

Review Article

Separation Strategies for Processing of Dilute Liquid Streams

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Received 17 June 2011; Revised 9 September 2011; Accepted 5 October 2011

Academic Editor: Adrian Schumpe

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Processing of dilute liquid streams in the industries like food, agro-, biotechnology, pharmaceuticals, environment, and so forth needs special strategy for the separation and purification of the desired product and for environment friendly disposal of the waste stream. The separation strategy adopted to achieve the goal is extremely important from economic as well as from environmental point of view. In the present paper we have reviewed the various aspects of some selected universal separation strategies such as adsorption, membrane separation, electrophoresis, chromatographic separation, and electroosmosis that are exercised for processing of dilute liquid streams.

1. Introduction

Processing of dilute liquid streams occurs in number of unit processes and unit operations in chemical industries. Whereas the separation strategies adopted by these industries sometimes follow the conventional processes such as distillation, crystallization, drying, and so forth, due to the familiarity of operation since several decades. In industry, handling of dilute liquid streams needs special strategies for the separation and purification of the desired product and for environmental friendly disposal of the waste stream. The separation strategy adopted is extremely important from economic as well as from environmental point of view. The suitability of a separation technique depends on number of factors that includes:

- (i) improved selectivity,
- (ii) improved energy efficiency,
- (iii) development of new process configurations and integration,
- (iv) economic viability,
- (v) environmental safety and compatibility, and
- (vi) sustainability (recycle and reuse).

Numerous new/modified techniques have been exercised by engineers and scientists to improve the efficiency and reduce the cost of the traditional separation techniques. Separation processes of commercial interests can be categorized according to the phases involved as

- (i) solid-solid separation (screening, classification, floatation, flocculation, and field-based),
- (ii) solid-liquid separation (thickening, centrifugation, filtration, drying, and crystallization),
- (iii) solid-gas separation (cyclone, filters, adsorption, etc.),
- (iv) liquid-liquid separation (distillation, extraction, membranes, and adsorption),
- (v) liquid-gas separation (absorption, stripping, and pervaporation),
- (vi) gas-gas separation (membranes), and
- (vii) solid-liquid-gas separation.

Each of these categories has several alternative ways to bring about separation. However, it is not possible to look at all such possible strategies exhaustively within a single frame. In the present paper, we wish to look into

the various aspects of the different universal separation strategies used for processing of dilute liquid streams, such as, adsorption, membrane separation, electrophoresis, chromatographic separation, and electroosmosis.

2. Separation Methodologies

2.1. Adsorption. Adsorption is a thermodynamically spontaneous surface phenomenon. When a multicomponent liquid mixture is contacted with a solid surface (adsorbent), certain component of the mixture (adsorbate) gets concentrated at the surface of the solid due to difference in the intermolecular forces of attraction between the components of the liquid mixture and the solid. This formation of adsorbed phase on the surface of the solid adsorbent having a composition different from that of the bulk liquid phase forms the basis of separation by adsorption technology. The process of adsorption is an exothermic phenomenon while its reverse, that is, desorption, is an endothermic phenomenon. Both adsorption and desorption forms equally essential steps in a practical adsorption process where the adsorbent is repeatedly used for carrying out the separation.

Adsorption technology is considered as an option for separation when high degree of purity is required. Adsorptive separation could provide an alternative to

- (i) systems for energy intensive cryogenic distillation and liquefaction,
- (ii) conventional distillation systems,
- (iii) systems require minimum use of inprocess air and water, and
- (iv) complex separation involving high boiling or thermally unstable compounds.

Development of adsorption technology primarily depends on the development and utilization of wide variety of micro- and mesoporous adsorbents with varying pore structure and surface properties, which are responsible for the selective adsorption of specific component from liquid mixtures. The usefulness of an adsorbent in a separation and purification process is a function of its composition, its pore structure and surface properties, the presence and type of functional groups at the surface, its degree of polarity, and its hydrophilic/hydrophobic characteristic. The adsorbent should not be vulnerable to fouling or degradation by the components of the feed stream. The commonly used adsorbents include aluminosilicates (zeolites and molecular sieves), activated carbon, natural and synthetic clays, activated and impregnated aluminas, silica gels, ion-exchange resins, and biopolymeric adsorbents. Each of these groups of adsorbents contains number of subgroups of materials. Development of new adsorbent materials and physicochemical modifications of the existing adsorbents is being continuously studied by the researchers.

The adsorption efficiency of a specific adsorbent-adsorbate system depends on a number of factors:

- (i) the physicochemical nature of the adsorbent—chemical composition, surface properties, and pore structure,

- (ii) the nature of the adsorbate such as its pKa, functional groups present, polarity, molecular weight, and size, and
- (iii) the solution conditions such as solution pH, ionic strength, and the adsorbate concentration.

2.1.1. Modes of Operation of Adsorption Process. The adsorptive separation process can be performed through various modes.

Batch Adsorption Process. The batch process is the intuitive way of studying the efficiency of an adsorbent for adsorptive separation of a specific molecule or ion. Here, a fixed amount of the adsorbent is contacted with a fixed volume of the adsorbate solution of known concentration at constant temperature. The change in concentration of the adsorbate after a fixed time interval gives the adsorption capacity of the adsorbent for the selected adsorbate. This is the first step to design an adsorptive separation process.

Continuous Flow Adsorption Process. In this process, the feed stream is percolated through a fixed-bed column packed with the adsorbent in a continuous flow mode. On near saturation of the adsorbent, as evidenced by breakthrough of adsorbate, the column is removed and regenerated. There are two basic modes for operation of bed or column type adsorbents relating to exhaustion and regeneration of adsorbents, namely, fixed beds and pulsed beds. For high concentration systems typical of certain industrial wastes, pulsed-bed systems are often effective and efficient. In continuous flow process, the reactor can be designed to operate in either upflow or downflow direction. A fixed-bed adsorber can be operated in the upflow mode to minimize pressure drop, channeling and fouling of the adsorbent. In addition, upflow design and operation allows smaller particle sizes of adsorbent to be employed to increase adsorption rate and hence decrease adsorber size.

Adsorption Chromatography. In this process, the feed stream is introduced as a pulse in a purge stream, similar to liquid phase chromatography. This method has been applied for small-scale production of fine chemicals. There are limitations in large-scale separation by adsorption chromatography.

2.1.2. Applications of Adsorption in Separation and Purification. The field of adsorption technology has grown extensively over the past years, and it will continue to grow in the prospective future because of its vast applicability. The endless choice of adsorbent materials and their use in the design of innovative separation processes provide bright future for this technology as a separation tool. Adsorption technology has found numerous applications for separation and purification of dilute liquid mixtures and for product recovery in the chemical, petrochemical, and biochemical industries, in biotechnology and biomedical applications and for water treatment (ground/surface water and effluent).

The technology has been used for olefin-paraffin separation, fructose and glucose separation, isomer separation (xylene, cresol, and cymene), for breaking azeotropes, recovery of antibiotics, removal of microorganisms, purification and recovery of biomolecules (proteins, vitamins, and enzymes), trace impurity removal, for municipal and industrial waste treatment, ground and surface water treatment, to name but a few. Development of new adsorbents and advanced adsorption methods specialized in compositions, structures, functions, and characteristics made this technology suitable to meet the industrial needs of modern era.

An overview of the separation and purification of different valuable products from dilute solutions and removal of various contaminants from dilute process streams by adsorption technique has been presented.

Industrial Applications. For large-scale industrial separation from dilute liquid streams, adsorption technique has been found to be more sustainable alternative in terms of low energy costs and process economics. One component can selectively be adsorbed in a bed of adsorbent particles, while the other passes through. The adsorbed component can be recovered afterwards by thermal swing adsorption (TSA) or pressure swing adsorption (PSA) depending on the nature of the adsorbent and adsorbate. In this way, the separation can be achieved at ambient temperature. Due to size-selective adsorption characteristics, different forms of zeolite and molecular sieves have gained considerable interest towards their industrial applications [1] for the separation of light olefin/paraffin mixtures [2], glucose-fructose mixtures [3], isomer separation [4, 5], breaking azeotropes [6], separation of aromatics for the purpose of purification of chemicals [7], and so forth. In addition to various forms of zeolite, polymeric adsorbents and advanced materials containing metal-organic framework (MOF) have been developed for adsorptive separation of aliphatic and aromatic isomers [8].

Continuous separations of olefin/paraffin mixtures are of high demand in chemical industries. Herden and his coresearchers have extensively studied the separation of olefin/paraffin mixtures using different modified forms of X- and Y-type zeolites [2, 9, 10]. The studies revealed that X-zeolites (Si/Al ratio 1.3) are more appropriate for olefin/paraffin separation. Recent development in this area has shown that adsorbents containing transition metal salts dispersed on high surface area substrates like zeolites, alumina, ion-exchange resins, silica, clays, and activated carbon are more efficient for enhanced separation of olefin/paraffin mixtures in bulk [11–13]. This type of adsorbent comprising of transition metal salts supported on high surface area substrates (zeolite, activated alumina, and silica) are also found useful for desulfurization of commercial diesel fuel [14, 15] and adsorptive removal of aromatics [16] in industries.

Biotechnology and Biomedical Applications. Separation and purification of biomolecules like, proteins, vitamins, enzymes, and antibiotics from their dilute solutions is an important task in biomedical and biotechnological applica-

tions. In this field of application, the primary focus is given on selectivity of the adsorbent for the specific molecule as well as easy recovery of the molecule from the adsorbent. Studies reporting the use of a wide variety of adsorbents including inorganic mesoporous silica, aluminosilicates, carbon nanotubes, natural and synthetic polymeric adsorbents, polymeric resins, and so forth are reviewed. Different modes of the adsorption process like batch process and continuous flow process are opted to achieve the separation and purification of the desired product.

Being a low-energy consuming and high-yield process, adsorptive separation and recovery of biomolecules, namely, antibiotics and vitamins, from fermentation broth are of great industrial importance. Adsorbents such as nonionic polymeric resins [17], ion-exchange resins [18, 19], activated carbon, molecular sieves, and so forth have been reported to be effective for isolation and recovery of these biomolecules. Separation of β -lactum antibiotics, such as amoxicillin, ampicillin, cephalixin and cefadroxil, trimethoprim, from bioreactors are achieved by adsorption on polymeric resins, activated carbon and biopolymeric adsorbents [20, 21].

DNA separation by adsorption on pure/modified silica and its composites is an important method used in novel technologies that uses microchannels [22]. The principle behind this type of separation relies on DNA molecules binding to silica surfaces in the presence of certain salts and under certain pH conditions [23]. The other adsorbents used for separation of DNA molecules by adsorption are natural/modified clays [24], aluminosilicates, oxidic minerals like goethite [24] and magnetic nanoparticles, and carbon nanotubes [25].

Separation and purification of proteins is usually carried out by adsorption onto different adsorbents materials packed in a chromatographic column. Adsorbents such as polymeric/composite ion exchangers [26], magnetic nanoparticles [27], cryogel [28], polypyrrole-based adsorbents [29], and mesoporous SBA-15 [30] have been developed and used for separation of proteins. Inorganic and organic-polymeric membranes are also studied by researchers for adsorptive separation of protein molecules [31, 32]. A new concept for the purification of protein in micellar aqueous two-phase system using magnetic adsorbent has been reported by Becker et al. [33].

Water Treatment. Adsorption technology is extensively exploited by several researchers for water treatment and its purification [34]. Though a wide variety of adsorbents have been studied for water treatment by adsorption, in practice, a few of them have been practically utilized for the purpose. Adsorbent cost is the key point while selecting the adsorbent for this specific application. The selection of adsorbent is done primarily on the basis of the quality of the required water (drinking/industry/environmentally safe wastewater) and the adsorbent cost. Activated carbon (AcC) obtained from different sources [35, 36], activated and impregnated alumina [37, 38], natural-modified clays [39] and minerals [40, 41], synthetic clays [42, 43], synthetic and modified zeolites [44, 45], polymers, and ion-exchange

resins [46, 47] are among the most exploited adsorbents for water treatment. Being low cost and capacity to adsorb both organic and inorganic contaminants, activated carbon adsorbents and their chemically modified forms are brilliant for ground/surface water as well as wastewater treatment [48, 49]. Activated carbon (AcC) is usually available in four different forms, powder (PAC), granular (GAC), fibrous (ACF), and clothe (ACC). All these four forms of activated carbon obtained from various sources have been investigated for drinking water as well as wastewater purification. Adsorption capacities of activated carbon for various contaminants in aqueous medium (as reported in literature) have been listed in Table 1.

An extensive survey of literature on the removal of inorganic contaminants from water reveals that activated carbon adsorbents are not very effective in removing inorganic contaminants including heavy metals from water/wastewater. In this context, a large number of low-cost materials that include agricultural wastes, natural bio-polymers (chitosan, alginic acid, and cellulose), industrial wastes/biproducs, natural clays, soils and minerals, and their chemically modified forms are studied by several researchers and found to show excellent adsorption property for heavy metal removal as well as for the removal of colorants/dyes from water/wastewater [65–68]. Natural soils have been successfully used by researchers for the removal of inorganic contaminants like, fluoride [69], arsenic [70, 71], iodate [72], phosphates [73], and so forth from surface/ground water. Unfortunately, very little information is available in the literature regarding the recovery of pollutants from these low-cost adsorbent materials, the regeneration of spent sorbents, and the stability and reproducibility of the sorbents. Hence, further research is required for real-life applicability of these low-cost adsorbents.

In addition to the traditional adsorbents, researches are going on for the development of new effective adsorbents that can be regenerated and reused for cost-effective separation process. Many advanced adsorbent materials such as carbon-natural zeolite composite [74], aluminium-loaded shirasu zeolite [75], carbon nanotubes [76], alumina-supported carbon nanotubes [77], zeolite-portland cement mixture [78], zeolite-vermiculite composite [79], cellulose-supported synthetic clay [80], carbon-fly ash composite, thiol-functionalized silica coated activated alumina [81], Ce-Ti oxide [82], and so forth with improved adsorption characteristics are being developed and tested for application in water treatment.

Over the last decade, large progress has been made toward the process development of this technology, but, unfortunately, the development in the field of adsorbent materials is not significant. Successful implementation of the technology for separation of industrial processed streams requires reasonably good understanding of the fundamentals of adsorption and adsorption processes, that is, forces responsible for adsorption, adsorption equilibrium, its temperature dependence, heat of adsorption, process cost, and so forth. The technical challenges involved for further growth in this area is the cost-effective quality separation, which require more efficient way to regenerate and reuse adsorbents,

to improve our understanding in tailoring adsorbents for complex system and to improve predictive models for mass transfer, adsorption, equilibrium, and other physical data.

2.2. Membrane Separation. During the past decades, membrane separation processes have been developed and optimized for large-scale industrial applications for separation and purification of desired products present in dilute solutions. In this separation technique, the liquid stream is passed through the membrane module when the solvent molecules pass through the membrane leaving desired product/molecule on the other side. This technology is generally used in bulk rather than precise separation.

The most significant advantage of membrane-based separation systems over other existing separation processes is the consumption of less energy. In addition to energy saving, membrane systems are compact and modular, which facilitate the system an easy retrofit to existing industrial processes. The technology is extensively used in food and beverage industry [83, 84], pharmaceutical industries, biotechnology [85, 86], in environmental, in the treatment of effluent and process streams [87], and in energy applications. The applications of different membrane-based separation processes used in various industries are discussed as follows.

2.2.1. Microfiltration and Ultrafiltration (MF and UF). This is a process for separating materials of colloidal size and larger from true solutions using polymeric membranes. It is used for purification of aqueous streams, concentration, purification, and recovery of valuable products. This is the most widely used among all other membrane processes.

Microfiltration/ultrafiltration (MF/UF) technique is mostly used for aqueous fluid treatments. The application mechanism comprises of purification by the rejection of impurities (e.g., purification of water), by retention and concentration of valuables (purification of biomolecules), and by permeation and purification of valuables (purification of fermentation fluid).

The two most important characteristics for a successful MF/UF process are pore size and economic efficiency of the membrane. For industrial application, the pore size of the membrane must be appropriate for the purpose of separation, and the economic efficiency must be sufficient to allow for the variations in pore sizes needed.

The MF/UF process has been largely used in water treatment for treating natural water, drinking water [88, 89], wastewater, reservoir water [90], and oily water [91]. The technique is also exploited for the treatment of algae-rich water [92], the removal of virus from water and wastewater [93], the removal of colloids and natural organic matter from surface water, and so forth. Several efficient water-treatment technologies that include MF/UF process along with other processes like precipitation/coagulation [94], electroperoxidation [95], ozonation [96], photooxidation [97], and so forth have also been developed. The MF/UF process is also a widely used method for pretreatment of water before reverse osmosis or nanofiltration. Tsai et al. [98] have reported electromicrofiltration method for the removal

TABLE 1: Adsorption characteristics of activated carbon derived from different sources, reported in the literature, for the removal of various contaminants from water at 25–30°C.

Carbon type and source	Activation	S.A. ¹ (m ² /g)	Adsorbate	Initial conc. (mg/L)	Ads. capacity (mg/g)	Model used	Ref.
GAC-coal	Untreated	689	Aniline	250–3000	242.92	Langmuir	[50]
GAC-coal	Untreated	689	Pyridine	250–3000	157.01	Langmuir	[50]
GAC-coal	Untreated	689	Phenol	250–3000	218.97	Langmuir	[50]
GAC-coal	Untreated	689	Benzene	250–3000	271.51	Langmuir	[50]
AcC-waste tire	HF, heating at 850°C, chlorination	1060	Toluene ^a	500	421.8	—	[51]
AcC-pine bark	Heating at 672°C under N ₂ flow	332	Phenol	99.75	28.20–40.42	Langmuir	[52]
ACC	Conductivity water at 60°C under N ₂ flow	2500	Pesticide (ametryn)	103.84	354.61	Langmuir	[53]
ACC	-Do-	2500	Pesticide (aldicarb)	103.96	421.58	Langmuir	[53]
ACC	-Do-	2500	Pesticide (dinoseb)	22.38	301.84	Langmuir	[53]
ACC	-Do-	2500	Pesticide (diuron)	32.27	213.06	Langmuir	[53]
ACC	-Do-	2500	Pesticide (bentazon)	20.90	151	Langmuir	[54]
ACC	-Do-	2500	Pesticide (propanil)	23.52	114	Langmuir	[54]
PAC-Bokbunja waste seeds	Untreated		Dye-procion red MX-5B	10–60	29.37	Langmuir	[55]
PAC-Bokbunja waste seeds	<i>n</i> -hexane		-Do-	10–60	30.65	Langmuir	[55]
AcC-sunflower seed hulls	H ₂ SO ₄	135.2	Dye-acid blue 15	—	125	Langmuir	[56]
AcC-pine-fruit shell	K ₂ CO ₃	1035	Brilliant green dye	600	216.1	Langmuir	[57]
AcC-pine-fruit shell	Heating at 600°C	1425	-Do-	600	284.3	Langmuir	[57]
AcC-water hyacinth	H ₂ SO ₄ followed by heating at 300°C	—	Fluoride	2–25	6.06	—	[58]
AcC-water hyacinth	H ₂ SO ₄ followed by heating at 600°C	—	-Do-	2–25	4.66	—	[58]
AcC-commercial (coconut)	Untreated	1050	NH ₃	340.1	5.26	—	[59]
AcC composite	Sodium alginate + chitosan + activated carbon	—	Hg ²⁺	—	576	—	[60]
AcC-coconut shell	Untreated	1280	Cr(VI)	120	107.1	—	[61]
AcC wood	Untreated	1700	Cr(VI)	120	87.6	—	[61]
AcC coal	Untreated	1120	Cr(VI)	120	101.9	—	[61]
GAC	Water wash	648	Cu(II)	—	6.14	Langmuir	[62]
GAC	Citric acid	431	Cu(II)	—	14.92	Langmuir	[62]
GAC	Citric acid followed by NaOH	448	Cu(II)	—	11.85	Langmuir	[62]

TABLE 1: Continued.

Carbon type and source	Activation	S.A. ¹ (m ² /g)	Adsorbate	Initial conc. (mg/L)	Ads. capacity (mg/g)	Model used	Ref.
AcC-rubber leaf	HCl	0.57	Cu(II)	5–50	8.39	Langmuir	[63]
AcC-saw dust	Untreated	686.3	Pb(II)	51.8–414.4	84.95	Langmuir	[64]

^aAdsorption experiments were performed at 22°C.

¹Surface area.

of natural organic matter and inorganic particles from natural surface water. In this method, the microfiltration is performed under an applied electric field when an enhanced removal of natural organic matter and inorganic particulates was obtained because of electrophoretic and electroosmotic effects.

In food processing industry, MF/UF separation technique is used for processing dairy products [99, 100], honey [101], fruit/vegetable juice [102, 103], clarification of wine, and decolourization of sugarcane solution [104].

This MF/UF technique is also used for recovery of biomolecules like proteins, enzymes, vitamins, and carbohydrates from milk products [105], vegetable oils [106], fishery products [107], poultry processing wastewater [108], fermentation products [109], and peels of citrus fruits [110].

However, the main problem of MF/UF process is the flux decrease caused by concentration polarization and membrane fouling. Several processes have been tried by researchers for preventing/reducing the membrane fouling.

2.2.2. Reverse Osmosis (RO). This is a liquid/liquid separation process that uses a dense semipermeable membrane, highly permeable to water and highly impermeable to microorganisms, colloids, dissolved salts, and organics. This is the first membrane-based separation process to be widely commercialized. This technique is largely used for water treatment [111, 112], namely, production of demineralized or potable drinking water, desalination of seawater and brackish water, and pure boiler water makeup in industrial fields, and in food processing industries, and wastewater treatment and reuse.

The largest single application area of reverse osmosis is desalination of seawater and brackish waters [113, 114]. Cellulose acetate membranes and thin-film composite membranes made from aromatic polyamides [115, 116] are widely used for this purpose. Several pretreatment methodologies like flocculation/precipitation, MF/UF [117], nanofiltration [118], adsorption, electrocoagulation [119], and so forth for seawater reverse osmosis are tried to increase the membrane life by reducing membrane fouling. RO separation of seawater and brackish water containing high total dissolved solid (TDS) is considered to be less energy consuming than electrodialysis. It is also used for the removal of boron from water [120].

In addition to the desalination of water, RO technique is also being used for the production of drinking water, water treatment for boilers, feed water treatment for industrial use, the removal of organic and inorganic contaminants from water, wastewater treatment and reuse [121–124].

Other applications of reverse osmosis separation technique include purification of lactic acid from fermentation broth [125], separation of organic/inorganic compounds from their aqueous solutions [126, 127], separation of organics from multicomponent mixtures [128], boric acid recovery [129], and so forth.

2.2.3. Electrodialysis (ED). This is an electrochemical separation process in which ionic species are separated from an aqueous solution or from other uncharged components using electrically charged membranes under the driving force of electrical potential difference. Though the separation technique was first developed for the desalination of brackish water as can be seen from the recent works of Sadrzadeh and Mohammadi [130, 131] and many other research groups but at present, the most important industrial application of electrodialysis is in the production of potable water. This technique is widely used for the removal of dissolved metal ions and solids from industrial processed/waste streams and concentration of metal ions from their solutions [132, 133]. The removal of inorganic contaminants like fluoride (F⁻), nitrate (NO₃⁻) [134], and boron [B(OH)₄⁻] from dilute aqueous streams are also performed by electrodialysis method [135] through different ion-exchange membranes [136]. It can also be utilized for separation and concentration of salts [137], acids (mineral and organic) [138–140] and bases from aqueous solutions, separation of monovalent ions from multiple charged components [141], and separation of ionic compounds from uncharged molecules [142]. Due to the diversity and practicability of the technique, it can be a versatile tool to meet specific needs from chemical [143], biochemical [144], biotechnological [145], food [146], and pharmaceutical industries [147, 148]. Electrodialysis-based separation techniques have been reviewed by Xu and Huang [149]. In recent days, slightly modified form of electrodialysis with ultrafiltration membrane has been developed to separate valuable biomolecules [150] on the basis of their electrical charge and size or molecular weight. In this process, a conventional electrodialysis cell is used, in which some ion exchange membranes are replaced with ultrafiltration membranes [151], compounds of higher molecular weight than the membrane cutoff can be separated so as to extend the field of application of electrodialysis to biological charged molecules.

2.2.4. Pervaporation. Pervaporation is a membrane-based separation technique used for separation and concentration of liquid mixtures, especially of aqueous-organic azeotropes [152]. In this technique, the liquid mixture to be separated

get contacted on one side of the membrane, and the permeate is removed as a vapor from the other side. The membrane acts as a selective barrier between the two phases, the liquid feed solution and the vapor phase permeate. Transport through the membrane is induced by the difference in partial pressure of the components on the two sides (the feed solution and the permeate vapor phase) of the membrane. The mass transport across the membranes involves three successive steps.

- (i) Upstream partitioning of the feed components between the flowing liquid feed and the upstream surface layer of the membrane.
- (ii) Diffusion of the components through the membrane.
- (iii) Desorption of the components at the permeate side of the membranes.

The steady-state mass transport system depends on the parameters, like, upstream pressure, downstream pressure, temperature, and film thickness. When the downstream pressure is low, the flux is inversely proportional to the film thickness. Though the first industrial application of pervaporation was for the dehydration of alcohol/water azeotropic mixtures, presently the technology finds wide industrial applications for separation of and recovery from various liquid mixtures. For being economical, safe, and eco-friendly process, pervaporation separation is considered to be a promising alternative to conventional energy intensive separation technologies, like extractive or azeotropic distillation in liquid mixtures. Pervaporation can be considered the so-called “clean technology,” especially for the separation of volatile organic compounds [153, 154]. The technology is highly used for the separation of organics like aliphatic and aromatic alcohols, acids, benzene, toluene, tetrahydrofuran, ethylene glycol, and so forth from dilute aqueous solutions [155, 156]. It is also extensively used for the separation of organic/organic mixtures [157], organic azeotropic mixtures [157–159], and separation of isomers [160, 161]. The technique has been studied for the recovery of natural aroma compounds in food industry [162].

Natural biopolymers like chitosan and sodium alginate have attracted considerable attention during the last decade as membrane material for pervaporation separation [163–165]. Due to hydrophilic nature and ability to modify/tune their structures to achieve the desired separation, sodium alginate has fascinated wide group of researchers. Sodium alginate is the widely studied membrane in pervaporation dehydration of industrial solvents like ethanol, isopropanol, acetic acid, tetrahydrofuran, and so forth. The performances of sodium alginate-based membranes are reported to be outstanding in dehydration of organics from aqueous-organic mixtures. Use of sodium alginate membrane and its various modified forms in pervaporation dehydration studies has been increasing over the years. Figure 1 shows the trend of published literature on the use of sodium alginate-based membranes for pervaporation separation of aqueous-organic mixtures for past few years.

Aminabhavi and his research group have extensively studied the application of sodium alginate and its modified

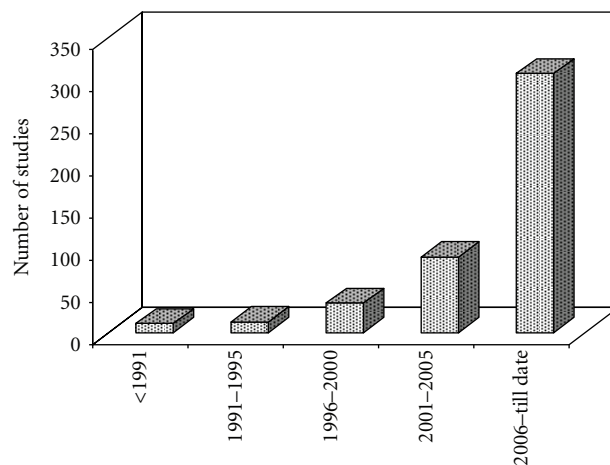


FIGURE 1: Number of studies reported in literature on the use of sodium alginate-based membranes for pervaporation separation of aqueous-organic mixtures (sources used: ScienceDirect online search, online ACS journals, online library of wiley publication and online journals of Taylor and Francis Publication).

membranes in pervaporation separation of aqueous-organic mixtures. Different types of blend, grafted, and mixed matrix sodium alginate membranes are prepared and tested for their pervaporation performances by the research group of Aminabhavi. A comparison in the pervaporation performance of sodium alginate-based membranes with that of other polymeric membranes for the separation of water-isopropanol mixture at 30°C has been listed in Table 2. The data presented are based on the reported works by Aminabhavi and his research group.

Table 2 shows that even though isopropanol separation has yielded poor selectivity with pure sodium alginate membrane, but large improvements were observed by incorporating sodium alginate with fillers like MCM-41, SBA-15, Na⁺MMT, AlPO₄-5, and so forth. However, the use of sodium alginate membrane for separation of organic-organic mixture by pervaporation is rare.

Although pervaporation through polymeric membranes is the most exploited one, several inorganic polymeric composite membranes with higher thermal and mechanical stability have also been developed by the researchers to make the transport process faster in pervaporation [168]. Apart from composite membranes, inorganic (zeolites and silica-based ceramic) membranes [169] also have been attracting attention of researchers in the recent years because of their tailored selectivity, high flux and low energy consumption in addition to provide a scope for combined reaction-separation systems.

Different hybrid pervaporation techniques such as pervaporation adsorption [170], distillation pervaporation [171], and so forth are also practiced for improved separation and enhanced recovery.

Simultaneous reaction separation by combination of pervaporation with chemical reactors has become an interesting alternative to the conventional process. In a pervaporation reactor, separation of product from the reaction system

TABLE 2: Pervaporation performance of different types of membranes for the separation of water-isopropanol mixture with 10 wt. % feed water at 30°C.

Membrane type	Selectivity	Ref.
PVA	77	[166]
PVA/PMMA blend membrane (5% PMMA)	400	[166]
PVA-PMA blend membrane (4% PMA)	2342	[167]
Pristine/blend/grafted sodium alginate membranes		
Sodium alginate (pristine)	650	[165]
Poly(acrylamide) grafted sodium alginate	100	[165]
Sodium alginate/PVA blend	580	[165]
Sodium alginate/pAAm grafted GG blend	890	[165]
Sodium alginate + 5 wt.% PVA + 10 wt.% PEG	3600	[165]
Mixed matrix membranes of sodium alginate		
MCM-41 (10 wt.%) filled sodium alginate	30,000	[165]
SBA-15 (10 wt.%) filled sodium alginate	∞	[165]
Fe-SBA-15 (10 wt.%) filled sodium alginate	∞	[165]
Na ⁺ MMT (10 wt.%) filled sodium alginate	∞	[165]
AlPO ₄ -5 (20 wt.%) filled sodium alginate	69,000	[165]
Al-MCM-41 (20 wt.%) filled sodium alginate	∞	[165]

PVA: poly (vinyl alcohol); PMMA: poly(methyl methacrylate); PMA: phosphomolybdic acid; NaAlg: sodium alginate; pAAm: poly(acrylamide); GG: guar gum; PEG: poly(ethylene glycol); Na⁺MMT: sodium montmorillonite; AlPO₄-5: aluminophosphate.

enhances the conversion and hence the products yield [172]. The removal of product during reaction in a pervaporation reactor suppresses the formation of byproduct. Pervaporation membrane reactor is one such reaction-separation system implemented for esterification reactions [172], production of butanol, extraction of aroma components from fermentation reactors, resin production [173], wastewater treatment, and so forth [174]. A new concept of hybrid pervaporation membrane reactor system described by Park and Tsotsis [175], which integrates pervaporation reactor system with adsorption in the permeate side. Park and Tsotsis have validated the hybrid pervaporation membrane reactor system by performing esterification of acetic acid by ethanol.

The major constraints for practical application of the membrane technology for processing of dilute liquid streams are the need for membrane that can work efficiently in real-world applications in complex matrix of the processed streams and high scaleup costs for large-scale applications.

The current needs for further development of the membrane technology include the following.

- (i) Development of low-cost membranes with high surface area per unit volume.
- (ii) Development of high temperature membranes (ceramic/metal), nanocomposites, targeted to specific commercial applications.
- (iii) Increasing membrane life with antifouling and anti-flux schemes.
- (iv) Regeneration/low-cost maintenance of the membranes.
- (v) Integration of the membrane technology with other separation technologies.
- (vi) Improved design and information tools for predicting membrane performance.
- (vii) Process scaleup.

2.3. *Electrophoresis.* Electrophoretic separation may be the major technique for molecular separation in today's cell biology laboratory for analytical as well as for preparative purposes. This is an inexpensive and powerful technique for separation in molecular level. Electrophoretic separation technique is based on the differential migration of electrically charged particles in an electric field. Hence, this technique is applicable only to ionic or ionogenic materials. The mediums used in biochemical applications are usually aqueous solutions, suspensions, or gels.

The key mechanism in the theory of electrophoresis is the electrical double layer, which is formed by the fixed charges of the macromolecules (or colloid) with the relatively mobile counter ions of the surrounding fluid. The thickness of the double layer is normally given by the inverse of the Debye-Huckel constant κ

$$\frac{1}{\kappa} = \left(\frac{\epsilon k T}{8 \pi e^2 n_o z^2} \right)^{1/2}, \quad (1)$$

where e is the electronic charge, k is the Boltzmann constant, n_o is the bulk concentration of each ionic species, z is the valence of the electrolyte, and ϵ is the dielectric constant.

The total charge of the electrical double layer is zero; however, the spatial distribution of charges is not random and hence gives rise to the electric potential. The mobile counter ions are bound sufficiently tightly to the macromolecules so that, during electrophoresis, the mobile counter ions moved together with the macromolecules.

Electrophoresis can be one dimensional (i.e., one plane of separation) or two dimensional. One-dimensional electrophoresis is used for most routine protein and nucleic acid separations. Two-dimensional separation of proteins is used for finger printing. Alternatively, the electrophoretic technique may be of the following types: moving boundary electrophoresis (MBE), zone electrophoresis (ZE), disc electrophoresis, isoelectric focusing (IEF), sodium dodecyl sulphate/polyacrylamide gel electrophoresis (SDS/PAGE), isotacophoresis (ITP), DNA sequencing, immobilized pH

gradients (IPG), pulsed-field gel electrophoresis, and capillary zone electrophoresis. The latest addition in the list is chromatophoresis, which is direct coupling of HPLC with SDS/PAGE and thus provide a new type of 2-D map. Moving boundary electrophoresis, capillary electrophoresis, and zone electrophoresis are the separation techniques primarily used in analytical methods. While most of the electrophoresis techniques have been used for analytical purposes, zone electrophoresis and isoelectric focusing are the two variations, which are also useful for preparative separations of protein mixtures.

Zone electrophoresis is characterized by the complete separation of charged solutes into separate zones. Many of the earlier separations of this type were carried out using filter paper in a Durum cell. Capillary electrophoretic technique has been used for the separation of DNA, proteins, in biotechnology and cell-biology applications [176, 177]. The technique is also used for chiral separation in pharmaceutical industry [178]. Prior to dramatic improvements in chromatographic techniques, continuous electrophoresis was popular for purifying proteins such as enzymes and amino acids [179, 180]. Electrophoresis is still invaluable on an analytical scale, but large scale electrophoretic separations were not established because the technique does not translate well to large sizes, mainly because of the difficulties to remove the generated heat during the separation and also because the process is very slow. During the recent decade, lot of progress has been made in electrophoretic separation technique.

2.4. Chromatographic Techniques. Different forms of chromatographic separation techniques are widely used in separation and purification of industrial process streams, such as for purification of groundwater, separation of chiral compounds in pharmaceutical industries, and separation of biomolecules in bio-chemical/biomedical applications. The chromatographic techniques are broadly classified into two categories depending on the physical state of the mobile phase, gas chromatography (GC), and liquid chromatography (LC). As the present paper deals with separation in solution; hence, the discussion is restricted within liquid chromatography.

2.4.1. Liquid Chromatography (LC). This is the chromatographic technique in which the mobile phase is a liquid. Depending on the separation mechanism, the liquid chromatography can be classified into the following subcategories.

High-Performance Liquid Chromatography (HPLC). This is a highly improved form of column chromatography. In this technique, the liquid mobile phase along with the sample to be separated is moved through the stationary phase (packed column) under high pressure with the help of a pump. Materials of much smaller particle size and hence very high surface area can be used for column packing. This allows a much better separation of the components in the mixture. The most common application of HPLC is in analysis [181].

Ion-Exchange Chromatography (IEC). IEC is often applied to the separation of acidic or basic samples, whose charge varies with pH. In this technique, the separation occurs through exchange or interchange of ions between the sample solution and the solid stationary phase. Primarily the ion exchange chromatography is regulated by electrostatic interactions between the ions being exchanged (the mobile ions in the sample) and the fixed ions that are attached covalently to the molecular lattice of the ion-exchanger.

Affinity Chromatography. This technique is largely used for isolation and purification of biological materials like, proteins, enzymes, antibodies, antigens, viruses, and intact cells by their reactivity with specific immobilized substances. This chromatographic technique is based on the principle that the molecule to be purified can form a selective but reversible interaction with another molecular species immobilized on a suitable chromatographic support. When the chromatographic support is a membrane, it is called as affinity membrane chromatography. Microporous/macroporous membranes containing functional ligands attached to their inner pore surface are used as adsorbents. Affinity membrane chromatography is a promising large-scale separation process for the isolation, purification, and recovery of proteins and enzymes [182–184]. Immobilized-metal affinity chromatography is relatively a new and advanced technique appropriate for protein purification [185]. Feng et al. [186] have synthesized a new immobilized-metal affinity chromatography adsorbent with paramagnetism for the separation and purification of protein. Separation through affinity chromatography can be performed by two different techniques, column chromatography and batch methods, of which batch method is usually applied for large-scale preparative separations. Affinity chromatography in batch mode is becoming more popular with the growth of biotechnology industry.

Size Exclusion Chromatography (SEC). Separation and retention in SEC are determined by the hydrodynamic diameter of the solute molecule relative to the size of the pores of the column packing. Thus, in SEC, the solutes are eluted according to decreasing molecular size and maximum available volume for separation is equal to the total pore volume of the packing medium. This technique is popular for the purification of protein molecules [187, 188] because of high recovery and its ability to remove undesirable aggregates (dimers, oligomers, etc.) from protein products [189]. Technical improvement of SEC to high-performance SEC (HPSEC) led to more rapid separation and increased resolution [190].

Reversed Phase Chromatography (RPC). This is the most popular liquid chromatographic technique of separation. In this technique, an aqueous/organic solvent mixture is commonly used as the mobile phase and a high surface area nonpolar solid (usually an alkyl-bonded silica packing) is used as the stationary phase.

Chiral Chromatography. This chromatographic technique is primarily used for separating stereoisomers, that is, chiral compounds.

Thin-Layer Chromatography (TLC). This is a planar chromatography in which the mobile phase moves through the stationary phase of a thin layer of adsorbent like silica gel, alumina, or cellulose, on a flat and inert substrate. The driving force of the solvent system and the retarding action of the stationary phase are responsible for the separation in TLC. Compared to other planar chromatographic techniques, it has the advantage of faster runs, better separations, and the choice of variety of adsorbents. High-performance TLC has also been developed for the better resolution. TLC is a laboratory separation technique that is used for the separation of organic compounds in solution.

The chromatographic separations can be performed in batch as well as in continuous mode [191]. Among all the above chromatographic techniques, different forms of column chromatography in continuous mode (simulated moving-bed chromatography, SMBC) are the most widely used technique for industrial separation. Simulated moving-bed chromatography (SMBC) is the most widely used technique as it requires less solvent for product elution and would be less cost intensive than for batch chromatography [191].

The continuous simulated moving bed chromatographic reactors have been extensively studied for many different separation schemes arising in the fine chemical, pharmaceutical, biotechnology, and petrochemical industries. Typical successful examples include *p*-xylene separation from its C8 isomers, *n*-paraffins from branched and cyclic hydrocarbons, olefins from paraffins, sugar-processing industry, chiral and enantiomers of isoflurane, enflurane, dilute binary gases, and other multicomponent systems.

The operation of a simulated moving bed provides a practically convenient way to mimic true moving bed acquiring all its advantages while eliminating the disadvantages arising due to solids motion. Over the years, a number of improvements in SMB operation modes such as in gas phase, supercritical conditions, and so forth have been made for specific applications. A generic design strategy for an SMBC separation system begins with the knowledge of the equilibrium and kinetic parameters with a view to determine the operating parameters, amount of adsorbent, pressure constraints, column geometry, and so forth for obtaining maximum productivity value. The results provide an assessment of whether the process is reasonable. Continuous models accounting for the mass transfer, heat transfer, pressure drop effects, and so forth are solved providing separation region analysis. An optimization procedure is then implemented to improve separation productivity for a given adsorbent/desorbant consumption, feed flow rates, constant columns number, and arrangement. The optimized solution is then detailed and simulated with a discontinuous model.

A typical case study employs the SMBC for the downstream processing of recombinant proteins using a two-step salt gradient in three-zone open loop continuous

countercurrent process for the purification of recombinant streptokinase. Possible process parameters and conditions for efficient separation are obtained through simulations. The model-based design of an SMBC unit requires the knowledge of the properties of the adsorbent phase such as its particle size, density, porosity, pore radius, heat capacity, and so forth. Likewise the model needs the data on the fluid phase components equilibrium adsorption parameters over the adsorbent materials such as its maximum loading capacity, adsorption equilibrium constants, and isosteric heat of adsorption of the components. Additionally, knowledge of Henry constants at different temperatures and mass transfer parameters (pore diffusion, axial dispersion, and external mass transfer coefficient) and heat transfer (heat conductivity, component fluid heat capacities, and Biot number) parameters is essential.

Simulated moving-bed chromatography (SMBC) is the most popular method for industrial separation of optical isomers [192–194], where a number of columns are connected in series with inlet/outlet lines connected between the columns. Recently, a multicolumn continuous chromatographic separation method named as “VARICOL” has been developed by Ludemann-Hombourger and his coworkers [195, 196] which is based on the principle of asynchronous shift of the inlet/outlet lines in a multicolumn system on a recycle loop. The newly developed method “Varicol” is proposed to be more efficient than the traditional simulated moving-bed technique. Another form of chiral resolution process for the separation of racemic mixture of difluoromethylornithine (DFMO HCl) in industrial scale has been proposed by Perrin et al. [197] involving a multicolumn continuous enantioselective chromatographic process coupled with enantioselective crystallization process. The other chromatographic techniques used for chiral separation are high-performance liquid chromatography (HPLC), gas chromatography (GC), supercritical fluid chromatography (SFC), thin-layer chromatography (TLC), and capillary electrochromatography (CEC).

The SMBC technique involving various separation mechanisms (adsorption, ion exchange, and so forth) is also being successfully employed for the separation of *p*-xylene isomers [198] and in the separation of glucose and fructose [199–201]. The new challenge for the SMB technology is its application to the separation and purification of biomolecules [202]. Examples of products that are considered for SMBC separation and purification are proteins [203, 204], amino acids [205], antibodies [206], nucleosides [207], and plasmid DNA [208].

Du et al. [209] have developed a system for low-speed rotary countercurrent chromatography by utilizing a convoluted multilayer helical tubing to be used for industrial separation. High-performance centrifugal partition chromatography (HPCPC) is also a practical and suitable method for the separation of biomolecules such as proteins, enzymes, and so forth, particularly on the preparative scale [210].

2.5. Electroosmosis. Electroosmosis, also called electroendosmosis, is the motion of polar liquid through a porous

membrane or any other porous structure under the influence of an applied electric field. If a solution is separated by a porous diaphragm and an e.m.f. is applied between the electrodes placed on each side of the diaphragm, there will be a flow of liquid from one side to the other. The movement of liquid is also known as electroosmotic flow. A porous diaphragm behaves as a mass of small capillaries. Glass capillaries can also be used for the electroosmotic flow to be observed. In each case, the charged layer attached to the solid cannot move and so the diffused layer in the liquid phase together with the liquid moves under the influence of an electric field. The direction of the electroosmotic flow depends on the diffuse part of the double layer. In moderately pure water, most solids acquire a negative charge so that the diffuse layer has a resultant positive charge, and hence, the flow of water is generally towards the cathode.

Electroosmotic separation technique has industrial importance for separation of water from colloidal suspensions as it consumes less energy than the conventional technique like evaporation. The most recent development in this technology has involved enhanced mixing efficiency by introducing a nonuniform zeta potential, and the enhancement in mixing was experimentally observed by Herr et al. [211]. In 1930, Bartow and Jebens [212] reported water purification by Electroosmosis through a diaphragm. The water so purified was claimed to be equivalent to distilled water and could be obtained at a much lower cost. Electroosmotic separation technique was applied along with vacuum separation technique for the separation of iron oxide ultrafines [213]. The cationic surfactant CTAB was used to maintain the zeta potential in order to achieve the electroosmotic separation of the uncharged ultrafines from iron oxide slurry. A sludge (water treatment process sludge) treatment method by electroosmotic dewatering has been proposed by Buijs et al. [214]. Buijs and coworkers have performed electroosmotic dewatering of commercial sludge on pilot plant scale and on real process scale. The energy consumption for dewatering was found to be within the range of 20–40 kJ kg⁻¹. The removal of water from food suspensions is of great interest in food technology. Al-Asheh et al. [215] reported a direct current Electroosmosis dewatering technique to concentrate tomato to the conventional paste suspension. The process was claimed to save 70% of energy as compared to the evaporation technique. The electroosmotic technique has been used by several researchers for removing water soluble organics from soil for soil remediation purpose [216], dewatering of filter cakes of activated sludge [217], and so forth.

2.6. Hybrid Separation Techniques. In addition to the separation techniques described above, several forms of hybrid separation processes have been developed and applied to achieve the desired separation in dilute liquid streams. These hybrid processes usually involve two or more than two different separation techniques. Sarangi and Pattanaik have developed such a separation process comprising of reverse osmosis (RO) and solvent extraction techniques for recovering copper from dilute solutions [218]. An integrative membrane coagulation-adsorption bioreactor was

developed by Tian et al. [219] for the removal of organic matter in drinking water treatment. Many novel separation processes involving electrophoresis and other separation techniques like solvent extraction, chromatography, isoelectric focusing are developed for the separation of ionic biomolecules as well as inorganic ions [180, 220]. Spoor et al. [221] reported pilot scale deionization of galvanic nickel solution using a hybrid ion-exchange/electrodialysis system. Decolourization of reactive dyes from an aqueous solution by combined coagulation/micellar-enhanced ultrafiltration process has been reported by Ahmad and Puasa [222]. Den and Wang [223] suggested a hybrid separation method for treatment of brackish water. The method consists of pretreatment of the brackish water by electrocoagulation (for removing silica) followed by reverse osmosis. According to Den and Wang, pretreatment of brackish water by electrocoagulation prevents the fouling of RO membrane and hence increases the membrane life. Nataraj et al. have developed hybrid separation techniques by combining nanofiltration (NF) with reverse osmosis (RO), microfiltration (MF) with electro dialysis (ED) and took the techniques upto pilot-scale level for water/wastewater treatment. Nataraj et al. [224] have reported a pilot-scale skid-mounted system comprising of nanofiltration (NF) and reverse osmosis membrane processes for the treatment of distillery wastewater. Commercial NF membrane and thin-film composite (TFC) polyamide RO membrane in spiral wound configuration was used in the process. The same NF-RO process was successfully used for removing dye and salts from simulated water in pilot scale by Nataraj et al. [225]. Pilot plant of a hybrid microfiltration (MF) and electro dialysis (ED) system was also designed, constructed, and employed successfully by Nataraj et al. [226] for the treatment of paper industry wastewater. In this hybrid MF-ED process, Nataraj et al. have used microfiltration module of ceramic membrane as a pretreatment step for the electro dialysis pilot-scale unit operation. The electro dialysis pilot-scale unit designed by them consisted of membrane stack of a series of cation exchange and anion exchange membranes. The hybrid MF-ED process could recover 80% of the wastewater.

3. Discussions and Future Needs

Developments of separation and purification technology for processing of dilute liquid streams have been reviewed with special focus on adsorption, membrane-based techniques, chromatography, and electrokinetic-based separation techniques (Electroosmosis, electrophoresis).

Because of the vast applicability of adsorption technology, it has grown extensively over the past years, and still new/modified adsorbents are being added into the list. Also in the recent years, a lot of novel adsorption processes have been developed for enhanced separation and purification of the processed streams. Despite the development of a large number of new/modified adsorbents, very few of them are set for their practical application in industrial processed streams. Successful implementation of adsorbent and adsorption necessitates reasonably good understanding

of the fundamentals of the process. Synthesis of advanced materials with high chemical and thermal stability, cost effectiveness of the process, improved predictive models for mass transfer, adsorption, equilibrium, and other physical data is the challenges for further growth of this technology in future.

The extensive literature on membrane separation indicates that the use of membranes in separation and purification processes is growing steadily, and it is believed that membrane separation can play an important role in reducing the environmental impact largely. A wide range of membrane materials has been investigated by the researchers to achieve enhanced and quality separation. Nevertheless, the major constraint for limited application of this technology is high scaleup costs for large-scale applications. It is required to develop robust functional tailored materials with high mechanical and thermal stability, enhanced permeability and selectivity, and economic process scaleup for extensive and versatile application of the technique and to meet the future needs.

Chromatographic separation in batch mode is considered to be very expensive technique. Nevertheless, the continuous chromatography have shown considerable advantages over the batch mode as it better utilizes the adsorbent materials, reduce solvent consumption, and increase productivity. Simulated moving bed chromatography is the most popular among all existing separation techniques for separation of chiral compounds in pharmaceutical industries and separation of biomolecules in bio-chemical and biomedical applications. Among a vast range of existing materials, only very few can practically serve as the perfect materials for specific separation to be used as stationary phase in industrial applications. Hence, there is a necessity to develop/identify materials suitable for stationary phase and mobile phase. Also there is urgent need to develop flexible, fast scaleup, and economically viable process for enhanced separation.

Notwithstanding the differences in the strategies for separation, the research needs for further improvements in the separation techniques can be covered under the common categories as [227] the following.

- (i) Synthesis of new advanced materials (adsorbents, membrane materials, specialty materials, functional polymers, etc.) improves performance.
- (ii) Their physicochemical data bases (thermodynamics and kinetics parameters).
- (iii) Understanding the role and effects of uncertainties in proposed mechanism (such as nucleation, growth, surface interaction, transport, etc.).
- (iv) Understanding the dynamics of exchange processes at the interface.
- (v) Lack of direct measurements of variables of interest (e.g., in situ sampling, analytical and flow visualization).
- (vi) Development of sensors and other analytical measurement instruments.
- (vii) Development of better predictive modeling tools covering length-time scales of interest.

- (viii) Use of models for product quality control and optimization of process systems.
- (ix) Hybridization: combined separation operations or reaction and separation.
- (x) Molecular recognition as a basis for separation.
- (xi) Fundamental understanding, new equipment, and test facilities.

Acknowledgment

The authors wish to acknowledge the financial support by Council of Scientific and Industrial Research, India.

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