques, where polymeric adsorbents play a crucial role. These adsorbents, tailored to the specific properties of each compound, enable efficient and sustainable extraction processes, ensuring the purity and integrity of these valuable substances.



Pharmaceutical Applications

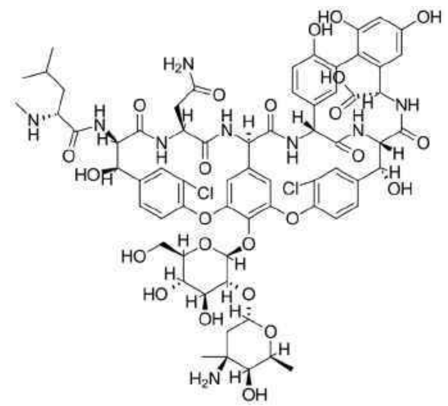
In the vast landscape of medical treatments, a class of biomolecules, notably antibiotics and hormonal treatments, stands as a cornerstone of modern healthcare. These compounds, each with unique properties and applications, have transformed the way diseases are treated and managed.

Antibiotics, the warriors against bacterial infections, have been pivotal in controlling and eliminating a wide range of bacterial diseases. Their discovery and development marked a turning point in medical history, significantly reducing mortality rates from infectious diseases. Each antibiotic, from the broad-spectrum Cephalosporin (Figure 12) to the potent Vancomycin (Figure 13), targets specific bacterial mechanisms, offering tailored solutions to combat various infections. Erythromycin and Gentamycin, for instance, are crucial in treating respiratory and severe bacterial infections, respectively, while Kanamycin and Neomycin are reserved for more specific, often resistant, bacterial challenges.



Cefazaflur

Figure 12. Chemical structure of a cephalosporin (MW 470).

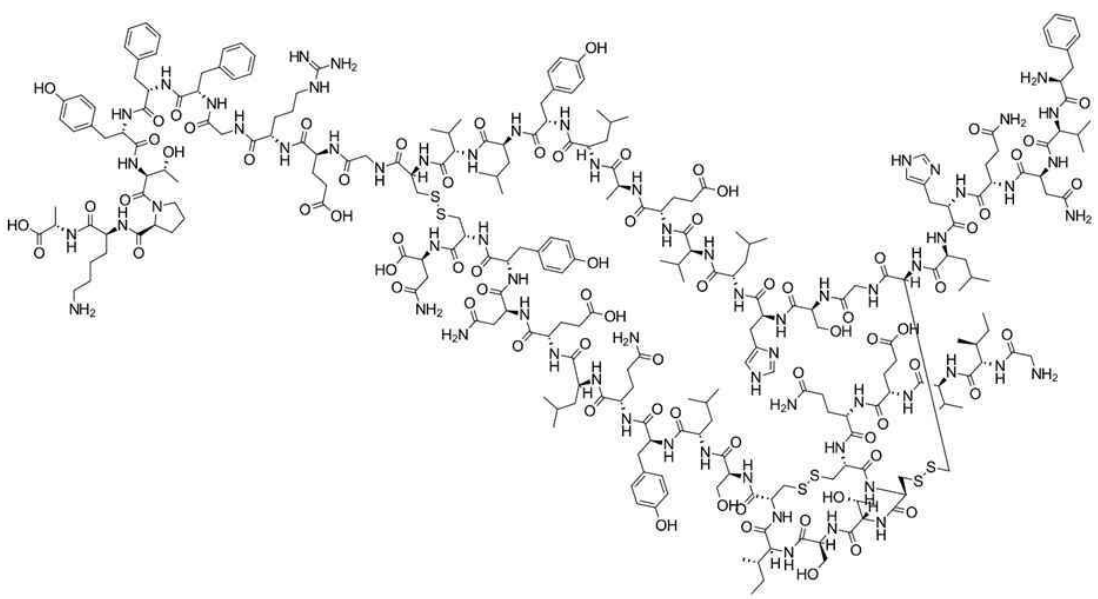


Vancomycin

Figure 13. Chemical structure of vancomycin (MW 1149).

Streptomycin, a landmark discovery in the fight against tuberculosis, exemplifies the life-saving impact of these biomolecules. Similarly, Daptomycin, with its unique mechanism, is effective against certain types of antibiotic-resistant bacteria, showcasing the ongoing evolution in antibiotic development.

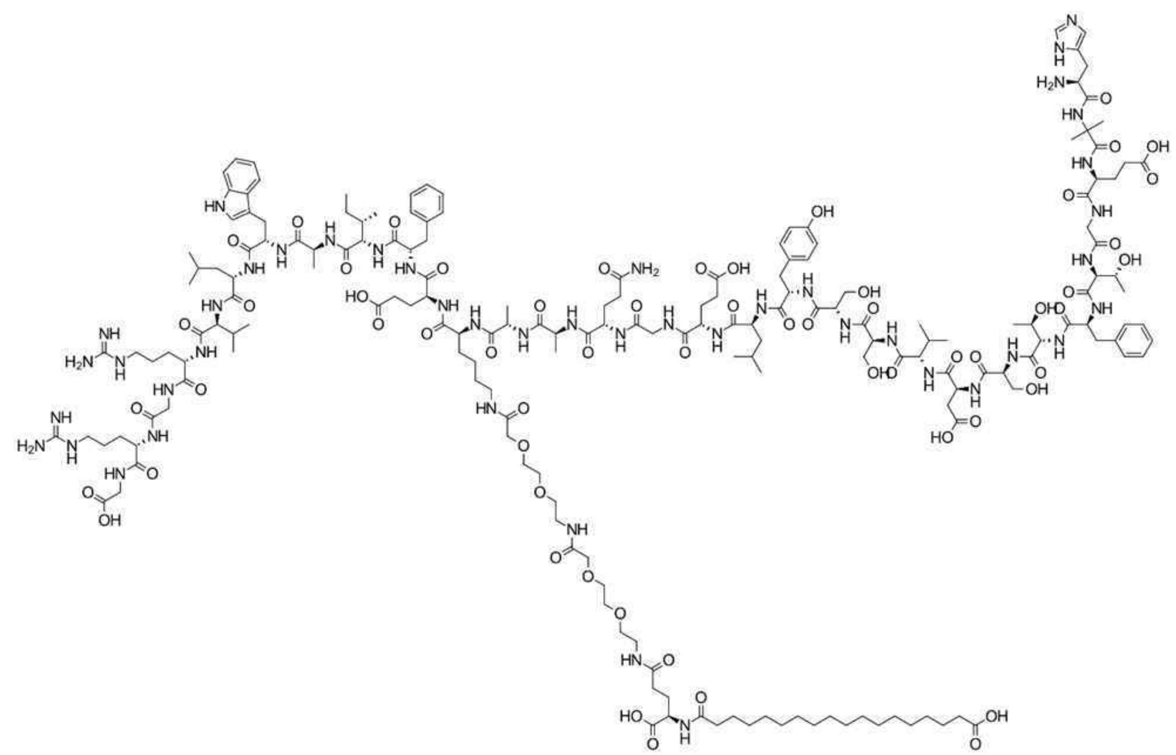
In the realm of hormonal treatments, Insulin (Figure 14) stands out as a life-sustaining treatment for diabetes. Its discovery and subsequent synthetic production have transformed the lives of millions of diabetics worldwide, turning a once-fatal disease into a manageable condition. GLP-1, another significant hormone, plays a role in glucose metabolism, illustrating the expanding scope of biomolecular applications in treating metabolic disorders. Another key peptide is Semaglutide, an antidiabetic medication used for the treatment of type 2 diabetes, that is manufactured by solid phase synthesis (Figure 15).



Insulin

Figure 14. Chemical structure of Insulin (MW 5734)

These biomolecules, while powerful, also present challenges such as the development of antibiotic resistance and the need for precise dosing in hormonal treatments. The ongoing research and development in this field aim to overcome these challenges, ensuring these vital compounds continue to serve as key elements in medical treatment and disease management.



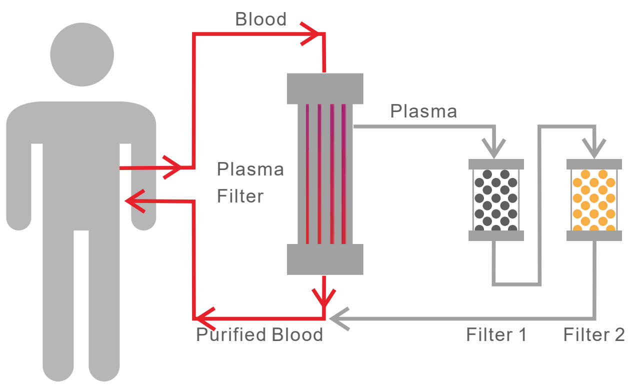
Semaglutide

Figure 15. Chemical structure of Semaglutide (MW 4113).

Medical Devices: Detoxification and Diagnostic Applications

• Transforming Plasma Detoxification in Critical Care

In the critical management of acute liver or renal failure, plasma detoxification emerges as a pivotal treatment strategy. Patients with these conditions often accumulate protein-bound toxins in their bloodstream, which are challenging to eliminate using traditional dialysis methods due to their molecular size and binding selectivity. This is where the innovative application of polymeric adsorbents in extracorporeal blood filtration systems becomes crucial.



These advanced systems, integrating specialized membrane and adsorption technologies, are adept at detoxifying plasma from albumin-bound toxins. They also play a key role in removing inflammatory mediators in sepsis patients, thus addressing the complications of this potentially life-threatening condition. The process involves separating plasma from blood cells using a membrane specifically designed to be permeable to protein-bound toxins. The plasma then undergoes filtration through filters filled with specially designed polymeric adsorbents, optimized for particle size, pore size, and surface activation, ensuring high efficacy in toxin removal.

• Managing Sepsis: Mitigating the Cytokine Storm

In sepsis, a condition often triggered by infection or injury, the body's immune response can lead to a dangerous cytokine storm. This excessive release of inflammatory mediators can cause significant cellular and tissue damage. Polymeric adsorbents offer a therapeutic approach by selectively removing these excess circulating mediators, aiding in re-establishing homeostasis and restoring a more physiological immune response. The combination of a plasma filter cartridge filled with a hydrophobic polymeric adsorbent and a high flux haemofilter allows for effective mediator removal while maintaining compatibility with the body's systems.

• Enhancing Diagnostic Accuracy

In the realm of diagnostics, polymeric adsorbents play a crucial role, especially in devices designed for the removal of antimicrobial drugs. These devices are essential when patients have been administered antibiotics that could interfere with the accurate identification of bacteria in blood tests. Typically comprising a vial with culture media and a polymeric adsorbent, these devices effectively remove antibiotics, ensuring the reliability of diagnostic results.

Additionally, ion exchange resins are utilized in the production of various radio-contrast agents, underscoring the adaptability of these adsorbents in diagnostic applications.

The integration of polymeric adsorbents in plasma detoxification and diagnostic procedures marks a significant advancement in medical technology. By enhancing treatment efficacy for conditions like acute liver or renal failure and sepsis, and improving the precision of diagnostic processes, polymeric adsorbents are becoming increasingly vital in contemporary healthcare. As advancements continue, the potential for further innovations in the application of polymeric adsorbents in medical settings remains extensive and promising.

Sunresin provides various resins including ion exchange resins and polymeric adsorbents as outlined in Table 5.

Chemical Industry and Water Treatment Applications

- **Waste Water and Landfill Leachate e.g. Phenol, Toluene, PFCs**
- **Pesticide Removal**
- **Plating / Galvanic Applications (removal of organics)**

- **Wastewater Treatment Solutions for Pyridine and Its Derivatives**

Overview of Pyridine Wastewater Challenges Pyridine and its derivatives, critical to the fine chemicals industry, serve essential roles across pharmaceuticals, pesticides, feed, dyes, and as solvents. These compounds result in wastewater that is notably complex and challenging to treat due to its non-biodegradable heterocyclic substances, high Chemical Oxygen Demand (COD) levels, elevated organic nitrogen content, and significant toxicity. Traditional water treatment methodologies frequently fall short in effectively managing these challenges, underlining the need for specialized treatment solutions.

Treatment Methods for Pyridine Wastewater Recent advancements have seen the adoption of physical treatment methodologies such as adsorption, distillation, and incineration, each with distinct advantages and challenges:

- **Distillation** emerges as a technique for pyridine recovery, achieving concentrations around 50%. Nevertheless, distillation-treated wastewater still contains high residual pyridine levels, necessitating further treatment steps and leading to complex, costly water treatment system configurations.
- **Incineration** offers a solution for high-calorific-value industrial wastewater with complex components, using high temperatures to break down pollutants. This process, however, generates emissions requiring comprehensive treatment to mitigate air pollution risks.
- **Ion Exchange Method** presents a refined strategy, employing ion exchange resin adsorption to capture pyridine compounds via intermolecular forces within the resin bed, thus purifying the wastewater. The method facilitates full desorption of adsorbed solutes, allowing resin reuse and optimizing treatment efficiency.

- **Pyridine Wastewater Treatment - A Sunresin Success Story**

A notable application involved a chemical company's management of 180 tons/day of pyridine-laden wastewater using Sunresin's proprietary XDA series resin. This approach demonstrated an impressive removal efficiency exceeding 99% for compounds such as 2-methylpyridine and 2-vinylpyridine, significantly lowering pyridine concentrations. Consequently, the treated wastewater could seamlessly proceed to biochemical treatment stages, ultimately enabling substantial water reuse and reducing production-related water consumption.

The XDA Series Resin is a superior solution for phenolic compound removal, and distinguishes itself through:

- High efficiency in adsorption and pollutant removal, coupled with straightforward regeneration.
- Robust treatment capability for large-scale applications.
- Long-term stability and durability of resin performance.
- Versatility across a broad range of operational conditions, ensuring practical utility.
  Facilitation of efficient phenolic compound recovery, amplifying value creation in wastewater treatment processes.

This technical overview encapsulates Sunresin's commitment to delivering advanced, effective wastewater treatment solutions tailored to the complexities of pyridine and its derivatives, underscoring our dedication to innovation, environmental stewardship, and sustainable industrial practices.

Sepsolut Separation Technology

High-Efficiency Chromatographic Separation Technology

Chromatographic separation is a key method for separating complex mixtures, leveraging differences in partition coefficients between stationary and mobile phases. Historically, single-column, intermittent feeding elution has limited efficiency, raising costs for equipment, space, and operation.

Simulated Moving Bed (SMB) Chromatography has been developed to improve the separation process.

- **Advantages:**

  SMB enables precise control and switching of process pipelines to simulate the effect of a moving mobile phase to realize high-efficiency and continuous chromatographic separation.

- **Sunresin's Contributions**

  Technological Development: Sunresin has developed high-performance resins and a continuous ion exchange system, along with the Sepsolut® system for SMB chromatography.

  Applications: Successfully applied in the industrial separation e.g. sugar and alcohol, amino acid purification, broth desalting and decolorization, and extraction of plant monomers.

  Chromatographic separation has evolved from low-efficiency traditional methods to high-efficiency SMB technology.

  Sunresin leads in this field with innovative resin technology and the Sepsolut® system, enabling wide-ranging industrial applications with significant benefits.

- **Sunresin's advantages in high-performance chromatographic separation system technology:**
  1. Development and production capacity of a full range of chromatographic packing technologies; high-level chromatographic separation technology.
  2. Innovative technology; customized equipment; perfect combination of material, applied technology and equipment.

- **Sunresin's advantages in polymer chromatographic separation filler:**
  1. High adsorption capacity.
  2. Applicable to a wide range of pH; sodium hydroxide resistance.
  3. Longer service life.

- **The advantages of Sepsolut® Simulated Mobile Bed Chromatographic Separation System:**
  1. High separation accuracy; high-quality purified products.
  2. High yield; low solvent consumption.
  3. Stable system; automatic and continuous operation; convenient.
  4. High efficiency.

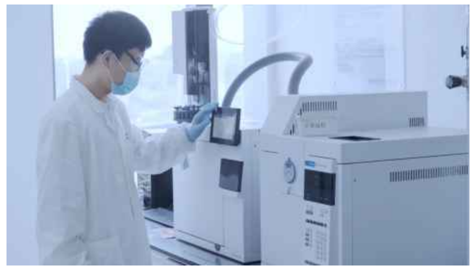
Regulatory Compliance

With a QC team of professionals, Sunresin maintains a very stringent system of QC in all of its operations, from raw material control to the intermediates and final products control.

All of Sunresin resins are manufactured under ISO standards and analyzed using world-class analytical instruments.

Table 7. Regulatory compliance summary

Resin	Composition	21CFR173.25	21CFR173.65	21CFR177.2710	ResAP (2004)	Halal	Kosher	GMO Free	TSE/BSE Free	Heavy Metal Free
CT10	Styrene-DVB			Yes	Yes			Yes	Yes	Yes
LXA8302	Styrene-DVB			Yes	Yes	Yes		Yes	Yes	Yes
LXA84	DVB		Yes		Yes	Yes	Yes	Yes	Yes	Yes
LXA816	Styrene-DVB			Yes	Yes	Yes	Yes	Yes	Yes	Yes
LXA8118	DVB		Yes		Yes	Yes	Yes	Yes	Yes	Yes
LXA8160	Styrene-DVB			Yes	Yes	Yes	Yes	Yes	Yes	Yes
LXA817	Acrylonitrile-DVB				Yes	Yes	Yes	Yes	Yes	Yes
LX207	Styrene-DVB + Bromine					Yes	Yes	Yes	Yes	Yes
LSF980	Styrene-DVB					Yes	Yes	Yes	Yes	Yes
LXA18S	Styrene-DVB							Yes	Yes	Yes



GB/T 19001 GB/T 24001 GB/T 45001 GB/T 23331

Testing and Application of Polymeric Adsorbents

• General Guidelines

General Guidelines for Handling, Testing, and Operating Polymeric Adsorbents

Topic	Key Guidelines
1. Pretreatment of Adsorbents	Soak and deair adsorbents using alcohol or cold water overnight with gentle mixing.
2. Loading and Column Preparation	Load adsorbents carefully to avoid leakage; ensure water at the column bottom for cushioning.
3. Batch and Dynamic Testing	Evaluate adsorbent capacity and efficiency through batch isotherms and dynamic column tests.
4. Pilot Scale Testing	Validate lab findings in real-world conditions; focus on breakthrough curves and mass transfer zones.
5. Breakthrough Curve Analysis	Monitor breakthrough curves to determine adsorbent saturation and effectiveness.
6. Optimizing Operational Parameters	Adjust flow rate, pH, and temperature to enhance adsorption efficiency.
7. Monitoring and Maintenance	Regularly check effluent quality and perform maintenance for consistent performance.
8. Regeneration Process	Use appropriate solvents for effective regeneration of adsorbent capacity.
9. Scale-Up and Full-Scale Operation	Plan scale-up carefully, optimizing system design and parameters for industrial use. Maintain constant linear velocity during scale-up.
10. Safety and Environmental Considerations	Ensure safety and environmental compliance in all handling, testing, and operating processes.

• Be mindful of the adsorbent's swelling behavior, especially when using solvents for regeneration or elution. In glass columns, take care to avoid breaking the adsorbents or the column during swelling of the adsorbent via solvent introduction.

By adhering to these guidelines, one can ensure the effective and efficient use of polymeric adsorbents in various industrial applications, from water treatment to chemical processing.

• Performing Adsorption Screening / Tests

Laboratory Guide: Effective Handling of Polymeric Adsorbents
Handling polymeric adsorbents in a laboratory setting requires a systematic approach to ensure their optimal functionality.

1. Pretreatment of the Adsorbent

- **Soaking for Air Removal:** To prevent air from being trapped in the adsorbent, it's essential to soak the resin thoroughly before use. A mixture of ethanol and water can be effective for this purpose. Soak the resin in a beaker with a 50:50 to 100% ethanol-water solution for 12-24 hours, ensuring complete wetting and removal of trapped air. Trapped air will cause floating adsorber beads.
- **Degas the Slurry:** If soaking method is not sufficient degassing of the slurry by placing it in a vacuum flask can be applied. Stir the mixture while under vacuum to remove any remaining air bubbles. Never sonicate since it can break the beads.

2. Loading into a Column

- **Column Preparation:** Ensure the outlet valve of the resin column is closed before loading. Add water or the solvent you are using and ensure the level is always above the resin bed.
- **Resin Transfer:** Gently transfer the soaked and degassed resin into the column. Pour the slurry mixture down the side of the column to minimize air bubble introduction. Use degassed solvents during the transfer.
- **Settling and Compaction:** Open the outlet valve briefly to allow the resin to settle and compact naturally. Then, close the valve again, preparing the column for operation.

3. Cleaning and Backwashing in the Column

- **Initial Rinse:** Rinse the column with deionized or distilled water to remove any residual soaking solution.
- **Backwashing:** Perform a backwash with deionized water at an expansion rate of about 50% for at least 3 bed volumes. This step helps remove fines and ensures a classified bed, enhancing the adsorbent's performance.
- **Final Rinse:** After backwashing, conduct a downflow rinse with deionized or distilled water at a flow rate of 3-6 BV/h for one hour or as required.

4. Practical Tips for Handling

- **Maintaining Liquid Level:** Always keep the liquid level above the resin bed. Draining the level below the resin bed can introduce air, leading to channelling and uneven flow distribution due to trapped air.
- **Handling Swelling:** Be mindful of the adsorbent's swelling behavior, especially when using solvents for regeneration or elution. In glass columns, take care to avoid breaking the adsorbents or the column. Do not over pressurize the bed as it needs to have the freedom to swell (less than 3 bars inlet pressure).
- **Counter-Current Operations:** For operations involving regeneration or elution, consider using a counter-current or upflow method through the adsorbent bed to ensure even distribution and effective processing.

• Adsorption Isotherm

Adsorption isotherm determination is a crucial process in evaluating the performance of polymeric adsorbents. This guide outlines a methodical approach for conducting batch tests, which are essential for the fast screening of adsorbents in a laboratory setting. The focus is on single solute isotherms, which provide insights into the adsorptive capacity of the adsorbent for specific solutes in a clean water/solvent matrix.

• Preparing the Adsorbent

1. Soaking and Degassing

- Mix the polymeric adsorbent with deionized water in a beaker to create a slurry.
- Soak the adsorbent in a 50:50 to 100% ethanol-water solution for 12-24 hours to ensure complete wetting and removal of trapped air.
- Degas the slurry by placing it in a vacuum flask and applying a vacuum while stirring.

• Batch Testing Procedure

1. Creating Stock Solutions:

Prepare a buffered stock solution at the appropriate pH of the target compound in ultrapure or deionized water.

From this stock solution, prepare 5-10 batches with varying amounts of the adsorbent.

2. Equilibrium and Filtration:

Stir the batches at a constant temperature for up to 24h, depending on the target compound, to reach equilibrium.

Separate the adsorbent from the solutions using pressure filtration over glass fiber filters.

3. Analyzing Solutions:

Analyze all solutions, including a blank sample (without adsorbent), for the target compound concentration.

4. Plotting and Interpreting Isotherms

Data Plotting:
Plot the empirical data on a log-log scale to linearize the relationship.
Use the Freundlich equation or similar models to calculate adsorption parameters.

$$\frac{x}{m} = KC^{\frac{1}{n}}$$

where
x = amount of solute adsorbed (mg or g)
m = mass of adsorbent (mg or g)
C = residual concentration of solute remaining after equilibrium is complete
K, n = constants to be determined for each solute and adsorbent and temperature. K relates to the kinetics of removal while n related to capacity via number of layers.

While the isotherm picked in this example is using the Freundlich isotherm, many other isotherms could be used in this work such as Langmuir.

- **Interpreting Results:**

  Assess the absorptivity of the compound based on the isotherm. Rank the adsorptivities (e.g., very good, good, moderate, very poor) based on the isotherm data.

- **Practical Considerations**

  1. Column vs. Batch Experiments:
  - For separation of multiple species, column experiments are recommended over batch stir experiments for clearer results. Column experimentation is also recommended when the concentrations are high therefore requiring chromatographic separations
  - For single solute adsorption, batch tests provide a quick and effective method for screening adsorbents. Further column tests can be done by selecting the 2 or 3 best performing adsorbents. Dilution might be needed during the batch testing so one can measure a drop in the concentration during the testing

  2. Handling Swelling and Regeneration:
  - Be aware of the adsorbent's swelling behavior, especially when using solvents for regeneration or elution.
  - Perform operations like regeneration in a counter-current or upflow manner to ensure even distribution.

- **Insights from Liquid Phase Isotherms for Polymeric Adsorbents**

  Liquid phase isotherms are critical tools in evaluating the effectiveness of polymeric adsorbents in various applications. They provide essential insights that guide the decision-making process in the utilization of these adsorbents. Here's what can be derived from these isotherms:

  1. **Viability of Adsorption:** Isotherms help in determining whether adsorption using polymeric adsorbents is a feasible method for a given application, particularly in the context of specific contaminants.
  2. **Estimating Equilibrium Capacity:** They offer valuable data on the equilibrium capacity or the approximate capacity at which breakthrough is likely to occur. This information is crucial for preliminary calculations of adsorbent usage. The information also helps to understand the kinetics of such system.
  3. **Contaminant Removal Assessment:** When examining single-constituent isotherms, it's possible to evaluate the relative challenge in removing individual contaminants. This also helps in identifying which compound may breakthrough first.
  4. **Effect of Concentration Variations:** Isotherms show how fluctuations in the concentration of contaminants within e.g. the waste stream impact the adsorbent's equilibrium adsorption capacity, which is vital for understanding adsorption dynamics under different conditions.
  5. **Maximum Adsorption Potential:** They indicate the highest amount of a contaminant that the polymeric adsorbent can adsorb at a specific concentration, providing a limit for adsorption capabilities.
  6. **Comparing Different Adsorbents:** By analyzing isotherms of various polymeric adsorbents, one can identify the most efficient types for further dynamic testing.

- **Complementary Data from Column Testing – Dynamic Operation**

  While liquid phase isotherms offer foundational data, column testing is indispensable for obtaining practical operational insights such as:
  - **Optimal Contact Time and Bed Depth:** Determining the most effective contact time and bed depth for the adsorption process. Linear velocity is a crucial factor in the process as it will remain constant during the scale-up.
  - **Pre-treatment Needs:** Identifying any necessary pre-treatment steps to enhance the performance of the polymeric adsorbent.
  - **Analyzing Breakthrough Curves:** Providing crucial data on the adsorption process over time through breakthrough curve analysis. One can use other column modelling techniques such as the Clark model for this work.
  - **Influence of Non-Target Contaminants:** Evaluating how non-target contaminants, such as certain metals or color-causing compounds, might affect the overall efficiency of the adsorption process.

Dynamic operation testing in column adsorption processes is essential for understanding the real-world performance of polymeric adsorbents. This section outlines key parameters and concepts necessary for designing and interpreting pilot-scale evaluations.

- **Breakthrough Curves**

  1. Definition and Importance:
  - A breakthrough curve is an "S" shaped sigmoidal representation of the effluent adsorbate concentration over time or volume. It's crucial for determining the efficiency of the adsorption process in dynamic conditions.
  - The breakthrough point is where the effluent concentration reaches its maximum allowable level, often aligned with regulatory or risk-based standards.

  2. Construction and Application:
  - These curves can be constructed for full-scale, dynamic, or pilot testing and are instrumental in assessing the treatment goals and the adsorbent's capacity to meet them.

- **Mass Transfer Zone (MTZ)**

  1. Understanding the MTZ:
  - The MTZ is the active region within the adsorbent bed where adsorption occurs. It moves from the influent end towards the effluent end as the adsorbent near the influent becomes saturated.
  - The MTZ is a critical concept in understanding the efficiency and lifespan of the adsorbent within the column.

  2. Characteristics of the MTZ:
  - The length of the MTZ (LMTZ) and its progression down the bed are key indicators of the adsorbent's performance. When LMTZ equals the bed depth, it becomes LCRIT, the theoretical minimum bed depth for desired removal.
  - The MTZ's advancement is influenced by factors like flow rate, temperature, and pH in liquid phase applications. Channelling can have negative impact on the MTZ

  3. Exhaustion of Adsorption Capacity:
  - The column may be considered exhausted when the effluent adsorbate concentration approaches 95–100% of the influent concentration. This indicates the need for regeneration or replacement of the adsorbent. But most applications will require regeneration once unacceptable breakthroughs occur such as 10% of the inlet concentration or lower.

- **Practical Considerations for Column Operation**

  1. Flow Rate and Temperature Control:
  - Maintaining optimal flow rates and temperature conditions is crucial for maximizing adsorption efficiency and extending the lifespan of the adsorbent.

  2. Monitoring and Adjusting pH:
  - Regular monitoring and adjustment of pH levels can significantly impact the adsorption process, especially in liquid phase applications.

  3. Regular Analysis of Effluent:
  - Continuous or periodic analysis of the effluent is necessary to accurately determine the breakthrough point and the overall effectiveness of the adsorption process.

Understanding and effectively managing the dynamic operation of adsorption columns is vital for the successful application of polymeric adsorbents. Breakthrough curves and the concept of the Mass Transfer Zone are central to this understanding, providing essential insights into the adsorbent's capacity, efficiency, and operational lifespan. Regular monitoring and adjustments based on these concepts ensure optimal performance of the adsorption system.

For any test it is important to run a full exhaustion and breakthrough of the column. This allows to achieve the desired information to design a process. A breakthrough curve can be thought of as the fingerprint or cardiogram of the dynamic adsorption process.

List of Parameters Influencing Adsorption Capacity

The efficiency and capacity of an adsorption process are influenced by a variety of factors. Understanding these parameters is crucial for optimizing the adsorption system. Here is a comprehensive list:

1. **Breakthrough Point Definition:** The point at which the effluent concentration reaches a predefined level, indicating the exhaustion of adsorbent capacity.
2. **Feed Concentration of Target Species:** Higher concentrations can lead to faster saturation of the adsorbent.
3. **Competing Species Concentration:** The presence of other species competing for adsorption sites can reduce the capacity for the target species. Controlling the selectivity through proper solvent introduction will help.
4. **pH of the Feed Solution:** pH can significantly affect the adsorption process by altering the charge and solubility of the target species and the adsorbent. The less ionic the target molecule, the more it is attracted to the polymeric adsorbent.
5. **Specific Flow Rate:** The rate at which the feed solution passes through the adsorbent bed can impact contact time and, consequently, adsorption efficiency. Porosity plays an important role in this step.
6. **Bed Depth and Number of Columns:** Deeper beds or multiple columns can increase the adsorption capacity and extend the service life of the system. But care should be taken to minimize pressure flow at the same time.
7. **Regeneration Efficiency:** The effectiveness of regeneration processes in restoring adsorbent capacity.
8. **Employed Temperature:** Temperature variations can influence the adsorption kinetics and equilibrium.

Each of these parameters can have a significant impact on the overall performance of an adsorption system. Careful consideration and optimization of these factors are essential for achieving the desired adsorption efficiency and capacity.

Upscaling: Pilot Testing and Upscaling of Polymeric Adsorbents

Pilot testing is a critical phase in the evaluation and upscaling of polymeric adsorbents, especially for liquid phase applications. Following initial batch and dynamic column testing, pilot studies provide essential data for understanding site-specific conditions and their impact on the adsorption process. This section outlines the key aspects and methodologies of pilot testing for polymeric adsorbents.

- **Objectives of Pilot Testing**

1. Verifying Breakthrough Characteristics:
• Pilot tests are designed to validate the characteristics of the breakthrough curve under various process parameters, such as surface loading rates and empty bed contact times.

2. Assessing Competition and Interferences:
• These tests help identify competition for adsorption sites among different compounds in the waste stream and evaluate the
• impact of water chemistry variations (pH, buffer capacity, solvent concentration etc.) on adsorbent performance.

3. Generating Scale-Up Factors:
• Pilot testing is crucial for generating accurate scale-up factors needed for full-scale design and implementation.

- **Methodologies in Pilot Testing**

1. Standard Pilot Column Test:
• Consists of multiple adsorbent columns in series, typically 50 to 150 mm in diameter, containing 80cm to 1.5 m of polymeric adsorbent.
• Operates in either downflow or upflow mode, with downflow preferred for liquid streams to avoid plugging and fines generation.
• Used to track the mass transfer zone through the columns, mimicking full-scale system characteristics.

2. MiniColumn Test:
• A rapid method using a small-scale column, typically 0.4- to 2.0-mm in diameter, with a bed depth ranging from 10 to 100 mm.
• Particularly useful for comparing multiple adsorbents and obtaining effective design data.

- **Introduction to Full-Scale Operation**

Practical Considerations

1. Selection of Testing Parameters:
• Choose parameters that closely resemble those expected in the full-scale system, including bed depth, flow rate, and influent concentration.

2. Monitoring and Data Analysis:
• Continuously monitor effluent quality to accurately determine the breakthrough point and overall adsorption efficiency.

3. Collaboration with Sunresin:
• Engage with Sunresin who offer mobile pilot systems and can conduct pilot testing, also supporting for full-scale implementation.

Pilot testing is a vital step in the upscaling process of polymeric adsorbents, bridging the gap between laboratory-scale studies and full-scale application. By carefully designing and conducting pilot tests, one can gain invaluable insights into the real-world performance of adsorbents, ensuring effective and efficient full-scale operation.

Industrial Scale Application of Polymeric Adsorbents

Transitioning from pilot testing to full-scale operation of polymeric adsorbents requires meticulous planning and execution. This section outlines the key steps and considerations for implementing polymeric adsorbent systems in industrial settings, ensuring optimal performance and efficiency.

- **Pre-Operational Setup and Resin Loading**

1. Column and Pipe Preparation:

• Prior to resin loading, clean the related pipes and the adsorption column with water and lye to remove impurities like welding slag, dust, and residues.

• Inspect and ensure the integrity of the filter plate and other components to prevent resin leakage.

2. Resin Loading Process:

• Begin by injecting 1/3 volume of water into the column.

• Load the resin through the manhole at the top of the exchange column, then close the manhole. Make sure water is present at the bottom of the column to reduce the impact on the resin with the column surface.

• Continue injecting water while opening the drainage valve at the bottom, using a ≥80 mesh screen to check for resin leakage.

- **Adsorption Process**

1. Pre-Treatment of Feed Stream:

• Ensure the feed stream is filtered and pre-treated to remove solid impurities, preventing blockage of resin pores and ensuring effective adsorption.

2. Operational Flow and Monitoring:

• Adopt a downflow flow method for the adsorption process, with a recommended flow rate of 1-3 BV/h.

• Monitor the content of the target substance in the outlet liquid to determine the adsorption state of the resin.

3. Systematic Approach:

• Maintain vertical fixation of the resin column to avoid tilting and ensure uniform adsorption.

• Regularly check and adjust operational parameters to maintain optimal performance.

- **Regeneration Process**

1. Initial Cleaning:

• Push the residual material liquid in the resin column with deionized water at a flow rate of 1-3 BV/h for 1-2 hours.

2. Regeneration with Solvents:

• Use an appropriate regenerant (e.g., ethanol, methanol) as per process design requirements.

• Perform co-current or counter current treatment with the regenerant at a flow rate of 1-2 BV/h for about 1.5 hours.

3. Post-Regeneration Cleaning:

• After regeneration, clean the column with deionized water at a flow rate of 2-3 BV/h until the effluent meets process requirements.

Implementing polymeric adsorbents at an industrial scale involves careful consideration of operational parameters, pre-treatment processes, and regular maintenance and regeneration of the adsorbent system. By adhering to these guidelines, industries can ensure efficient and effective removal of target substances, maintaining consistent performance and prolonging the lifespan of the adsorption system.

Pretreatment

The pretreatment of polymeric adsorbents is a critical step in ensuring their optimal performance for their intended applications. This chapter provides a comprehensive guide on the standard procedures and best practices for the pretreatment of adsorbent resins. However, some applications may require unique and individual pretreatment procedures to achieve the desired performance and quality of the final product.

Please be aware that the user of the adsorbents is responsible to ensure the appropriate pretreatment of the polymeric adsorbent to achieve the level of purity for the use to remove by-products which may be present from the manufacturing process.
Overview of standard pretreatment procedures:

Sunresin

1. General Pretreatment

• Load the resin into the service vessel with demineralized water and soak for several hours or overnight. Ensure the resin is fully wetted and not floating. Backwash with demineralized water at about 50% expansion for at least 3 bed volumes, then rinse downflow at 3-6 BV/h for one hour or as required.

• If the adsorbent has partially dried floating resin can be observed. In this case ensure fully rewetting is achieved before backwashing. Alcohol and water/alcohol mixture can be applied to allow for a better rewetting. Cold water for overnight wetting is better than warm water since it has lower air miscibility.

2. Alkaline and Acidic treatment

• Alkaline Treatment: Pass a 4% sodium hydroxide solution through the resin column at 1-2 BV/h for 3-4 BV. After treatment, rinse with deionized water until the outlet pH is less than 10. Maintain a liquid layer 1-2 cm above the resin bed.

• Acidic Treatment: Use a 1% HCl solution (phosphoric, sulfuric, and citric acid can also be used) at 1-2 BV/h for 3-4 BV. Post-treatment, rinse with deionized water until the outlet pH is 4 or higher, keeping the liquid layer above the resin bed.

3. Ethanol Treatment

• Soak the resin in >95% ethanol for 2-4 hours, then pass the same ethanol solution through the column at 1-2 BV/h for 2-4 BV. Continue until the effluent is clear upon dilution. Rinse with deionized water until the ethanol content is below 1% (about 2 to 4 bed volumes at 3 to 6 bed volumes per hour).

Storage

Proper storage of polymeric adsorbents is crucial for their efficacy and longevity. The following chapter will give some guidelines for storing on preventing issues like mold growth, dehydration, freezing and contamination.
Recommended Storage Solutions:

1. Salt Solution Preservation:

• A 10% or higher salt solution (e.g., NaCl) is effective for preserving both new and used adsorbent resins during extended storage periods.

2. Alkaline Solution:

• If salt cannot be used, a dilute NaOH solution (0.01 to 0.02 N) is acceptable, as mold cannot survive at pH levels above 12.

3. Alcohol Storage:

• Storing resins in a 20% alcohol solution, such as ethanol or 2-propanol, is ideal. Alcohol not only prevents mold growth but also helps keep the resin clean.

• Avoiding Freezing Temperatures:

• Freezing temperatures can stress the resin matrix, leading to breakage and increased particulates. Therefore, such conditions should be avoided. Storing polymeric adsorbents in sodium chloride and alcohol solutions will reduce the chance of freezing.

Remember: polymeric adsorbent resins are susceptible to mold growth if not stored correctly.

Troubleshooting

Troubleshooting Issue	Possible Cause	Recommended Action
High pressure	Resin bed compaction	Perform backwashing to loosen the resin bed
Low capacity with good pressure	Resin contamination	Reclean the resin to remove contaminants
Low capacity with high pressure	Resin bed compaction and contamination	Backwash and clean the resin to address both issues
Resin odor	Mold presence	Treat with caustic or alcohol overnight to remove mold
Resin floating	Oils or air trapped in resin	Conduct pretreatment to remove oils or trapped air
Shift in resin properties	Resin degradation or fouling	Take a representative sample for analysis of resin integrity, moisture content, surface area, and porosity. Consider contacting Sunresin for detailed evaluation and advice on resin replacement

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