BISMUTH-BASED ADSORBENT COMPOSITIONS FOR TREATING PROCESS STREAMS

CROSS-REFERENCE TO RELATED APPLICATION

This application claimed benefit of prior-filed, copending, commonly-owned provisional US patent application 63/569,858, filed 26 March 2024, which is hereby incorporated by reference.

BACKGROUND

The removal of impurities from the process and exhaust streams of industrial processes is extremely important to reduce pollutants and toxins emitted into the environment, recover valuable byproducts, maintain the performance of downstream operations, and ensure the safety of workers. Such industrial processes include petroleum, petrochemical, polymerization, synthesis gas ("syngas"), and semiconductor processes.

Hydrocarbon process streams, in particular, refinery off gas ("ROG") streams may contain reactive compounds that induce exotherms and/or produce further non-desirable compounds (e.g., acetylide, green oil/cuprene, etc.). Such reactive compounds include acetylene, methyl acetylene and propadiene ("MAPD"), other dienes, and heavy olefins as well as hydrogen and carbon monoxide.

Adsorbents containing lead oxide are often used to remove arsine and carbonyl sulfide (COS) from hydrocarbon streams containing reactive compounds (e.g., acetylene and MAPD) or streams with significant reducing capacity such as hydrogen-containing streams. Lead oxide, however, imposes substantial environmental and health concerns and can affect individual organisms and threaten ecosystems. Therefore, it is of interest to employ alternative materials that would enable safe handling, operation, and disposal of adsorbents. Adsorbents containing copper oxide are also used to remove arsine, phosphine, and COS from hydrocarbon streams. However, copper has a tendency to form acetylides and to promote green oil formation, such that copper oxide adsorbents are primarily employed in "non-reactive" streams containing small concentrations or no acetylene, MAPD, dienes, etc. Moreover, in addition to the environmental health and safety concerns mentioned above, lead oxide-based media are generally characterized by somewhat lower impurity removal capacities as compared to copper- based

materials.

Therefore, there is a need for alternative and/or improved adsorbents having a higher adsorption capacity of targeted reactive compounds (e.g., arsine, phosphine, COS, or other compounds that contain arsenic, phosphorus, or sulfur), no hydrogenation capacity to minimize exotherm risk, and that do not form further non-desirable compounds, such as, acetylide or green oil/cuprene, for example.

SUMMARY

Disclosed and described herein are adsorbents, methods of their preparation, and methods of their use. In at least one aspect of the present disclosure, an adsorbent composition comprises: a bismuth material; an iron material; and optionally a support material. In at least one embodiment, the bismuth material and the iron material are present collectively from about 50 wt.% to about 90 wt.% based on the total weight of the adsorbent composition.

In at least one embodiment, the bismuth material and the iron material are present collectively from about 60 wt.% to about 90 wt.%, about 70 wt.% to about 90 wt.%, or about 80 wt.% to about 90 wt.%.

In at least one embodiment, the bismuth material is present as bismuth oxide (Bi_2O_3). In at least one embodiment, the bismuth oxide is present from about 15 wt.% to about 60 wt.% based on the total weight of the adsorbent composition. In at least one embodiment, the iron material is present as iron oxide (Fe_2O_3). In at least one embodiment, the iron oxide is present from about 25 wt.% to about 75 wt.% based on the total weight of the adsorbent composition.

In at least one embodiment, the bismuth material is present as bismuth oxide (Bi_2O_3) from about 15 wt.% to about 60 wt.% based on the total weight of the adsorbent composition, and the iron material is present as iron oxide (Fe2O3) from about 25 wt.% to about 75 wt.%, based on the total weight of the adsorbent composition, with the proviso that the sum of the bismuth oxide and the iron oxide is from about 50 wt.% to about 90 wt.% based on the total weight of the adsorbent composition.

In at least one embodiment, the support material is the balance of the total weight of the adsorbent composition. In at least one embodiment, the support material is selected from a group consisting of metal oxides, metalloid oxides, activated carbons, high surface area metal oxides, molecular sieves, and combinations thereof. In at least one embodiment, the support material

comprises aluminum oxide, titanium oxide, silica, or a combination thereof.

In at least one embodiment, the support material comprises silica. In at least one embodiment, the bismuth material and the iron material are dispersed onto the support material via a coprecipitation process. In at least one embodiment, the adsorbent composition exhibits at least one of: an arsine capacity of greater than about 6 wt.% elemental As, a carbonyl sulfide capacity of greater than about 4 wt.% elemental S, or a phosphine capacity of greater than about 1 wt.% elemental P.

In at least one embodiment, the adsorbent composition exhibits an arsine capacity that is at least about 100% greater than an adsorbent composition having a fixed bismuth material amount without the iron material or having a fixed iron material amount without the bismuth material.

Another aspect of the present disclosure relates to a method of treating a process stream comprising one or more of arsine, phosphine, or carbonyl sulfide, the method comprising: contacting the process stream with an adsorbent composition comprising a bismuth material, an iron material, and a support material having the bismuth material and the iron material dispersed therewith. In at least one embodiment, the bismuth material and the iron material are present collectively from about 50 wt.% to about 90 wt.% based on the total weight of the adsorbent composition.

In at least one embodiment, the adsorbent composition exhibits at least one of: an arsine capacity of greater than about 6 wt.% elemental As, a carbonyl sulfide capacity of greater than about 4 wt.% elemental S, or a phosphine capacity of greater than about 1 wt.% elemental P.

In at least one embodiment, the adsorbent composition exhibits an arsine capacity that is at least about 100% greater than an adsorbent composition having a fixed bismuth material amount without the iron material or having a fixed iron material amount without the bismuth material.

In at least one embodiment, the method results in at least one of: an arsine removal efficiency of greater than about 90% as measured by a dry colorimetry method, a carbonyl sulfide removal efficiency of greater than about 90% as measured by a dry colorimetry method, or a phosphine removal efficiency of greater than about 90% as measured by a dry colorimetry method.

In at least one embodiment, the process stream is a stream of a process selected from a

group consisting of a petroleum process, a petrochemical process, a polymerization process, a synthesis gas process, and a semiconductor process.

In at least one embodiment, the process stream is a stream of a process selected from a group consisting of refinery off-gas, fluid catalytic cracking off-gas, steam cracker off-gas, shale gas, and a combination thereof. In at least one embodiment, the process stream comprises ethylene and/or propylene. In at least one embodiment, the process stream comprises natural gas.

In at least one embodiment, the bismuth material and the iron material are present collectively from about 60 wt.% to about 90 wt.%, about 70 wt.% to about 90 wt.%, or about 80 wt.% to about 90 wt.%. In at least one embodiment, the bismuth material is present as bismuth oxide (Bi_2O_3). In at least one embodiment, the bismuth oxide is present from about 15 wt.% to about 60 wt.% based on the total weight of the adsorbent composition.

In at least one embodiment, the iron material is present as iron oxide (Fe_2O_3). In at least one embodiment, the iron oxide is present from about 25 wt.% to about 75 wt.% based on the total weight of the adsorbent composition.

In at least one embodiment, the bismuth material is present as bismuth oxide (Bi_2O_3) from about 15 wt.% to about 60 wt.% based on the total weight of the adsorbent composition, and the iron material is present as iron oxide (Fe_2O_3) from about 25 wt.% to about 75 wt.%, based on the total weight of the adsorbent composition, with the proviso that the sum of the bismuth oxide and the iron oxide is from about 50 wt.% to about 90 wt.% based on the total weight of the adsorbent composition.

In at least one embodiment, the support material is the balance of the total weight of the adsorbent composition. In at least one embodiment, the support material is selected from a group consisting of metal oxides, metalloid oxides, activated carbons, high surface area metal oxides, molecular sieves, and combinations thereof. In at least one embodiment, the support material comprises aluminum oxide, titanium oxide, silica, or a combination thereof. In at least one embodiment, the support material comprises silica. In at least one embodiment, the bismuth material and the iron material are dispersed onto the support material via a coprecipitation process.

In at least one embodiment, the adsorbent composition exhibits an arsine capacity that is at least about 100% greater than an adsorbent composition having a fixed bismuth material

amount without the iron material or having a fixed iron material amount without the bismuth material.

Another aspect of the present disclosure relates to a method of forming an adsorbent composition, the method comprising: coprecipitating a bismuth material and an iron material with a support material.

In at least one embodiment, the bismuth material and the iron material are present collectively from about 60 wt.% to about 90 wt.%, about 70 wt.% to about 90 wt. %, or about 80 wt.% to about 90 wt.%. In at least one embodiment, the bismuth material is present as bismuth oxide (Bi_2O_3). In at least one embodiment, the bismuth oxide is present from about 15 wt.% to about 60 wt.% based on the total weight of the adsorbent composition.

In at least one embodiment, the iron material is present as iron oxide (Fe_2O_3). In at least one embodiment, the iron oxide is present from about 25 wt.% to about 75 wt.% based on the total weight of the adsorbent composition.

In at least one embodiment, the bismuth material is present as bismuth oxide (Bi_2O_3) from about 15 wt.% to about 60 wt.% based on the total weight of the adsorbent composition, and the iron material is present as iron oxide (Fe_2O_3) from about 25 wt.% to about 75 wt.%, based on the total weight of the adsorbent composition, with the proviso that the sum of the bismuth oxide and the iron oxide is from about 50 wt.% to about 90 wt.% based on the total weight of the adsorbent composition.

In at least one embodiment, the support material is the balance of the total weight of the adsorbent composition.

In at least one embodiment, the support material is selected from a group consisting of metal oxides, metalloid oxides, activated carbons, high surface area metal oxides, molecular sieves, and combinations thereof. In at least one embodiment, the support material comprises aluminum oxide, titanium oxide, silica, or a combination thereof. In at least one embodiment, the support material comprises silica. In at least one embodiment, the bismuth material and the iron material are dispersed onto the support material via a coprecipitation process. In at least one embodiment, the adsorbent composition exhibits at least one of: an arsine capacity of greater than about 6 wt.% elemental As, a carbonyl sulfide capacity of greater than about 4 wt.% elemental S, or a phosphine capacity of greater than about 1 wt.% elemental P.

In at least one embodiment, the adsorbent composition exhibits an arsine capacity that is

at least about 100% greater than an adsorbent composition having a fixed bismuth material amount without the iron material or having a fixed iron material amount without the bismuth material.

BRIEF DESCRIPTION OF THE DRAWINGS

The various aspects and advantages of the embodiments of the present invention will become apparent to those skilled in the art upon an understanding of the following detailed description of the invention, read in light of the accompanying drawings which are made a part of this specification. In the drawings:

FIG. 1 shows the results of an evaluation of adsorption capacity of adsorbents according to one or more embodiments, where adsorbent capacities represent weight of removed S, As, or P per weight of fresh adsorbent.

FIG. 2 shows arsine adsorption capacity for samples in accordance with one or more embodiments, using a liquid feed stream with 100 ppmw AsH_3 in liquid propane.

FIG. 3 depicts an X-ray diffraction (XRD) of a sample in accordance with one or more embodiments, and comparative samples, characterizing presence or absence of crystallites.

DETAILED DESCRIPTION

Embodiments of the present disclosure relate to adsorbent compositions for removing one or more impurities from a process stream. Exemplary adsorbent compositions include bismuth-containing materials, including elemental bismuth or bismuth oxides (e.g., Bi_2O_3), in combination with one or more additional metal materials (such as iron oxide) that are dispersed with a support material.

Current methods of producing bismuth-based adsorbents, for example, utilize bismuth oxide on a titania support prepared by impregnating a titania support with a precursor solution containing bismuth. Such methods, however, can lead to inefficient impregnation resulting in a low dispersion of the final bismuth species due to the low solubility of bismuth, and thus a subsequent decrease in product performance. In addition, portions of the titania surface that are not covered by the bismuth material could promote undesired side reactions. While such materials can exhibit adequate arsine and phosphine removal capacities, COS removal capacity is relatively lower.

Certain embodiments of the present disclosure advantageously address the limitations of prior approaches by coprecipitating a bismuth material (e.g., bismuth oxide) and an iron material (e.g., iron oxide) with a support (e.g., an alumina support). Without wishing to be bound by theory, these embodiments are believed to exhibit enhanced impurity removal performance due to the presence of well-dispersed bismuth and iron species which demonstrate removal activity for compounds such as arsine, phosphine, and COS (carbonyl sulfide). Advantages of the present embodiments include, but are not limited to, increased levels of active bismuth and iron species, and improved removal capacity compared to adsorbents with bismuth oxide on titania.

In at least one embodiment, the adsorbent composition comprises a bismuth material and an iron material dispersed with a support material. For example, the bismuth material and the iron material may be dispersed with the support material via a coprecipitation process. The dispersed bismuth and iron materials may be present collectively from about 50 wt.% to about 90 wt.% based on the total weight of the adsorbent material (e.g., from about 60 wt.% to about 90 wt.%, about 70 wt.% to about 90 wt.%, or about 80 wt.% to about 90 wt.%).

In at least one embodiment, the bismuth material is present as elemental bismuth, bismuth oxide (e.g., Bi_2O_3), or a combination thereof. In embodiments where the bismuth material is in the form of bismuth oxide, the bismuth oxide may be present from about 15 wt.% to about 60 wt.% based on the total weight of the adsorbent composition (e.g., about 15 wt.%, about 20 wt.%, about 25 wt.%, about 30 wt.%, about 35 wt.%, about 40 wt.%, about 45 wt.%, about 50 wt.%, about 55 wt.%, about 60 wt.%, or within any range defined by and including these points). In at least one embodiment, the iron material is present as iron oxide (e.g., Fe_2O_3), and may be present from about 25 wt.% to about 75 wt.% based on the total weight of the adsorbent composition (e.g., about 25 wt.%, about 30 wt.%, about 35 wt.%, about 40 wt.%, about 45 wt.%, about 50 wt.%, about 55 wt.%, about 60 wt.%, about 65 wt.%, about 70 wt.%, about 75 wt.%, or within any range defined by and including these points) with the proviso that the sum of the bismuth oxide and the iron oxide is from about 50 wt.% to about 90 wt.% based on the total weight of the adsorbent composition. In some embodiments, the bismuth material and the iron material are dispersed onto the support with no other metal materials.

In at least one embodiment, the support material is the balance of the total weight of the adsorbent composition (e.g., from about 10 wt.% to about 50 wt.%). Exemplary support

materials include metal oxides, metalloid oxides, activated carbons, and molecular sieves. For example, supports include titanium oxide, ceria, alumina, silica, zirconia, magnesium oxide, zeolites, and combinations thereof. In certain embodiments, supports include titanium dioxide, for example, anatase titanium dioxide. In certain embodiments, supports include silica. Supports include high surface area metal oxides. In some embodiments, supports may comprise aluminum oxide. In other embodiments, supports may comprise a mixture of titanium dioxide and aluminum oxide. Metal oxide mixtures, for example, a mixture of titanium dioxide and aluminum oxide, may contain metal oxides in a weight/weight ratio of titanium dioxide to aluminum oxide of from any of about 9/1, about 8/1, about 7/1, about 6/1, about 5/1, about 4/1, about 3/1, about 2/1 or about 1/1 to any of about 1/2, about 1/3, about 1/4, about 1/5, about 1/6, about 1/7, about 1/8, or about 1/9.

In at least one embodiment, the support material may have a surface area of from about 10 m^2/g or about 20 m^2/g to about 450 m^2/g or about 600 m^2/g, measured according to the Brunauer-Emmett-Teller (BET) methodology. The support material may be in particulate form, for example, comprising particles having an average particle size of from about 1 μm or about 25 μm to about 1 mm or 10 mm.

The support may have a pore volume of from about 0.01 cm^3/g or about 0.1 cm^3/g to about 2.5 cm^3/g or about 5.0 cm^3/g. The support may have pores having an average pore size (pore diameter) of from about 1 angstrom or about 5 angstroms to about 450 or about 750 angstroms. The pore volume and pore size are prior to having any materials dispersed thereon.

Advantageously, the adsorbent compositions contain little or no lead. For instance, the adsorbent compositions may comprise ≤ 20 wt.%, < 20 wt.%, ≤ 10 wt.%, ≤ 5 wt.% or ≤ 1 wt.% lead, as lead oxide (PbO), based on the total weight of the composition. The adsorbent compositions may be free of or substantially free of lead.

The adsorbent composition may further comprise one or more compounds selected from a group consisting of silver oxide, manganese oxide, cerium oxide, vanadium oxide, tin oxide, and niobium oxide. For example, one or more of these materials may be present on the support material prior to dispersing the bismuth material and/or the iron material, or may be co-dispersed (e.g., coprecipitated) with the bismuth material and/or the iron material.

The adsorbent composition may exhibit one or more of an arsine removal efficiency, a phosphine removal efficiency, or a COS removal efficiency of ≥ 90%, ≥ 91%, ≥ 92%, ≥ 93%, ≥

94%, ≥ 95%, ≥ 96%, ≥ 97%, ≥ 98% or ≥ 99%, measured, for example, by a dry colorimetry method.

The adsorbent composition may exhibit an improved arsine, phosphine, or COS removal efficiency of ≥ 15%, ≥ 20%, ≥ 25%, ≥ 35%, ≥ 45%, ≥ 55%, ≥ 65%, ≥ 75%, ≥ 85%, ≥ 95%, ≥ 105%, ≥ 110%, ≥ 115%, ≥ 125%, or ≥ 135%, compared to a similarly prepared composition not containing both the bismuth material and the iron material, measured, for example, by a dry colorimetry method. Removal efficiency may be determined as in the working Examples, where adsorbent capacity is determined on spent adsorbent after adsorbing a target impurity. Capacity represents wt.% of impurity element (e.g., As, P, or S) per weight of fresh adsorbent at a certain point during the adsorption process, for example, at a point of 90% efficiency. Capacity is a measure of an adsorbent to uptake a particular impurity, which in turn is a measure of removal efficiency for that impurity.

Also subject of the invention are the above-mentioned adsorbent compositions further comprising an adsorbed impurity, such as arsine, phosphine, or COS. Arsenic materials, for example, are selected from a group consisting of elemental arsenic and arsenic compounds, for example, arsine. The adsorbent compositions may comprise from about 0.01 wt.% or about 0.1 wt.% to about 14.0 wt.% or about 20.0 wt.% arsenic material, phosphorus material, or sulfur material, based on the total weight of the composition.

The adsorbent compositions may be prepared by a variety of approaches. For instance, bulk powders of a bismuth material, an iron material, and a support material may be combined by a variety of methods including coprecipitation, dispersion, or physical mixing. Physical mixing includes, for example, compaction methods and coating methods.

Impregnated in general means that the materials are “in” pores of the support. Reported pore volume and pore size of a support are without any materials impregnated therein.

It may be advantageous to dry the support prior to having suitable components dispersed thereon. The support may, for instance, have a moisture content of ≤ 15%, ≤ 10%, ≤ 5%, or ≤ 0.5%, based on the total weight of the support. The support may contain essentially no moisture. The term “suitable components” refers to a bismuth material and one or more additional materials (such as an iron material). In some embodiments elemental bismuth or bismuth oxide may be physically mixed with one or more additional materials and the support material. A mixture of suitable components, for example, in a bulk powder form, may be compacted

together.

Coatings of suitable components may, for example, be applied via a washcoat technique. For example, a coating (washcoat) may be formed by preparing a slurry containing a specified solids content (e.g., 10-60% by weight) of a suitable component in a liquid vehicle, which is then coated onto a desired substrate such as a support and dried and calcined to provide a coating layer. When multiple coating layers are applied, the substrate may be dried and calcined after each layer is applied and/or after the number of desired multiple layers are applied.

The suitable components may be present in the adsorbent compositions in a bulk form, meaning in a continuous form in general not interrupted by other materials. A bulk form may contain substantially no other materials. The adsorbent compositions may be in any suitable final form, for instance, tablets, extrudates, pellets, rods, moldings, or monoliths, etc., in various shapes and sizes. For instance, the shapes may have an average largest diameter of from about 1 mm, about 2, about 3, about 4 mm, about 5 mm, about 6, about 7, about 8, about 9, about 10 mm, or within any range defined therebetween (e.g., about 2 mm to about 4 mm).

Embodiments of the invention also include a method of treating a process stream comprising one or more impurities, such as an arsenic material (e.g., arsine), a phosphorus material (e.g., phosphine), or a sulfur material (e.g., carbonyl sulfide). The process stream may contain, for example, alkenes, carbon monoxide, carbon dioxide, nitrogen oxides (NO_x), oxygen, thiol, hydrogen sulfide, sulfur oxides (SO_x), carbonyl sulfide, mercaptans, and other sulfur compounds. In at least one embodiment, the method comprises contacting a process stream containing the one or more impurities with any of the adsorbent composition embodiments described herein. The process stream may be a stream of a petroleum process, a petrochemical process, a polymerization process, a synthesis gas process, or a semiconductor process. For instance, the process stream may be a stream of a process selected from a group consisting of refinery off-gas, fluid catalytic cracking off-gas, steam cracker off-gas, shale gas, and combinations thereof. The process stream may comprise acetylene, methyl acetylene, propadiene, or a combination thereof. In at least one embodiment, the process stream comprises ethylene and/or propylene. In at least one embodiment, the process stream comprises a natural gas.

In at least one embodiment, the process stream comprises an arsenic material, for instance, arsine (AsH_3), at a level of (based on the process stream) about 0.1 ppmw (parts per

million by weight), about 0.5 ppmw, about 1 ppmw, about 10 ppmw, about 25 ppmw, about 50 ppmw, about 100 ppmw, about 150 ppmw, about 200 ppmw, about 300 ppmw, about 400 ppmw, about 500 ppmw, within any range defined by any of these points, or greater.

In at least one embodiment, the process stream comprises a phosphorus material, for instance, phosphine (PH_3), at a level of (based on the process stream) about 0.1 ppmw (parts per million by weight), about 0.5 ppmw, about 1 ppmw, about 10 ppmw, about 25 ppmw, about 50 ppmw, about 100 ppmw, about 150 ppmw, about 200 ppmw, about 300 ppmw, about 400 ppmw, about 500 ppmw, within any range defined by any of these points, or greater.

In at least one embodiment, the process stream comprises a sulfur material, for instance, COS, at a level of (based on the process stream) about 0.1 ppmw (parts per million by weight), about 0.5 ppmw, about 1 ppmw, about 10 ppmw, about 25 ppmw, about 50 ppmw, about 100 ppmw, about 150 ppmw, about 200 ppmw, about 300 ppmw, about 400 ppmw, about 500 ppmw, about 1000 ppmw, about 2000 ppmw, about 3000 ppmw, about 4000 ppmw, about 5000 ppmw, about 7500 ppmw, about 10000 ppmw, or any range defined by any of these points, or greater.

The adsorbent compositions may be employed in suitable equipment including packed bed columns, fluidized beds, monoliths, cartridge filters, semiconductor process tools, and the like. Operating temperatures during an adsorbent process may be, for example, about 10 °C, about 20 °C, about 25 °C, about 30 °C, about 50 °C, about 60 °C, about 80 °C, about 100 °C, about 125 °C, about 150 °C, or within any range defined by any of these points (e.g., from about 10 °C to about 30 °C). For instance, an adsorption process for a liquid stream may be performed at about 50 °C and for a gaseous stream at about 130 °C. Operating pressures for an adsorption process may be from about 1 bar, about 5 bar, about 10 bar, about 20 bar, about 30 bar, about 50 bar, about 70 bar, about 90 bar, about 100 bar, or within any range defined by any of these points. Operating hourly space velocities may be about 5 h^{-1}, about 10 h^{-1}, about 20 h^{-1}, about 30 h^{-1}, about 50 h^{-1}, about 100 h^{-1}, about 500 h^{-1}, about 1000 h^{-1}, about 2000 h^{-1}, about 5000 h^{-1}, about 7500 h^{-1}, about 10000 h^{-1}, or within any range defined by any of these points. For example, an hourly space velocity for a liquid stream may be about 20 h^{-1} or less and for a gaseous stream may be about 10000 h^{-1}.

In at least one embodiment, the adsorbent composition exhibits at least one of: an arsine capacity of greater than about 6 wt.% elemental As, a phosphine capacity of greater than about 1

wt.% elemental P, or a carbonyl sulfide capacity of greater than about 4 wt.% elemental S.

In at least one embodiment, the adsorbent composition exhibits an arsine capacity that is at least about 100% greater than an adsorbent composition having a fixed bismuth material amount without the iron material or having a fixed iron material amount without the bismuth material.

In at least one embodiment, one or more analytical methods known to those of ordinary skill in the art may be used to assess the efficiency of impurity removal with the adsorbent composition, such as a dry calorimetry method. For example, dry calorimetry may be used to assess arsine removal efficiency, phosphine removal efficiency, and/or carbonyl sulfide removal efficiency for an adsorbent composition prepared in accordance with the embodiments described herein. In at least one embodiment, the adsorbent composition may exhibit at least one of: an arsine removal efficiency of greater than about 90% as measured by a dry colorimetry method, a phosphine removal efficiency of greater than about 90% as measured by a dry colorimetry method, or a carbonyl sulfide removal efficiency of greater than about 90% as measured by a dry colorimetry method.

As used herein, the term "particle size" is synonymous with particle diameter (largest diameter) and may be determined, for instance, by scanning electron microscopy (SEM) or transmission electron microscopy (TEM). Average particle size is synonymous with D50, meaning half of the population resides above this point, and half below. Particle size refers to primary particles. Particle size may be measured by laser light scattering techniques, with dispersions or dry powders.

Unless otherwise indicated, all parts and percentages are by weight. Weight percent (wt.%), if not otherwise indicated, is based on an entire composition free of any volatiles, that is, based on dry solids content.

Various exemplary clauses that describe aspects of the present disclosure, are now described.

Clause 1: An adsorbent composition comprising: a bismuth material; an iron material; and optionally a support material, wherein the bismuth material and the iron material are present collectively from about 50 wt.% to about 90 wt.% based on the total weight of the adsorbent composition.

Clause 2: The adsorbent composition according to Clause 1, wherein the bismuth

material and the iron material are present collectively from about 60 wt.% to about 90 wt.%, about 70 wt.% to about 90 wt.%, or about 80 wt.% to about 90 wt.%.

Clause 3: The adsorbent composition according to either Clause 1 or Clause 2, wherein the bismuth material is present as bismuth oxide (Bi_2O_3).

Clause 4: The adsorbent composition according to Clause 3, wherein the bismuth oxide is present from about 15 wt.% to about 60 wt.% based on the total weight of the adsorbent composition.

Clause 5: The adsorbent composition according to any one of the preceding Clauses, wherein the iron material is present as iron oxide (Fe_2O_3).

Clause 6: The adsorbent composition according to Clause 5, wherein the iron oxide is present from about 25 wt.% to about 75 wt.% based on the total weight of the adsorbent composition.

Clause 7: The adsorbent composition according to any one of the preceding Clauses, wherein: the bismuth material is present as bismuth oxide (Bi_2O_3) from about 15 wt.% to about 60 wt.% based on the total weight of the adsorbent composition, and the iron material is present as iron oxide (Fe_2O_3) from about 25 wt.% to about 75 wt.%, based on the total weight of the adsorbent composition, with the proviso that the sum of the bismuth oxide and the iron oxide is from about 50 wt.% to about 90 wt.% based on the total weight of the adsorbent composition.

Clause 8: The adsorbent composition according to any one of the preceding Clauses, wherein the weight of the support material is the balance of the total weight of the adsorbent composition.

Clause 9: The adsorbent composition according to any one of the preceding Clauses, wherein the support material is selected from the group consisting of metal oxides, metalloid oxides, activated carbons, high surface area metal oxides, molecular sieves, and combinations thereof.

Clause 10: The adsorbent composition according to any one of the preceding Clauses, wherein the support material comprises aluminum oxide, titanium oxide, silica, or a combination thereof.

Clause 11: The adsorbent composition according to any one of the preceding Clauses, wherein the support material comprises silica.

Clause 12: The adsorbent composition according to any one of the preceding Clauses,

wherein the bismuth material and the iron material are dispersed onto the support material via a coprecipitation process.

Clause 13: The adsorbent composition according to any one of the preceding Clauses, wherein the adsorbent composition exhibits at least one of: an arsine capacity of greater than about 6 wt.% elemental As, a carbonyl sulfide capacity of greater than about 4 wt.% elemental S, or a phosphine capacity of greater than about 1 wt.% elemental P.

Clause 14: The adsorbent composition according to any one of the preceding Clauses, wherein the adsorbent composition exhibits an arsine capacity that is at least about 100% greater than an adsorbent composition having a fixed bismuth material amount without the iron material or having a fixed iron material amount without the bismuth material.

Clause 15: A method of treating a process stream comprising one or more of arsine, phosphine, or carbonyl sulfide, the method comprising: contacting the process stream with an adsorbent composition comprising a bismuth material, an iron material, and a support material having the bismuth material and the iron material dispersed therewith, wherein the bismuth material and the iron material are present collectively from about 50 wt.% to about 90 wt.% based on the total weight of the adsorbent composition.

Clause 16: The method according to Clause 15, wherein the adsorbent composition exhibits at least one of: an arsine capacity of greater than about 6 wt.% elemental As, a carbonyl sulfide capacity of greater than about 4 wt.% elemental S, or a phosphine capacity of greater than about 1 wt.% elemental P.

Clause 17: The method according to either Clause 15 or Clause 16, wherein the adsorbent composition exhibits an arsine capacity that is at least about 100% greater than an adsorbent composition having a fixed bismuth material amount without the iron material or having a fixed iron material amount without the bismuth material.

Clause 18: The method according to any one of Clauses 15 to 17, wherein the method results in at least one of: an arsine removal efficiency of greater than about 90% as measured by a dry colorimetry method, a carbonyl sulfide removal efficiency of greater than about 90% as measured by a dry colorimetry method, or a phosphine removal efficiency of greater than about 90% as measured by a dry colorimetry method.

Clause 19: The method according to any one of Clauses 15 to 18, wherein the process stream is a stream of a process selected from a group consisting of a petroleum process, a

petrochemical process, a polymerization process, a synthesis gas process, and a semiconductor process.

Clause 20: The method according to any one of Clauses 15 to 19, wherein the process stream is a stream of a process selected from a group consisting of refinery off-gas, fluid catalytic cracking off-gas, steam cracker off-gas, shale gas, and a combination thereof.

Clause 21: The method according to any one of Clauses 15 to 20, wherein the process stream comprises ethylene and/or propylene.

Clause 22: The method according to any one of Clauses 15 to 21, wherein the process stream comprises natural gas.

Clause 23: The method according to any one of Clauses 15 to 22, wherein the bismuth material and the iron material are present collectively from about 60 wt.% to about 90 wt.%, about 70 wt.% to about 90 wt.%, or about 80 wt.% to about 90 wt.%.

Clause 24: The method according to any one of Clauses 15 to 23, wherein the bismuth material is present as bismuth oxide (Bi_2O_3).

Clause 25: The method according to Clause 24, wherein the bismuth oxide is present from about 15 wt.% to about 60 wt.% based on the total weight of the adsorbent composition.

Clause 26: The method according to any one of Clauses 15 to 25, wherein the iron material is present as iron oxide (Fe_2O_3).

Clause 27: The method according to Clause 26, wherein the iron oxide is present from about 25 wt.% to about 75 wt.% based on the total weight of the adsorbent composition.

Clause 28: The method according to any one of Clauses 15 to 27, wherein: the bismuth material is present as bismuth oxide (Bi_2O_3) from about 15 wt.% to about 60 wt.% based on the total weight of the adsorbent composition, and the iron material is present as iron oxide (Fe_2O_3) from about 25 wt.% to about 75 wt.%, based on the total weight of the adsorbent composition, with the proviso that the sum of the bismuth oxide and the iron oxide is from about 50 wt.% to about 90 wt.% based on the total weight of the adsorbent composition.

Clause 29: The method according to any one of Clauses 15 to 28, wherein the weight of the support material is the balance of the total weight of the adsorbent composition.

Clause 30: The method according to any one of Clauses 15 to 29, wherein the support material is selected from the group consisting of metal oxides, metalloid oxides, activated carbons, high surface area metal oxides, molecular sieves, and combinations thereof.

Clause 31: The method according to any one of Clauses 15 to 30, wherein the support material comprises aluminum oxide, titanium oxide, silica, or a combination thereof.

Clause 32: The method according to any one of Clauses 15 to 31, wherein the support material comprises silica.

Clause 33: The method according to any one of Clauses 15 to 32, wherein the bismuth material and the iron material are dispersed onto the support material via a coprecipitation process.

Clause 34: The method according to any one of Clauses 15 to 33, wherein the adsorbent composition exhibits an arsine capacity that is at least about 100% greater than an adsorbent composition having a fixed bismuth material amount without the iron material or having a fixed iron material amount without the bismuth material.

Clause 35: A method of forming an adsorbent composition, the composition optionally in accordance with clause 1, the method comprising: coprecipitating a bismuth material and an iron material with a support material.

Clause 36: The method according to Clause 35, wherein the bismuth material and the iron material are present collectively from about 60 wt.% to about 90 wt.%, about 70 wt.% to about 90 wt. %, or about 80 wt.% to about 90 wt.%.

Clause 37: The method according to either Clause 35 or Clause 36, wherein the bismuth material is present as bismuth oxide (Bi_2O_3).

Clause 38: The method according to Clause 37, wherein the bismuth oxide is present from about 15 wt.% to about 60 wt.% based on the total weight of the adsorbent composition.

Clause 39: The method according to any one of Clauses 35 to 38, wherein the iron material is present as iron oxide (Fe_2O_3).

Clause 40: The method according to Clause 39, wherein the iron oxide is present from about 25 wt.% to about 75 wt.% based on the total weight of the adsorbent composition.

Clause 41: The method according to any one of Clauses 35 to 40, wherein: the bismuth material is present as bismuth oxide (Bi_2O_3) from about 15 wt.% to about 60 wt.% based on the total weight of the adsorbent composition, and the iron material is present as iron oxide (Fe_2O_3) from about 25 wt.% to about 75 wt.%, based on the total weight of the adsorbent composition, with the proviso that the sum of the bismuth oxide and the iron oxide is from about 50 wt.% to about 90 wt.% based on the total weight of the adsorbent composition.

Clause 42: The method according to any one of Clauses 35 to 41, wherein the weight of the support material is the balance of the total weight of the adsorbent composition.

Clause 43: The method according to any one of Clauses 35 to 42, wherein the support material is selected from the group consisting of metal oxides, metalloid oxides, activated carbons, high surface area metal oxides, molecular sieves, and combinations thereof.

Clause 44: The method according to any one of Clauses 35 to 43, wherein the support material comprises aluminum oxide, titanium oxide, silica, or a combination thereof.

Clause 45: The method according to any one of Clauses 35 to 44, wherein the support material comprises silica.

Clause 46: The method according to any one of Clauses 35 to 45, wherein the bismuth material and the iron material are dispersed onto the support material via a coprecipitation process.

Clause 47: The method according to any one of Clauses 35 to 46, wherein the adsorbent composition exhibits at least one of: an arsine capacity of greater than about 6 wt.% elemental As, a carbonyl sulfide capacity of greater than about 4 wt.% elemental S, or a phosphine capacity of greater than about 1 wt.% elemental P.

Clause 48: The method according to any one of Clauses 35 to 47, wherein the adsorbent composition exhibits an arsine capacity that is at least about 100% greater than an adsorbent composition having a fixed bismuth material amount without the iron material or having a fixed iron material amount without the bismuth material.

ILLUSTRATIVE EXAMPLES

The following examples are set forth to assist in understanding the disclosure and should not, of course, be construed as specifically limiting the embodiments described and claimed herein. Such variations of the embodiments, including the substitution of all equivalents now known or later developed, which would be within the purview of those skilled in the art, and changes in formulation or minor changes in experimental design, are to be considered to fall within the scope of the embodiments incorporated herein.

Example 1: Sample preparation

124.5 g of bismuth nitrate solution (20 wt.% Bi) is mixed with 348.0 g of iron nitrate

solution (4 wt.% Fe) and heated to 70 °C to form a metal nitrates solution. In a separate vessel, 10.0 g of PURAL® SB alumina hydrate powder (D50 = 45 μm, BET surface area = 250 m^2/g and pore volume = 0.50 mL/g) is dispersed in 500.0 g of deionized water and heated to 70 °C. Coprecipitation is conducted by co-dosing the metal nitrates solution and a potassium carbonate solution (22 wt.% K_2CO_3) into the alumina dispersion held at pH 7.0 and 70 °C over a period of 1 h. The resulting suspension is allowed to age for an additional 2 h at 70 °C. The solid precipitates are then filtered, washed with deionized water, and dried overnight at 110 °C. Dried solids are subsequently calcined in a muffle furnace at 300 °C for 3 h. The resulting sample is referred to as "Sample 1."

Two comparative samples were also obtained for comparison to Sample 1. "Comparative Sample 1" is a commercially-available bismuth oxide/titania adsorbent (PuriStar® R9-PAR, available from BASF). "Comparative Sample 2" is a commercially-available lead oxide/alumina adsorbent (E-315, available from BASF).

Example 2: Evaluation of adsorption capacity

Table 1 summarizes the compositions of each of the adsorbent compositions of Sample 1 and Comparative Samples 1 and 2.

Table 1: Compositions of adsorbents

Component (wt.%)	**Sample 1 (Bi2O3-Fe2O3/Al2O3)**	**Comparative Sample 1 (Bi2O3/TiO2)**	**Comparative Sample 2 (PbO/Al2O3)**
PbO	-	-	25.7
Bi2O3	49.6	10.8	-
Al2O3	18.0	0.56	74.3
TiO2	-	86.2	0.25
Fe2O3	32.4	-	-

[0130] The adsorption capacity of each adsorbent from Table 1 for various impurities was evaluated with respect to three different liquid feed streams: (1) 0.5 wt.% COS in liquid propane, (2) 100 ppmw AsH_3 in liquid propane, and (3) 110 ppmw PH_3 in liquid propane. Prior

to testing, each sample was pre-treated for 4 hours in an N_2 gas flow at 200 °C (except for the samples for the COS streams, which were pre-treated at 120 °C). Each liquid stream with a liquid hourly space velocity (LHSV) of 10 h^{-1} was passed through the reactor housing the sample at ambient temperature (25 °C) and 220 psig. The liquid stream passing the reactor was then analyzed for impurity content. For COS capacity determination, testing was terminated after 72 hours of flow. For arsine and phosphine capacity determination, testing was conducted until 10% of the impurity broke through the reactor, indicating 90% removal efficiency.

FIG. 1 shows the results from testing, where adsorbent capacities represent weight of removed S, As, or P per weight of fresh adsorbent at the point of testing termination. FIG.1 reveals improved performance of Sample 1 compared to each of the two Comparative Samples for all three impurities. COS adsorption compacity of Sample 1 was greater than about 8 wt.% (calculated based on elemental sulfur), and roughly 3-4 times greater than each of the Comparative Samples. Arsine adsorption capacity was greater than about 10 wt.% (calculated based on elemental arsenic), and roughly twice as great as Comparative Sample 1, and 5 times greater than Comparative Sample 2. Phosphine adsorption capacity was about 1.6 wt.% (calculated based on elemental phosphorus), and roughly twice that of Comparative Sample 1. Phosphine adsorption capacity by Comparative Sample 2 was negligible.

Example 3: Effect of combination of bismuth oxide and iron oxide

Further samples were tested to evaluate the effects of bismuth oxide and iron oxide in combination. "Sample 4" was prepared in a similar manner as Sample 1. "Comparative Sample 3" was prepared using a similar protocol to that described in Example 1, except that only bismuth oxide was precipitated with the alumina support. "Comparative Sample 4" was prepared using a similar protocol to that described in Example 1, except that only iron oxide was precipitated with the alumina support.

Table 2 summarizes the compositions of each of the adsorbent compositions of Sample 2 and Comparative Samples 3 and 4.

Table 2: Compositions of adsorbents with alumina support

Component (wt.%)	Sample 2 (Bi_2O_3-Fe_2O_3/Al_2O_3)	Comparative Sample 3 (Bi_2O_3/Al_2O_3)	Comparative Sample 4 (Fe_2O_3/Al_2O_3)
Bi_2O_3	31.4	30.7	-
Fe_2O_3	54.4	-	56.2
Al_2O_3	13.8	68.4	43.5

[0134] Arsine adsorption capacity was evaluated for each sample using a liquid feed stream with 100 ppmw AsH_3 in liquid propane. Prior to testing, each sample was pre-treated for 4 hours in an N_2 gas flow at 200 °C. The liquid stream with an LHSV of 10 h^{-1} was passed through the reactor housing with each sample at ambient temperature (25 °C) and 220 psig. Testing was conducted until 10% of the impurity broke through the reactor, indicating 90% removal efficiency.

FIG. 2 shows the results from testing, where arsine capacity represents weight of removed As (arsenic) per weight of fresh adsorbent at the point of testing termination. FIG. 2 reveals improved performance of Sample 2 compared to each of the two Comparative Samples. The arsine adsorption capacity of Sample 2 was greater than about 10 wt.%, which was significantly higher than the combined sum of the arsine capacities of Comparative Sample 3 (slightly less than 4 wt.%) and Comparative Sample 4 (less than 1 wt.%). These results reveal the synergetic increase in adsorption capacity for Sample 2, which contains both the bismuth oxide and iron oxide.

Example 4: X-ray diffraction analysis of adsorbent materials

X-ray diffraction (XRD) analysis was performed on each of Sample 2 and Comparative Samples 3 and 4 to investigate the dispersion of the precipitated metal oxide(s). XRD patterns are shown in FIG. 3. The diffractograms for Comparative Samples 3 and 4 both reveal a series of sharp crystalline peaks, indicating the presence of large crystallites. In contrast, the diffractogram for Sample 2 lacks these crystalline peaks, indicating the presence of well-dispersed amorphous oxide structures devoid of large crystallites. Without wishing to be bound by theory, it is believed that the well-dispersed mixture of bismuth oxide and iron oxide advantageously improves the adsorption performance.

In the foregoing description, numerous specific details are set forth, such as specific

materials, dimensions, processes parameters, etc., to provide a thorough understanding of the embodiments of the present disclosure. The particular features, structures, materials, or characteristics may be combined in any suitable manner in one or more embodiments. The words "example" or "exemplary" are used herein to mean serving as an example, instance, or illustration. Any aspect or design described herein as "example" or "exemplary" is not necessarily to be construed as preferred or advantageous over other aspects or designs. Rather, use of the words "example" or "exemplary" is intended to present concepts in a concrete fashion. As used in this application, the term "or" is intended to mean an inclusive "or" rather than an exclusive "or". That is, unless specified otherwise, or clear from context, "X includes A or B" is intended to mean any of the natural inclusive permutations. That is, if X includes A; X includes B; or X includes both A and B, then "X includes A or B" is satisfied under any of the foregoing instances.

In addition, the use of the terms "a," "an," "the," and similar referents in the context of describing the materials and methods discussed herein (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context.

Recitation of ranges of values herein are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. Moreover, any permutations of recited values are contemplated as defining the bounds of ranges. For example, a range of 1, 2, or 3 to 4, 5, or 6 is understood to include not just 1 to 4, 1 to 5, 1 to 6, 2 to 4, 2 to 5, etc., but also 1 to 2, 1 to 3, 2 to 3, 4 to 6, etc.

The term "about" used throughout is used to describe and account for small fluctuations that may be introduced via experimental or measurement error (e.g., ± 1%). All numeric values are modified by the term "about" whether or not explicitly indicated. Numeric values modified by the term "about" include the specific identified value. For example, "about 5.0" includes 5.0.

The term "essentially no" or "substantially no" or "substantially free of" means "not purposefully added" and only trace or inadvertent amounts may be present, for instance, $\leq$ 5 wt.%, $\leq$ 4 wt.% ,$\leq$ 3 wt.%, $\leq$ 2 wt.%, $\leq$ 1 wt.%, $\leq$ 0.5 wt.%, or $\leq$ 0.25 wt.%, based on the

weight of the composition referred to, for example, the total adsorbent composition. For example, an adsorbent composition that is substantially free of lead may refer to an adsorbent composition for which lead is below a detectable limit, or its presence has a negligible effect on the performance of the adsorbent.

Reference throughout this specification to "at least one embodiment," "one embodiment," "certain embodiments," "one or more embodiments," "an embodiment," or "some embodiments" means that a particular feature, structure, material, or characteristic described in connection with the embodiment is included in at least one embodiment of the present disclosure. Thus, the appearances of the phrases such as "at least one embodiment," "one embodiment," "certain embodiments," "one or more embodiments," "an embodiment," or "some embodiments" in various places throughout this specification are not necessarily referring to the same embodiment of the present disclosure. Furthermore, the particular features, structures, materials, or characteristics may be combined in any suitable manner in one or more embodiments.

It is to be understood that the above description is intended to be illustrative, and not restrictive. Many other embodiments will be apparent to those of ordinary skill in the art upon reading and understanding the above description. The scope of the disclosure should, therefore, be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled. The use of any and all examples, or exemplary language (e.g., "such as") provided herein, is intended merely to better illuminate the materials and methods and does not pose a limitation on the scope unless otherwise claimed. No language in the specification should be construed as indicating any non-claimed element as essential to the practice of the disclosed materials and methods.

Although the embodiments disclosed herein have been described with reference to particular embodiments, it is to be understood that these embodiments are merely illustrative of the principles and applications of the present disclosure. It will be apparent to those of ordinary skill in the art that various modifications and variations can be made to the method and apparatus of the present disclosure without departing from the spirit and scope of the disclosure. Thus, it is intended that the present disclosure include modifications and variations that are within the scope of the appended claims and their equivalents, and the above-described embodiments are presented for purposes of illustration and not of limitation.

CLAIMS

WHAT IS CLAIMED IS:

1. An adsorbent composition comprising:

a bismuth material;

an iron material; and

optionally a support material,

wherein the bismuth material and the iron material are present collectively from about 50 wt.% to about 90 wt.% based on the total weight of the adsorbent composition.

2. The adsorbent composition according to claim 1, wherein the bismuth material and the iron material are present collectively from about 60 wt.% to about 90 wt.%, about 70 wt.% to about 90 wt.%, or about 80 wt.% to about 90 wt.%.

3. The adsorbent composition according to claim 1, wherein the bismuth material is present as bismuth oxide (Bi_2O_3).

4. The adsorbent composition according to claim 3, wherein the bismuth oxide is present from about 15 wt.% to about 60 wt.% based on the total weight of the adsorbent composition.

5. The adsorbent composition according to claim 1, wherein the iron material is present as iron oxide (Fe_2O_3).

6. The adsorbent composition according to claim 5, wherein the iron oxide is present from about 25 wt.% to about 75 wt.% based on the total weight of the adsorbent composition.

7. The adsorbent composition according to claim 1, wherein:

the bismuth material is present as bismuth oxide (Bi_2O_3) from about 15 wt.% to about 60 wt.% based on the total weight of the adsorbent composition, and

the iron material is present as iron oxide (Fe_2O_3) from about 25 wt.% to about 75 wt.%, based on the total weight of the adsorbent composition,

with the proviso that the sum of the bismuth oxide and the iron oxide is from about 50 wt.% to about 90 wt.% based on the total weight of the adsorbent composition.

8. The adsorbent composition according to claim 1, wherein the support material is present and is the balance of the total weight of the adsorbent composition.

9. The adsorbent composition according to claim 1, wherein the support material is present and is selected from the group consisting of metal oxides, metalloid oxides, activated carbons, high surface area metal oxides, molecular sieves, and combinations thereof.

10. The adsorbent composition according to claim 1, wherein the support material is present and comprises aluminum oxide, titanium oxide, silica, or a combination thereof.

11. The adsorbent composition according to claim 1, wherein the support material is present and comprises silica.

12. The adsorbent composition according to claim 1, wherein the bismuth material and the iron material are dispersed onto the support material via a coprecipitation process.

13. The adsorbent composition according to claim 1, wherein the adsorbent composition exhibits at least one of:

an arsine capacity of greater than about 6 wt.% elemental As,
a carbonyl sulfide capacity of greater than about 4 wt.% elemental S, or
a phosphine capacity of greater than about 1 wt.% elemental P.

14. The adsorbent composition according to claim 1, wherein the adsorbent composition exhibits an arsine capacity that is at least about 100% greater than an adsorbent composition having a fixed bismuth material amount without the iron material or having a fixed iron material amount without the bismuth material.

15. A method of treating a process stream comprising one or more of arsine, phosphine, or carbonyl sulfide, the method comprising:

contacting the process stream with an adsorbent composition comprising a bismuth material, an iron material, and a support material having the bismuth material and the iron material dispersed therewith, wherein the bismuth material and the iron material are present collectively from about 50 wt.% to about 90 wt.% based on the total weight of the adsorbent composition.

16. The method according to claim 15, wherein the adsorbent composition exhibits at least one of:

an arsine capacity of greater than about 6 wt.% elemental As,

a carbonyl sulfide capacity of greater than about 4 wt.% elemental S, or

a phosphine capacity of greater than about 1 wt.% elemental P.

17. The method according to claim 15, wherein the adsorbent composition exhibits an arsine capacity that is at least about 100% greater than an adsorbent composition having a fixed bismuth material amount without the iron material or having a fixed iron material amount without the bismuth material.

18. The method according to claim 15, wherein the method results in at least one of:

an arsine removal efficiency of greater than about 90% as measured by a dry colorimetry method,

a carbonyl sulfide removal efficiency of greater than about 90% as measured by a dry colorimetry method, or

a phosphine removal efficiency of greater than about 90% as measured by a dry colorimetry method.

19. The method according to claim 15, wherein the process stream is a stream of a process selected from the group consisting of a petroleum process, a petrochemical process, a polymerization process, a synthesis gas process, and a semiconductor process.

20. The method according to claim 15, wherein the process stream is a stream of a process selected from the group consisting of refinery off-gas, fluid catalytic cracking off-gas, steam

cracker off-gas, shale gas, and a combination thereof.

21. The method according to claim 15, wherein the process stream comprises ethylene and/or propylene.

22. The method according to claim 15, wherein the process stream comprises natural gas.

23. The method according to claim 15, wherein the bismuth material and the iron material are present collectively from about 60 wt.% to about 90 wt.%, about 70 wt.% to about 90 wt.%, or about 80 wt.% to about 90 wt.%.

24. The method according to claim 15, wherein the bismuth material is present as bismuth oxide (Bi_2O_3).

25. The method according to claim 24, wherein the bismuth oxide is present from about 15 wt.% to about 60 wt.% based on the total weight of the adsorbent composition.

26. The method according to claim 15, wherein the iron material is present as iron oxide (Fe_2O_3).

27. The method according to claim 26, wherein the iron oxide is present from about 25 wt.% to about 75 wt.% based on the total weight of the adsorbent composition.

28. The method according to claim 15, wherein:

the bismuth material is present as bismuth oxide (Bi_2O_3) from about 15 wt.% to about 60 wt.% based on the total weight of the adsorbent composition, and

the iron material is present as iron oxide (Fe_2O_3) from about 25 wt.% to about 75 wt.%, based on the total weight of the adsorbent composition,

with the proviso that the sum of the bismuth oxide and the iron oxide is from about 50 wt.% to about 90 wt.% based on the total weight of the adsorbent composition.

29. The method according to claim 15, wherein the support material is the balance of the total weight of the adsorbent composition.

30. The method according to claim 15, wherein the support material is selected from the group consisting of metal oxides, metalloid oxides, activated carbons, high surface area metal oxides, molecular sieves, and combinations thereof.

31. The method according to claim 15, wherein the support material comprises aluminum oxide, titanium oxide, silica, or a combination thereof.

32. The method according to claim 15, wherein the support material comprises silica.

33. The method according to claim 15, wherein the bismuth material and the iron material are dispersed onto the support material via a coprecipitation process.

34. The method according to claim 15, wherein the adsorbent composition exhibits an arsine capacity that is at least about 100% greater than an adsorbent composition having a fixed bismuth material amount without the iron material or having a fixed iron material amount without the bismuth material.

35. A method of forming an adsorbent composition in accordance with claim 1, the method comprising: coprecipitating a bismuth material and an iron material with a support material.

36. The method according to claim 35, wherein the bismuth material and the iron material are present collectively from about 60 wt.% to about 90 wt.%, about 70 wt.% to about 90 wt. %, or about 80 wt.% to about 90 wt.%.

37. The method according to claim 35, wherein the bismuth material is present as bismuth oxide (Bi_2O_3).

38. The method according to claim 37, wherein the bismuth oxide is present from about 15 wt.% to about 60 wt.% based on the total weight of the adsorbent composition.

39. The method according to claim 35, wherein the iron material is present as iron oxide (Fe_2O_3).

40. The method according to claim 39, wherein the iron oxide is present from about 25 wt.% to about 75 wt.% based on the total weight of the adsorbent composition.

41. The method according to claim 35, wherein:

the bismuth material is present as bismuth oxide (Bi_2O_3) from about 15 wt.% to about 60 wt.% based on the total weight of the adsorbent composition, and

the iron material is present as iron oxide (Fe_2O_3) from about 25 wt.% to about 75 wt.%, based on the total weight of the adsorbent composition,

with the proviso that the sum of the bismuth oxide and the iron oxide is from about 50 wt.% to about 90 wt.% based on the total weight of the adsorbent composition.

42. The method according to claim 35, wherein the support material is the balance of the total weight of the adsorbent composition.

43. The method according to claim 35, wherein the support material is selected from the group consisting of metal oxides, metalloid oxides, activated carbons, high surface area metal oxides, molecular sieves, and combinations thereof.

44. The method according to claim 35, wherein the support material comprises aluminum oxide, titanium oxide, silica, or a combination thereof.

45. The method according to claim 35, wherein the support material comprises silica.

46. The method according to claim 35, wherein the bismuth material and the iron material are dispersed onto the support material via a coprecipitation process.

47. The method according to claim 35, wherein the adsorbent composition exhibits at least one of:

an arsine capacity of greater than about 6 wt.% elemental As,

a carbonyl sulfide capacity of greater than about 4 wt.% elemental S, or
a phosphine capacity of greater than about 1 wt.% elemental P.

48. The method according to claim 35, wherein the adsorbent composition exhibits an arsine capacity that is at least about 100% greater than an adsorbent composition having a fixed bismuth material amount without the iron material or having a fixed iron material amount without the bismuth material.