

ADSORBENT BIOPROCESSING CLARIFICATION AGENTS AND METHODS OF MAKING AND USING THE SAME

FIELD OF THE INVENTION

[0001] The present invention is directed to adsorbent clarification agents suitable for use in bioprocessing procedures. The present invention is further directed to methods of making and using adsorbent clarification agents for the removal of or separation of undesirable biological substances during bioprocessing procedures.

BACKGROUND

[0002] In recent years biopharmaceutical manufacturing has demonstrated major improvements in MAb production, exhibiting product titers as high as 25 g/L often associated with very high cell densities. High-density cell cultures with >150 million cells/mL pose a great challenge in further downstream processing because of a need to remove a large amount of biomass and increased levels of contaminants from cell debris generated during cell culture and harvesting. Production of biological substances (MAbs, in particular) usually involves processing a complex cell culture broth from which desired biological substances must be isolated and purified while maintaining high overall product recovery and quality. Traditionally, centrifugation and a combination of filtration techniques (tangential-flow filtration and depth filtration) have been widely accepted as workhorses for clarifying these complex cell culture broths. However, improvement of mammalian cell culture processes is providing for total cell densities far beyond traditional levels of 20×10^6 cells/mL for CHO cells to $>150 \times 10^6$ cells/mL for PER.C6 cells. Thus, limitations of both centrifugation and filtration techniques are apparent by the high ($\leq 40\%$) solids content of such harvests.

[0003] Centrifugation can be applied to process feed streams with high levels of solids, for instance. However, product recovery can be low because of increased pellet volumes and a need to desludge frequently (especially in large-scale continuous centrifugation). Additionally, cell disruption from shear forces generated during centrifugation can further decrease the efficiency of harvest clarification and potentially cause product damage and/or entrapment.

[0004] Depth filters are advantageous because they remove contaminants, and many come in single-use format, reducing the need for cleaning and validation. However, depth filters are currently unable to handle high-solids feedstreams and are often used in series with

centrifugation. TFF can handle high solids loading, but this technique can exhibit poor yield because of polarization of solids at the membrane surface when processing highly dense feed streams. Excessive product dilution and cell lysis caused by shear forces can also limit the utility of TFF.

[0005] Flocculation of cell culture harvests has also been widely used to enhance clarification throughput and downstream filtration operations. Current techniques include the use of soluble polyionic polymers (such as DEAE dextran, acryl-based polymers, and polyethylene amine) and inorganic materials such as diatomaceous earth and perlites, which remove cells and cell debris. However, polymers must subsequently be removed from process streams, which requires monitoring and quantification by in-process and product-release assays. If IEX chromatography is included as a purification step in the downstream process, binding capacities will be greatly affected by the charged nature of flocculants. The high viscosity of polycation stock solutions presents an additional process challenge.

[0006] In recent years, various new clarification techniques have been developed. For example, (<http://www.selectscience.net/product-news/sartorius-stedim-biotech>) single use harvesting technology for high cell density cultures using diatomaceous earth (DE) as filter aid has been introduced. (Minow B., et al, BioProcess Int. , April 1st, 2014). However, given its low surface area (BET $\sim 1 \text{ m}^2/\text{g}$) and non-porous nature, DE has no function in adsorption of proteins and/or other types of biologics, but only as filter aid.

[0007] In other processes, functionalized particulate materials have been used as adsorbents for clarification of cell broths. For example, WO2010043700 and WO2010043703 methods of clarification or removing host cell proteins by the utilization of anion exchange material in the process. The property or optimal conditions for the ion exchange materials are not described in the patent applications.

[0008] Efforts continue to further develop clarification materials and processes having improved agents in the form of functionalized particulate materials so as to improve binding capacity (i.e., the amount and the variety of biomaterials that can be bound to the adsorbent clarification agents) and/or binding selectivity of the functionalized particulate materials.

SUMMARY

[0009] The present invention addresses the need in the art for improved bioprocesses by the discovery that the use of certain functionalized porous inorganic oxide materials provide enhanced performance as clarification adsorbents. The adsorbents of the present invention unexpectedly provide exceptional binding capacity, as well as binding selectivity in bioprocesses (e.g., biopurification, bioseparation, etc.) when compared to known functionalized particulate materials.

[0010] In particular, the present invention provides improved bioprocesses employing polymeric functionalized inorganic oxide materials comprised of porous inorganic oxide particles having a sufficiently wide pore size distribution to enable the particles to capable of selectively bind to a wide variety of biomolecules including, but not limited to, cells, host cell proteins, nucleic acids, cell debris, chromatins, etc., so as to remove these materials during one or more bioprocessing steps. In some embodiments, the porous inorganic oxide particles have a pore size distribution as measured by a pore size distribution span 90 value of at least about 1.0. In other embodiments, wherein the porous particles having a pore size distribution as measured by a pore size distribution span 90 value of as much as about 5.0 to about 10.0.

[0011] Accordingly, the present invention is directed to polymer functionalized porous inorganic oxide particles having a specified pore size distribution (also referred to herein as “adsorbents”) which are useful as clarification agents in a variety of bioprocesses. In one exemplary embodiment, the present invention is directed to the the adsorbents comprises polymeric material covalently bonded to the surface of porous inorganic oxide particles wherein said particles have a pore size distribution as measured by a pore size distribution span 90 value of at least about 1.0 and. In some desired embodiments, the invention comprise the adsorbents useful as a bioprocessing clarification agent, wherein the adsorbents comprise a polyelectrolyte material covalently bonded to the surface of porous inorganic oxide particles, wherein the porous particles having a pore size distribution as measured by a pore size distribution span 90 value of as much as about 5.0 to about 10.0. . In preferred embodiments of the invention, the polymeric material comprises a polyelectrolyte, e.g. polyethyleneimine. In an even more preferred embodiment of the invention, the porous metal oxide particle comprise silica.

[0012] The present invention is even further directed to methods of making adsorbents in the form of functionalized particulate material. In one exemplary embodiment, the method of making adsorbents of the present invention comprises: contacting porous inorganic metal oxide particles with one or more reactants under reaction conditions that result in at least one polymeric material covalently bonded to at least one surface of the metal oxide particles, wherein the metal oxide particles have a wide pore size distribution as measured by a pore size distribution span 90 value of at least about 1.0.

[0013] The present invention is also directed to a method for the clarification of a bioprocess mixture during a bioprocessing procedure. The method provides for the removal or separation of the undesirable biological substances, e.g. cell debris, from a bioprocessing mixture by using the adsorbents of the invention.

[0014] These and other features and advantages of the present invention will become apparent after a review of the following detailed description of the disclosed embodiments and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] FIGURE graphically shows the comparison in pore size distributions (from mercury porosimetry) for two different silicas.

DETAILED DESCRIPTION

[0016] To promote an understanding of the principles of the present invention, descriptions of specific embodiments of the invention follow and specific language is used to describe the specific embodiments. It will nevertheless be understood that no limitation of the scope of the invention is intended by the use of specific language. Alterations, further modifications, and such further applications of the principles of the present invention discussed are contemplated as would normally occur to one ordinarily skilled in the art to which the invention pertains.

[0017] It must be noted that as used herein and in the appended claims, the singular forms "a", "and", and "the" include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to "an oxide" includes a plurality of such oxides and reference to "oxide" includes reference to one or more oxides and equivalents thereof known to those skilled in the art, and so forth.

[0018] "About" modifying, for example, the quantity of an ingredient in a composition, concentrations, volumes, process temperatures, process times, recoveries or yields, flow rates, and like values, and ranges thereof, employed in describing the embodiments of the disclosure, refers to variation in the numerical quantity that may occur, for example, through typical measuring and handling procedures; through inadvertent error in these procedures; through differences in the ingredients used to carry out the methods; and like proximate considerations. The term "about" also encompasses amounts that differ due to aging of a formulation with a particular initial concentration or mixture, and amounts that differ due to mixing or processing a formulation with a particular initial concentration or mixture. Whether modified by the term "about" the claims appended hereto include equivalents to these quantities.

[0019] As used herein, the terms "bioprocess" or bioprocessing" refer to a batch process that forms, alters and/or utilizes one or more biomolecules. The term "bioprocess" includes, but is not limited to, bioseparation processes, biopurification processes, processes for forming biopharmaceuticals, and processes for purifying biopharmaceuticals. As used herein, the term "bioprocess" or bioprocessing" refers to processing that may take place prior to a chromatography process (e.g., removing cell debris from a batch of material), does not encompass chromatography processes (e.g., liquid chromatography).

[0020] As used herein, the term "biomolecule" means any molecule that is produced by a living organism, including large molecules such as proteins, polysaccharides, lipids, and nucleic acids; and small molecules such as primary metabolites, secondary metabolites, and natural products. Examples of biomolecules include cells and cell debris; antibodies, proteins and peptides; nucleic acids, such as DNA and RNA; endotoxins; viruses; vaccines and the like. Other examples of biomolecules include those recited in WO 2002/074791 and U.S. 5,451,660.

[0021] As used herein, "porous inorganic metal oxide particles" includes particles comprised of inorganic metal oxide materials having intra-particle pores or inter-particle pores in cases where smaller particles are agglomerated to form larger particles. Inorganic metal oxides include, but is not limited to, silica, alumina, zirconia or the combination of them.

[0022] As used herein, the term "functionalized" as it relates to the surface of the inorganic oxide particles means porous inorganic metal particles that have been surface modified by reaction with at least one functional compound to alter the selectivity of at least a portion of the particle surface, including the surface area on the external portion of the particles, and/or on

the surface area of the internal pores. The functionalized surface of the particles may be used to form a bonded phase (covalently or ionically), a coated surface (e.g., reverse phase C18 bonded), a polymerized surface (e.g., ion exchange), an inherent surface (e.g., inorganic/organic hybrid material), or the like. For example, reacting porous inorganic oxide particles with octadecyltrichlorosilane forms a “reverse phase” by covalently bonding the silane to the inorganic surface (e.g., C4, C8, C18, etc.). In another example, reaction of the inorganic particles with aminopropyltrimethoxysilane followed by quaternization of the amino group forms an “anion exchange phase.” In a third example, a bonded phase may be formed by reaction of the inorganic particles with aminopropyltrimethoxysilane followed by formation of an amide with an acid chloride. Other bonded phases include diol, cyano, cation, affinity, chiral, amino, C18, hydrophilic interaction (HILIC), hydrophobic interaction (HIC), mixed mode, size exclusion, etc. As part of the bonded phase or functionalized surface, a ligand may be used to show specific interaction with the target molecule or biomolecule (e.g., ligate), such as those set forth in U.S. 4,895,806.

[0023] As used herein, the term “polyelectrolyte” is defined as meaning a polymer comprising repeating units such as (i) a cation, (ii) an anion, or (iii) an electrolyte functional group that associates or dissociates with a proton in aqueous solutions to form a positive or negative charge. For example, cationic polyelectrolytes suitable for use in the present invention include, but are not limited to, polyethyleneimine (PEI), polyallylamine, polyvinyl pyridine, polydiallyldimethylammonium chloride (pDADMAC), and copolymers containing similar functional groups. Anionic polyelectrolytes suitable for use in the present invention include, but are not limited to, polyacrylic acids, polymethacrylic acids, polystyrene sulfonic acids, nucleic acids, and copolymers containing similar functional groups (e.g., poly(styrene-co-maleic acid, poly(styrene sulfonic acid-co-maleic acid))

[0024] As used herein, the term “polyethyleneimine” is defined as meaning a polymer comprising repeating units of an amine bonded to a $-\text{CH}_2\text{CH}_2-$ spacer, wherein the polymer may be linear or branched and may contain primary, secondary and/or tertiary amino groups.

[0025] As used herein, the term “BET particle surface area” is defined as meaning a particle surface area as measured by the Brunauer Emmet Teller nitrogen adsorption method.

[0026] As used herein, the term median pore diameter (size) distributions were measured by mercury intrusion using an Autopore® IV 9520, available from Micromeritics Instrument Corporation (Norcross, GA).

[0027] As used herein, the term “pore size distribution” means the relative abundance of each pore size in a representative volume of porous inorganic particles.

[0028] As used herein “median pore diameter” is the Median pore diameter (PD50) is defined as the midpoint at which 50% of the pore volume is contributed by smaller pores and 50% is contributed by larger pores.

[0029] As used herein, the term “pore volumes” referenced herein represent cumulative volumes from mercury intrusion into 50-10,000 Å size pores.

[0030] As used herein, the term “molecular weight” is defined as meaning the molar mass of a single molecule of a particular compound or polymer.

[0031] As used herein, the “pore size distribution span 90 value” is calculated as $[(PD90 - PD10)/PD50]$, whereas PD10 is the pore diameter at 10% cumulative pore volume contribution, PD50 is the pore diameter at 50% cumulative pore volume contribution, and PD90 is the pore diameter at 90% cumulative pore volume contribution, all based on mercury intrusion data.

Porous Particles

[0032] As discussed above, the porous inorganic metal oxide particles useful to prepare the adsorbents of the present invention possess a wide pore size distribution as measured by a pore size distribution span 90 value of at least about 1.0 (or at least about 2.0, or at least about 3.0, or at least about 4.0, or at least about 5.0, or at least about 6.0, or at least about 7.5, desirably, from about 5.0 to about 10.0, more desirably, from about 7.5 to about 8.5, and in some embodiments, about 7.8). The wide pore size distribution enables the formation of adsorbent clarification agents that provide exceptional binding capacity, binding selectivity, as well as binding of a wide variety of biomolecules.

[0033] Generally, the porous inorganic metal oxide particles have a pore size distribution of from about 30 to about 5000 Å.

[0034] Advantageously, the wide pore size distribution of the porous inorganic metal oxide particles used to form the adsorbents of the present invention enables controlled binding

capacity, binding selectivity, and binding of a wide variety of biomolecules by choosing (1) specific polymeric material bound to surfaces of the metal oxide particles, (2) the amount of polymeric material bound to surfaces of the metal oxide particles, and/or (3) the molecular weight of the polymeric material bound to surfaces of the metal oxide particles. As shown and discussed in the example section below, the wide pore size distribution of the metal oxide particles used to form the adsorbents of the present invention provides more flexibility and binding capacity when compared to known, commercially available adsorbents.

[0035] Typically, the porous metal oxide particles useful to prepare the adsorbents of the invention possess a median pore size of at least about 100 Å. In another embodiment, the porous inorganic particles have a median pore size of at least about 150 Å (or at least about 200 Å; or at least about 250, or at least about 300 Å; or at least about 350 Å; or at least about 400 Å, or at least about 500 Å; or at least about 600 Å; or at least about 800 Å. In some embodiments, the porous inorganic particles have a median pore size of from about 100Å to about 800 Å. In some embodiments, the porous inorganic particles have a median pore size of from about 150 Å to about 250 Å. In other embodiments, the porous inorganic particles have a median pore size of less than 2000 Å. In other embodiments, the porous inorganic particles have a median pore size of less than 1000 Å.

[0036] The metal oxide particles typically have a particle size, as measured by a median particle dimension, of less than 150 µm. The porous inorganic metal oxide particles typically have a median particle dimension of about 1 µm, more typically, less than about 100 µm. In some embodiments, the porous inorganic particles have a median particle dimension of from about 10 to about 50 µm, more desirably, about 30 µm.

[0037] Typically, the metal oxide particles typically have an irregular shape, but may have any shape (e.g., spherical, elliptical, etc.). Regardless of shape, the porous inorganic metal oxide particles typically have a median particle dimension as discussed hereinabove.

[0038] In additional embodiments, the porous inorganic metal oxide particles may have an aspect ratio of at least about 1.0 as measured, for example, using Transmission Electron Microscopy (TEM) techniques. As used herein, the term “aspect ratio” is used to describe the ratio between (i) the median particle dimension of the porous inorganic particles and (ii) the median cross-sectional particle dimension of the porous inorganic particles, wherein the cross-sectional particle dimension is substantially perpendicular to the largest particle dimension of the

porous inorganic particles. In some embodiments of the present invention, the porous inorganic particles have an aspect ratio of at least about 1.1 (or at least about 1.2, or at least about 1.3, or at least about 1.4). Typically, the porous inorganic particles have an aspect ratio of from about 1.0 to about 1.5.

[0039] The pore volume of the porous inorganic metal oxide particles as measured by mercury intrusion into 50-10,000 Å size pores. In another embodiment, the porous inorganic metal oxide particles as measured by mercury intrusion into 50-10,000 Å size pores - is at least about 0.25 cc/g 0.50 cc/g. In one exemplary embodiment of the present invention, the porous inorganic particles have a pore volume as measured by mercury intrusion into 50-10,000 Å size pores - of from at least about 1.0 cc/g ; at least about 1.50 or at least about 1.77 cc/g. In another exemplary embodiment of the present invention, the porous inorganic particles have a pore volume as measured by mercury intrusion into 50-10,000 Å size pores - of from about 1.0 cc/g to about 3.0 cc/g.

[0040] The surface area of porous inorganic metal oxide particles also have a surface area as measured by the BET nitrogen adsorption method (i.e., the Brunauer Emmet Teller method) of at least about 100 m²/g, or at least about 300 m²/g, or at least about 500 m²/g. In one exemplary embodiment of the present invention, the porous inorganic oxide particles have a BET surface area of from about 100 m²/g to about 1000 m²/g, or from 600 m²/g to about 800 m²/g. In a further exemplary embodiment of the present invention, the porous inorganic oxide particles have a BET surface area of from about 700 m²/g.

[0041] The porous inorganic metal oxide particles useful to prepare the adsorbents of the invention may comprise a variety of inorganic materials including, but not limited to, silica, alumina, zirconia, or mixtures thereof. In one desired embodiment, the metal oxide particles comprise silica. When the metal oxide particles comprise silica, the particles desirably comprise silica having a purity of at least about 93% by weight SiO₂, or at least about 93% by weight SiO₂, at least about 94% by weight SiO₂, at least about 95% by weight SiO₂, at least about 96% by weight SiO₂, at least about 97% by weight SiO₂, or at least about 98% by weight SiO₂ up to 100% by weight SiO₂ based upon the total weight of the particle.

Adsorbents

[0042] In accordance with the present invention, the adsorbent comprises porous metal oxide particles as described herein above and a polymeric material covalently bonded to surfaces of said metal oxide particles. In one embodiment the adsorbents comprises at least one bifunctional moiety extending from said surfaces of said metal oxide particles, each of said at least one bifunctional moiety comprising (i) one or more functional groups capable of bonding to said surfaces, and either (iia) said polymeric material, or (iib) one or more reactive groups capable of bonding to said polymeric material.

[0043] In another embodiment, the adsorbents comprises at least one bifunctional moiety extending from the surfaces of said metal oxide particles, each of said at least one bifunctional moiety comprising (i) one or more functional groups capable of bonding to said surfaces, and (iia) said polymeric material.

[0044] In yet another embodiment, the adsorbents comprises at least one bifunctional moiety extending from said surfaces of said metal oxide particles, each of said at least one bifunctional moiety comprising (i) one or more functional groups capable of bonding to said surfaces, and (iib) one or more reactive groups capable of bonding to said polymeric material.

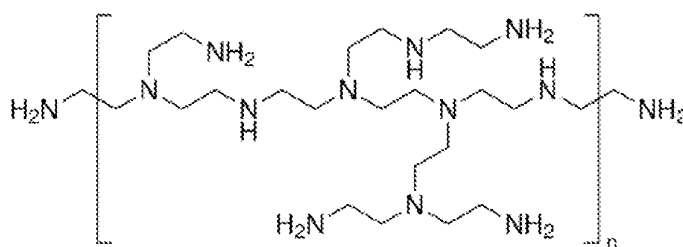
[0045] Suitable bifunctional moiety extending from the surface of said metal oxide particle comprises epoxy rings that can react with amine groups from the polymer chains of the polyelectrolytes. In one embodiment, the at least one bifunctional moiety comprising the adsorbent comprises product from reaction of metal oxide surface with an epoxy silane. In a preferred embodiment, the epoxy silane comprises (3-glycidoxypentyl)-trimethoxysilane.

[0046] In one embodiment of the invention, the polymeric material is covalently bonded to the surface of the metal oxide particles via a covalent bond linkage consisting of one or more atoms selected from the group consisting of C, O, Si and N.

[0047] Typically, the polymeric material comprises a polyelectrolyte. The polyelectrolyte may be cationic or anionic. Suitable cationic polyelectrolyte materials comprise polyethyleneimine, polyallylamine, polyvinyl pyridine, polydiallyldimethylammonium chloride (pDADMAC), a copolymer containing one or more cationic or cationic-forming functional groups, or combinations thereof. The cationic polyelectrolyte may also comprises a reaction product of said metal oxide particles and an aqueous trimethoxysilyl-polyethyleneimine solution. In a preferred embodiment, the polymeric material comprises polyethyleneimine. In even more

preferred embodiment, the polyethyleneimine have (i) a weight average molecular weight, Mw, and (ii) a number average molecular weight, Mn, each of which is less than about 5000. In still a more preferred embodiment, the polyethyleneimine has (i) a weight average molecular weight, Mw, and (ii) a number average molecular weight, Mn, each of which ranges from about 500 to about 2500; or. (i) a weight average molecular weight, Mw, ranging from about 800 to about 2000, and (ii) a number average molecular weight, Mn, ranging from about 600 to about 1800.

[0048] In one embodiment, the polymeric material comprise a polyethyleneimine has a structure:



prior to being covalently bonded to said surfaces, and n is a number greater than or equal to 1.

[0049] Suitable anionic polyelectrolyte materials comprises polyacrylic acid, polymethacrylic acid, polystyrene sulfonic acid, nucleic acid, a copolymer containing one or more anionic or anionic-forming functional groups or combinations thereof. In a preferred embodiment, the anionic polyelectrolyte material comprises polyacrylic acid, polymethacrylic acid, or a combination thereof. In a more preferred embodiment, the anionic polyelectrolyte material comprise a polyacrylic acid or a polymethacrylic acid having a weight average molecular weight, Mw, greater than about 50,000. In an even more preferred embodiment, the polyacrylic acid or polymethacrylic acid has a weight average molecular weight, Mw, of from about 100,000 to about 250,000.

[0050] The amount of the polymeric material present in the absorbent is any amount suitable to provide charge interactions with biologics and therefore selectively bind to these biologics of opposite charge. In one embodiment, the polymeric materials comprise an amount such that less than 100% of said surfaces of the metal oxide particles are bonded to said polymeric material. In another embodiment, said the polymeric material is present on the adsorbent in an amount representing up to about 20.0 wt% of said adsorbents based on a total weight of said adsorbents. In other embodiments, the polymeric material is present in an amount

representing from about 1.0 to about 15.0 wt% of said adsorbents based on a total weight of said adsorbents.

[0051] In a preferred embodiment of the invention, the porous metal oxide particles comprising the adsorbents comprise silica particles.

Methods of Making Adsorbents

[0052] The adsorbent of the invention are generally prepared by contacting the metal oxide particles with one or more reactants under reaction conditions that result in covalently bonding the polymeric material to the surfaces of the metal oxide particles. The contacting step may utilize a solvent. In one embodiment, the contacting step utilizes a reaction mixture free of organic solvent.

[0053] In one embodiment of the invention, the one or more reactants comprise at least one bifunctional compound comprising (i) one or more functional groups capable of bonding the compound to the surfaces of the metal oxide particles, and either (iia) the polymeric material, or (iib) one or more reactive groups capable of bonding to the polymeric material.

[0054] Suitable reactants comprising at least one bifunctional compound comprising (i) one or more functional groups capable of bonding the compound to the surfaces of the metal oxide particles, and (iia) the polymeric material include, but is not limited to, polyethyleneimines.

[0055] Suitable reactants comprising at least one bifunctional compound comprising (i) one or more functional groups capable of bonding the compound to the surfaces of the metal oxide particles, and (iib) one or more reactive groups capable of bonding to the polymeric material, include but is not limited to, polyacrylic acids.

[0056] It is also within the scope of the invention to choose the one or more reactants so as to produce adsorbents having a desired degree of affinity for one or more particular biological compounds through attraction due to opposite charges. For example, the affinity of negatively charged DNA towards positively charged surface. The amount of each of the one or more reactants may also be chosen so as to form adsorbents having a desired degree of particle surface coverage by the polymeric material.

Use of Adsorbents

[0057] Adsorbent in accordance with the present invention comprise porous inorganic metal oxides surface functionalized with polyelectrolytes. To achieve the adsorption of higher amount of undesirable biological substances, the requirements of the porous molecules are high pore volume (>1.0 cc/g) and high pore size distribution span 90 value (>1.0). If these conditions are met, with the bonding of polyelectrolyte, either positively or negatively charged, the adsorbent materials can be effectively used for use as both adsorbents and clarification agents. In one embodiment, the functionalize adsorbents are used as a bioprocessing clarification agent, wherein the adsorbents comprises: metal oxide particles having a wide pore size distribution as measured by a pore size distribution span 90 value of at least about 1.0; and polymeric material covalently bonded to surfaces of the metal oxide particles.

[0058] The adsorbent may be used by contacting the functionalized porous adsorbent in a bioprocessing vessel containing undesirable biologics obtained during a bioprocessing procedure; allowing a sufficient incubation time to permit adsorption of the undesirable biologics to the adsorbent or formation of cell pellet and a supernatant layer; separating the resulting mixture through either filtration or decanting or pumping out the supernatant layer and thereafter extracting the desired biological substance from either the filtrates or supernatant or carrying out further purification steps including depth filtration and downstream chromatography steps.

[0059] In one embodiment, the adsorbents in accordance with the present invention are added to a bioprocessing vessel containing one or more biomolecules selected from the group consisting of a protein, a polysaccharide, a lipid, a nucleic acid, a metabolites, a mammalian cell, mammalian cell debris, an antibody, a peptide, DNA, RNA, an endotoxin, a virus, a vaccine, an enzyme, or any combination thereof. In other embodiment, the bioprocessing vessel contain at least one of: host cells, cell debris, host cell proteins, nucleic acids, chromatins, antibodies, virus, or vaccines. The functionalized adsorbents bind to one or more biomolecules that come into contact with the adsorbents. Following the binding step in which the adsorbents binds to one or more biomolecules that come into contact with the adsorbents, the adsorbents bound to the one or more biomolecules is separated from other components of the bioprocessing procedure.

[0060] It should be understood that although the above-described adsorbents and methods are described as “comprising” one or more components or steps, the above-described adsorbents and methods may “comprise,” “consists of,” or “consist essentially of” any of the

above-described components or steps of the adsorbents and methods. Consequently, where the present invention, or a portion thereof, has been described with an open-ended term such as “comprising,” it should be readily understood that (unless otherwise stated) the description of the present invention, or the portion thereof, should also be interpreted to describe the present invention, or a portion thereof, using the terms “consisting essentially of” or “consisting of” or variations thereof as discussed below.

[0061] As used herein, the terms “comprises,” “comprising,” “includes,” “including,” “has,” “having,” “contains”, “containing,” “characterized by” or any other variation thereof, are intended to encompass a non-exclusive inclusion, subject to any limitation explicitly indicated otherwise, of the recited components. For example, an adsorbent and/or method that “comprises” a list of elements (e.g., components or steps) is not necessarily limited to only those elements (or components or steps), but may include other elements (or components or steps) not expressly listed or inherent to the adsorbent and/or method.

[0062] As used herein, the transitional phrases “consists of” and “consisting of” exclude any element, step, or component not specified. For example, “consists of” or “consisting of” used in a claim would limit the claim to the components, materials or steps specifically recited in the claim except for impurities ordinarily associated therewith (i.e., impurities within a given component). When the phrase “consists of” or “consisting of” appears in a clause of the body of a claim, rather than immediately following the preamble, the phrase “consists of” or “consisting of” limits only the elements (or components or steps) set forth in that clause; other elements (or components) are not excluded from the claim as a whole.

[0063] As used herein, the transitional phrases “consists essentially of” and “consisting essentially of” are used to define a adsorbents and/or method that includes materials, steps, features, components, or elements, in addition to those literally disclosed, provided that these additional materials, steps, features, components, or elements do not materially affect the basic and novel characteristic(s) of the claimed invention. The term “consisting essentially of” occupies a middle ground between “comprising” and “consisting of”.

[0064] Further, it should be understood that the herein-described adsorbents and/or methods may comprise, consist essentially of, or consist of any of the herein-described components and features, as shown in the figures with or without any feature(s) not shown in the figures. In other words, in some embodiments, the adsorbents and/or methods of the present

invention do not have any additional features other than those shown in the figures, and such additional features, not shown in the figures, are specifically excluded from the adsorbents and/or methods. In other embodiments, the adsorbents and/or methods of the present invention do have one or more additional features that are not shown in the figures.

[0065] The present invention is further illustrated by the following examples, which are not to be construed in any way as imposing limitations upon the scope thereof. On the contrary, it is to be clearly understood that resort may be had to various other embodiments, modifications, and equivalents thereof which, after reading the description herein, may suggest themselves to those skilled in the art without departing from the spirit of the present invention and/or the scope of the appended claims.

EXAMPLES

[0066] Median particle sizes were determined by laser light scattering using a Malvern Mastersizer 2000, available from Malvern Instrument Ltd. (per ASTM B822-10). Particle size is defined as median particle size by volume distribution. BET surface areas were obtained from the nitrogen sorption analysis described in the literature. Median pore size, pore volume and pore size distribution were calculated based on mercury intrusion into 35-10000 Å size pores. Pore volume is defined as cumulative pore volume in the same pore size range, and median pore size is determined a pore diameter (size) at which 50% pore volume is contributed from smaller pores and 50% pore volume is contributed from bigger pores. Span 90 is defined as a relative pore size span and calculated as $(PD90 - PD10)/PD50$, whereas PD10 is pore diameter at 10% cumulative pore volume contribution and PD50 and PD90 is as defined as 50% and 90% cumulative pore volume contributions based on mercury data, respectively.

1. Polyethyleneimine (PEI) bonding for cationic surface

[0067] Six different grades of silica (A, B, C, D, E, F), available from W. R. Grace, were used in the these examples, and their properties (BET Surface Area, Pore Volume, Pore size distribution Span 90, and median pore size PD50) are listed in the Table I below:

Table I

Silica	Surface Area (m ² /g)	Pore Volume (cc/g)	Span 90	PD50 (Å)
A	699	1.77	7.80	432
B	253	1.19	2.80	154
C	79	1.21	1.25	500
D	711	0.10	0.94	90
E	314	0.57	1.10	569
F	713	0.58	0.93	104
G	247	0.18	0.43	50
H	1	0	0	0

[0068] The particle size of these silica ranges from 5 μm to 70 μm . Silica B is commercial silica with a Trade name of Syloid® W900, Silica C is a commercial silica with a Trade name of Davisil® XWP 500, Silica F is a commercial silica with a Trade name of Trisyl®. All these are available from W. R. Grace & Co. Silica G is a commercially available (Polyethyleneimine on silica gel, powder, 40-200 mesh from Sigma-Aldrich Corporation) PEI bonded silica sample. Silica H in the Table is a diatomaceous earth (powder, suitable for most filtrations, from Sigma-Aldrich Corporation) and the bonding with PEHA was attempted using the same procedure as the other samples.

[0069] Silica A, B had the properties of Pore Volumes of greater than 1.0 cc/g and Span 90 values of greater than 1.0.

[0070] In the examples, pentaethylenhexamine (PEHA) was used, a mixture of small molecule polyamines to represent PEI in our examples.

[0071] The bonding process consisted of two steps: 1). Surface bonding with epoxy silane (3-glycidoxypropyl-trimethoxysilane), and then 2). Reaction of PEHA with surface epoxy groups (attacking of nucleophilic amino groups to the epoxy ring, and this leads to amine attachment with opening of epoxy ring, forming β -amino alcohols (N. Azizi, M. R. Saidi, *Org. Lett.*, 2005, 7, 3649-3651).

1A. Initial Bonding procedure

[0072] Modified silica samples were prepared by treating the bare silica gel particles (dried in a 120°C oven overnight) with epoxy silane. A 1 L, round bottom indented flask was

charged with silica particles (100 g), and then 10 g (10 w/w% to silica) of epoxy silane is added drop-wise into the flask while rotating. The mixture was allowed to roll on a rotovap overnight (16 h). A small portion (2 g) of the sample was separated and washed with 10 ml of acetone five times and dried in a 70°C oven for 20 hours. The dried sample was subjected to elemental analysis for the amount of carbon content by using a LECO instrument.

1B. PEI reaction

[0073] 20g of bonded silica was weighed from the sample obtained in 1A above and placed in an Erlenmeyer Flask. 6 g of PEHA was weighed in a small beaker (30% w/w to silica), and mixed with **100 g** of DIW to dissolve PEHA, to provide ~15% silica slurry for the reaction). The mixture was shaken well and allowed to sit in a water bath (65°C for 30 min). After the reaction, the silica was further diluted with DI water, filter. Then the silica was soaked with 50 ml 0.5 M HCl for 20-30 minutes and filtered. The resulting silica was washed with DIW for three times (3 x 100 ml) and dried a small sample at 90°C overnight. The dried sample was sent for C% analysis. The rest of sample was dried inside the hood in ambient conditions prior to analysis.

1C. Batch Binding Capacity test

[0074] Two model compounds were used in these examples: 1. DNA oligonucleotides (Deoxyribonucleic acid from herring sperm from Sigma-Aldrich), less than 50 base pairs, MW < 15000. 2. Bovine serum albumin (BSA) (lyophilized powder, crystallized, ≥98.0% From Sigma), MW ~ 66000.

[0075] **Test method:** The binding capacities were performed using BSA solution (5 mg/ml) at a pH of 8.0 with 20 mM Tris-HCl buffer, or DNA solution (2 mg/ml) at pH 3.45 with 10 mM sodium phosphate buffer. Dried silica samples were weighed into vials, and then protein solutions (UV/Vis adsorption was measured at 280 nm using a Genesys®10S Bio UV-Vis spectrophotometer). After 2 hr, the supernatants were collected the adsorptions were again measured under the same conditions. The percentage of UV/Vis signal drop were calculated (the higher drop before and after the adsorption, the greater binding capacity). Three parallel adsorption measurements were carried out for one sample and the averages were calculated and reported.

[0076] The following table shows the binding capacity results of Examples 1-10:

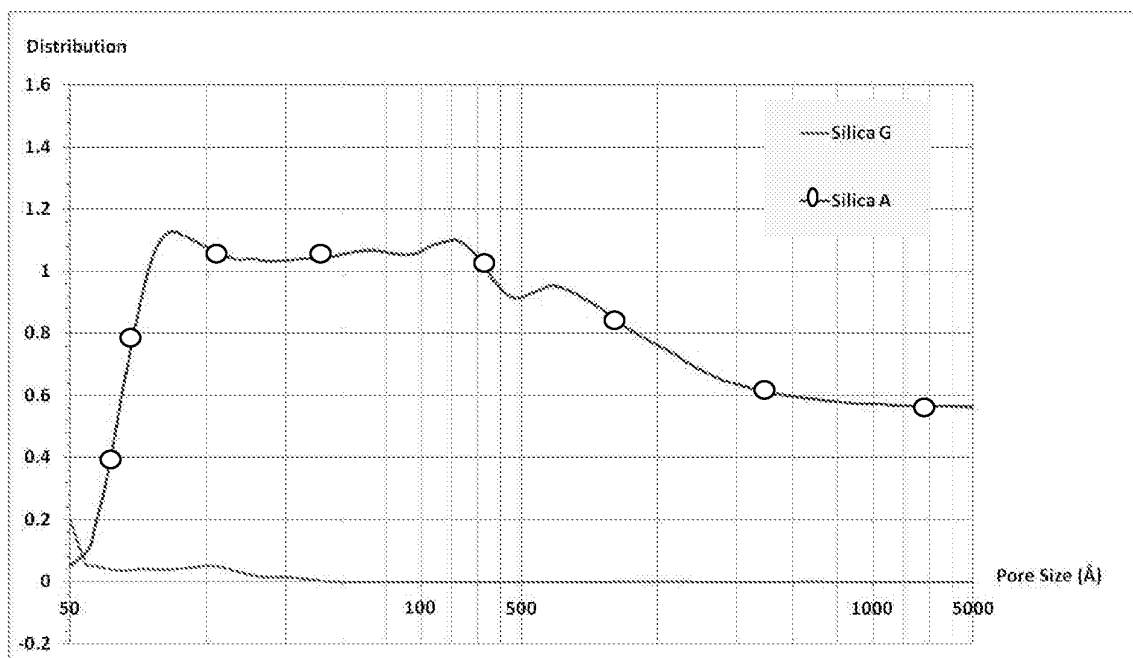
Table 2

Examples	Silica	C%	DNA Binding	BSA Binding
1	A	3.19	94%	33%
2	B	1.70	77%	41%
3	C	1.25	37%	23%
4	D	4.17	89%	0.1%
5	E	0.92	38%	5.6%
7	F	4.06	61%	1.1%
8	G	8.07	8.4%	0.0%
9	H	0.05	2.0%	0.0%
10	A	Unmodified	20%	4.1%

[0077] As mentioned above, Examples 1-6 were made by treating the dried silica with epoxysilane and then followed by reacting the silica intermediates with PEHA. The C% numbers, calculated by subtracting the total C% from the C% from the epoxy bonded silica, are indications of the total amount of amines are attached from the reactions. For Sample 7 (commercial PEI-silica) (BET and Hg measurements were carried out after the surface groups of the sample were burnt off by placing samples in an 460°C muffler oven in air overnight) the binding of DNA and BSA were measured using the same measurement method. The diatomaceous earth (Silica H) for Example 8 was also bonded with PEHA using the same procedure. As shown, Example 8 has very low level of amount of PEHA bonded (due to very low surface area) and the amount of DNA adsorbed.

[0078] The results shown above indicate that in order to get high amount of DNA and BSA adsorbed, high pore volume and span 90 are required. Samples 1, 2, and 3 had both pore volume and Span 90 greater than 1.0, and these samples have showed higher binding of both DNA and BSA. Other samples all showed lower binding. In Example 9, due to its high surface area, unbounded silica A had some binding capability of DNA and BAS, but the binding were very low when compared to PEHA bonded Sample 1.

[0079] The following Figure shows the comparison in pore size distributions (from mercury porosimetry) for Silica A and Silica G. As noted, Silica A has the widest pores size distribution ranging from 50 Å to over 5000 Å.



FIGURE

2. Bonding silica with anionic polymers for binding of basic proteins

2A. Preparation

[0080] The preparation of anionic polymer bonded silica was achieved by mixing the neutral aqueous solution of polymers (neutralized by base such as ammonium hydroxide or sodium hydroxide) with silica, and then baking the mixture at 190°C for 5 hrs to force the bonding formation of the polymer and the surface groups. The solutions of commercial poly(acrylic acid) or poly(methacrylic acid) (from Sigma-Aldrich Corporation) were made by dissolving (or diluting if commercial product is an aqueous solution) polymer in DI water and the pH of the solution is adjusted to 7-8 with ammonium hydroxide (or sodium hydroxide). The concentration for the solutions was about 18%.

[0081] 20 g of silica (Silica A) was mixed with polymer solution containing about 10 g of net polymer. The mixture was placed in a ceramic container and place in an oven in a well ventilated fume hood. The mixture was heated at 90°C until no liquid is seen, and then baked at 190°C for 5 hrs. The resulting mixture was re-slurried with DI water, and washed with 5 x 200 ml of 10% NaCl and 1 x 200 ml of NaHCO₃, followed by 3 x 100 ml DI water.

2B. Protein binding evaluation

[0082] The procedure was similar to procedure as described in 1C, with exception that lysozyme (from chicken egg white, lyophilized powder, protein ≥90 %, ≥40,000 units/mg protein from Sigma) was used in this test, and the concentration of the protein was 25 mg/ml in 50 mM sodium phosphate, pH 7.0. The amount of adsorbed protein was measured through the amount of signal loss after 2 hr incubation at room temperature, from UV/Vis at 280 nm wavelength, and calculated by lysozyme absorption coefficient.

The following Table 3 shows the protein binding results for Examples 11-14 below:

Table 3.

Example #	Polymer	Polymer MW	C%	Lysozyme Binding (mg/mg)
10	PAA	100000	18.24	1.44
11	PAA	240000	20.55	1.44
12	PAA	15000	5.05	0.67
13	PMA	9500	0.50	0.45
14	None (Control)	None	0.00	0.52

[0083] Table 3 shows that higher lysozyme binding is associated with high molecular weight of polymer. Low molecular weight polymer samples had similar binding to that of control, non-polymer bonded silica (Sample 14).

[0084] While the invention has been described with a limited number of embodiments, these specific embodiments are not intended to limit the scope of the invention as otherwise

described and claimed herein. It may be evident to those of ordinary skill in the art upon review of the exemplary embodiments herein that further modifications, equivalents, and variations are possible. All parts and percentages in the examples, as well as in the remainder of the specification, are by weight unless otherwise specified. Further, any range of numbers recited in the specification or claims, such as that representing a particular set of properties, units of measure, conditions, physical states or percentages, is intended to literally incorporate expressly herein by reference or otherwise, any number falling within such range, including any subset of numbers within any range so recited. For example, whenever a numerical range with a lower limit, R_L , and an upper limit R_U , is disclosed, any number R falling within the range is specifically disclosed. In particular, the following numbers R within the range are specifically disclosed: $R = R_L + k(R_U - R_L)$, where k is a variable ranging from 1% to 100% with a 1% increment, e.g., k is 1%, 2%, 3%, 4%, 5% ... 50%, 51%, 52% ... 95%, 96%, 97%, 98%, 99%, or 100%. Moreover, any numerical range represented by any two values of R , as calculated above is also specifically disclosed. Any modifications of the invention, in addition to those shown and described herein, will become apparent to those skilled in the art from the foregoing description and accompanying drawings. Such modifications are intended to fall within the scope of the appended claims. All publications cited herein are incorporated by reference in their entirety.

CLAIMS

1. Adsorbents comprising:
 - metal oxide particles having a wide pore size distribution as measured by a pore size distribution span 90 value of at least about 1.0; and
 - polymeric material covalently bonded to surfaces of said metal oxide particles.
2. The adsorbents of claim 1, wherein said metal oxide particles have a median particle size of less than about 150 μm ,
 - preferably less than about 100 μm ,
 - more preferred about 10 to about 50 μm ,
 - in particular about 30 μm .
3. The adsorbents of any one of claims 1 or 2, wherein said metal oxide particles have a median pore size of less than about 2000 $\text{\AA}$,
 - preferably less than about 1000 $\text{\AA}$,
 - more preferred about 100 to about 800 $\text{\AA}$,
 - still more preferred about 150 to about 250 $\text{\AA}$,
 - in particular about 200 $\text{\AA}$.
4. The adsorbents of any one of claims 1 to 3, wherein said metal oxide particles have a pore size distribution of from about 30 to about 5000 $\text{\AA}$,
 - preferably about 50 to about 3000 $\text{\AA}$.
5. The adsorbents of any one of claims 1 to 4, wherein said metal oxide particles have a BET particle surface area of at least about 100 m^2/g ,
 - preferably at least about 300 m^2/g ,
 - more preferred at least about 500 m^2/g ,
 - still more preferred about 600 to about 800 m^2/g ,
 - in particular about 700 m^2/g .
6. The adsorbents of any one of claims 1 to 5, wherein said metal oxide particles have a pore volume, as measured by mercury intrusion, of at least about 0.25 ml/g ,
 - preferably at least about 0.50 ml/g ,

more preferred at least about 1.00 ml/g,
still more preferred at least about 1.50 ml/g,
in particular about 1.77 ml/g.

7. The adsorbents of any one of claims 1 to 6, wherein said metal oxide particles have a pore size distribution span 90 value of at least about 2.0,
preferably at least about 3.0,
more preferred about 5.0 to about 10.0,
still more preferred about 7.5 to about 8.5,
in particular about 7.8.

8. The adsorbents of any one of claims 1 to 7, further comprising at least one bifunctional moiety extending from said surfaces of said metal oxide particles, each of said at least one bifunctional moiety comprising (i) one or more functional groups capable of bonding to said surfaces, and either (iia) said polymeric material, or (iib) one or more reactive groups capable of bonding to said polymeric material.

9. The adsorbents of claim 8, wherein said at least one bifunctional moiety comprises an epoxy silane.

10. The adsorbents of any one of claims 8 or 9, wherein said at least one bifunctional moiety comprises (3-glycidoxypentyl)-trimethoxysilane.

11. The adsorbents of any one of claims 1 to 10, wherein said polymeric material is covalently bonded to said surfaces via a covalent bond linkage consisting of one or more atoms selected from the group consisting of C, O, Si and N.

12. The adsorbents of any one of claims 1 to 11, wherein said polymeric material comprises a polyelectrolyte,

Preferably said polymeric material comprises polyethyleneimine, polyallylamine, polyvinyl pyridine, polydiallyldimethylammonium chloride (pDADMAC), or a copolymer containing one or more cationic or cationic-forming functional groups, in particular polyethyleneimine.

13. The adsorbents of any one of claims 1 to 12, wherein said adsorbents comprises a reaction product of said metal oxide particles and an aqueous trimethoxysilyl-polyethyleneimine solution.

14. The adsorbents of any one of claims 12 or 13, wherein said polyethyleneimine has (i) a weight average molecular weight, M_w , and (ii) a number average molecular weight, M_n , each of which is less than about 5000,

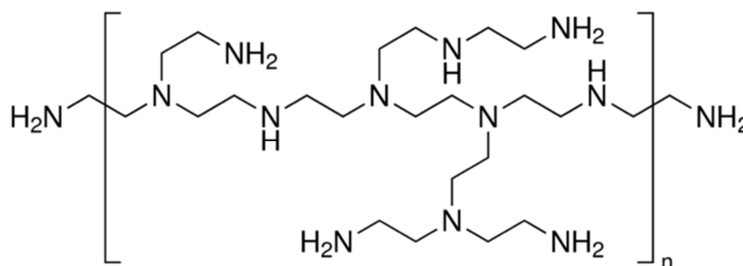
preferably (i) a weight average molecular weight, M_w , and

(ii) a number average molecular weight, M_n , each of which ranges from about 500 to about 2500,

more preferred (i) a weight average molecular weight, M_w , ranging from about 800 to about 2000, and

(ii) a number average molecular weight, M_n , ranging from about 600 to about 1800.

15. The adsorbents of any one of claims 12 to 14, wherein said polyethyleneimine has a structure:



prior to being covalently bonded to said surfaces, and n is a number greater than or equal to 1.

16. The adsorbents of any one of claims 1 to 12, wherein said polymeric material comprises an anionic polyelectrolyte.

17. The adsorbents of any one of claims 1 to 12 and 16, wherein the polymeric material comprises polyacrylic acid, polymethacrylic acid, polystyrene sulfonic acid, nucleic acid, or a copolymer containing one or more anionic or anionic-forming functional groups,

preferably polyacrylic acid, polymethacrylic acid, or a combination thereof,

wherein said polyacrylic acid or said polymethacrylic acid preferably has a weight average molecular weight, M_w , greater than about 50,000,

more preferred about 100,000 to about 250,000.

18. The adsorbents of any one of claims 1 to 17, wherein said polymeric material is present in an amount representing up to about 20.0 wt% of said adsorbents based on a total weight of said adsorbents,

preferably about 1.0 to about 15.0 wt% of said adsorbents based on a total weight of said adsorbents.

19. The adsorbents of any one of claims 1 to 18, wherein said metal oxide particles comprise silica particles.

20. The adsorbents of any one of claims 1 to 19 bound to one or more particular biological compounds,

wherein the one or more particular biological compounds preferably comprise a protein, a polysaccharide, a lipid, a nucleic acid, a metabolites, a mammalian cell, mammalian cell debris, an antibody, a peptide, DNA, RNA, an endotoxin, a virus, a vaccine, an enzyme, or any combination thereof.

21. A method of making the adsorbents of any one of claims 1 to 19 said method comprising: contacting the metal oxide particles with one or more reactants under reaction conditions that result in the polymeric material covalently bonded to the surfaces of the metal oxide particles.

22. The method of claim 21 wherein the one or more reactants comprise at least one bifunctional compound comprising (i) one or more functional groups capable of bonding the compound to the surfaces of the metal oxide particles, and either (iia) the polymeric material, or (iib) one or more reactive groups capable of bonding to the polymeric material.

23. The method of any one of claims 21 and 22, wherein said contacting step utilizes a reaction mixture free of organic solvent.

24. Use of adsorbents as defined in any of claims 1 to 19 as a bioprocessing clarification agent.

25. Use of the adsorbents according to claim 24, wherein the adsorbents is added to a bioprocessing vessel containing one or more biomolecules, the one or more biomolecules preferably comprising a protein, a polysaccharide, a lipid, a nucleic acid, a metabolites, a mammalian cell, mammalian cell debris, an antibody, a peptide, DNA, RNA, an endotoxin, a virus, a vaccine, an enzyme, or any combination thereof.

26. Use of the adsorbents according to any one of claims 24 or 25, wherein the adsorbents bind to one or more biomolecules that come into contact with the adsorbents.

27. Use of the adsorbents according to any one of claims 24 to 26, wherein the adsorbents is added to a bioprocessing vessel containing at least one of: host cells and cell debris; antibodies, proteins and peptides; nucleic acids, such as DNA and RNA; endotoxins; viruses; vaccines.

28. Use of the adsorbents according to any one of claims 24 to 27, wherein following a binding step in which the adsorbents binds to one or more biomolecules that come into contact with the adsorbents, separating the adsorbents bound to the one or more biomolecules from other components of a bioprocessing procedure.