production of nonwoven fabrics. PBT nonwoven materials are inherently hydrophobic in nature leading to a high degree of nonspecific protein adsorption, making the base material itself a poor platform for bioseparations. Direct hydrolysis of polyGMA grafts on PBT using acidic conditions makes the fiber surface completely hydrophilic and substantially decreases nonspecific hydrophobic protein adsorption. Each monomer unit of GMA contains an epoxy end group that can be used to covalently attach ligands via nucleophilic substitution with available amines, thiols, and hydroxyl groups. In the study by Liu et al., diethylene glycol covalently attached to the polyGMA brushes was also found to substantially eliminate protein adsorption by nonspecific hydrophobic interactions.

PolyGMA grafted nonwovens offer a convenient platform for the development of effective ion exchange membranes. Saito et al. successfully grafted polyGMA brushes to polypropylene fabrics and polyethylene hollow fibers. See K. Saito, T. Kaga, H. Yamagishi, S. Furasaki, T. Sugo, J. Okamoto, Phosphorylated hollow fibers synthesized by radiation grafting and crosslinking, J. Membr. Sci. 43 (1989) 131-141. These grafted materials were functionalized with phosphoric acid groups to develop strong cation exchange membranes to capture divalent metal cations.

In a study by Zheng et al., polyGMA was grafted to polypropylene nonwoven and functionalized with diethyl amine (DEA) to develop a weak anion exchanger. See Y. Zheng, H. Liu, P. Gurgel, R. Carbonell, Polypropylene nonwoven fabrics with conformal grafting of poly(glycidyl methacrylate) for bioseparations, J. Membr. Sci. 364 (2010) 362-371. This material achieved equilibrium binding capacities for bovine serum albumin (BSA) of 120 mg/g of membrane.

Liu et al. investigated the effects of various degrees of polyGMA grafting on nonwoven PBT for the capture of BSA by anion exchange. See H. Liu, Surface modified nonwoven membranes for bioseparations, Raleigh NC USA, North Carolina State Univ., PhD thesis, 2012. In that study, polyGMA grafts were converted to weak anion exchangers with DEA and challenged with BSA. It was determined that the overall protein binding capacity increased with the degree of grafting (% weight gain). The largest equilibrium binding capacity of 800 mg/g was observed at a 12% polyGMA weight gain. This investigation also showed that residence times of several hours to a full day were required to reach maximum binding, and that these binding times increased with increased grafting weight % gain. These long residence times preclude the use of these polyGMA grafted nonwoven PBT membranes for the development of high throughput, high capacity protein capture devices for downstream processing.

Accordingly, there remains a need for grafted nonwoven membranes capable of high throughput, high capacity protein capture.

SUMMARY

In one embodiment of the present disclosure, polybutylene terephthalate (PBT) nonwovens having an average fiber diameter of less than about 1.5 microns can be readily grafted with glycidyl methacrylate (GMA) or similar methacrylate polymers via, for example, UV-induced radical polymerization, to create uniform and conformal polymer brush networks around each fiber that can be chemically modified to

function as anion or cation exchangers. The rates of adsorption of proteins by ion exchange were measured in an islands-in-the-sea (I/S) PBT nonwoven with average fiber diameter of approximately 1 μm in accordance with the present disclosure and in a commercially available PBT nonwoven with average fiber diameter of approximately 3 μm. Both nonwovens were grafted successfully with polyGMA and showed similar ion exchange equilibrium protein binding capacities at similar weight % grafting. However, the grafted I/S nonwoven membrane of the disclosure exhibited a substantially higher amount of protein binding in early stages and was able to reach equilibrium in a fraction of the time required by the grafted commercial nonwoven with larger fiber diameters. Although not bound by a theory of operation, the faster rate of protein adsorption observed with the I/S PBT nonwoven of the disclosure is believed to be the result of the thinner polyGMA graft layer thicknesses around the fibers compared to those in the commercial PBT with the same weight % grafting.

The disclosure provides a polymer-grafted and functionalized nonwoven membrane adapted for use in bioseparation processes, comprising a nonwoven web comprising a plurality of polyester fibers (e.g. polybutylene terephthalate fibers), having an average fiber diameter of less than about 1.5 microns (more typically about 1 micron or less), each of the plurality of polyester fibers having grafted thereon a plurality of polymer segments constructed of a methacrylate polymer (e.g., polyGMA), each polymer segment carrying a functional group adapted for binding to a target molecule. In certain embodiments, the methacrylate polymer is constructed from one or more monomers selected from the group consisting of glycidyl methacrylate, methacrylic acid, 2-(diethylamino)ethyl methacrylate, [2-(methacryloyloxy)ethyl]trimethyl-ammonium chloride, 2-hydroxyethyl methacrylate, 2-acrylamido-2-methylpropane sulfonic acid, 2-(dimethylamino)ethyl methacrylate, butyl methacrylate, 3-chloro-2-hydroxypropyl methacrylate, 2-ethylhexyl methacrylate, and combinations thereof. The functional group can vary depending on the target molecule, but will typically be a group adapted for cation or anion exchange with the target molecule.

In one aspect, there is provided a polymer-grafted and functionalized nonwoven membrane adapted for use in bioseparation processes, comprising a nonwoven web comprising a plurality of polyester fibers having an average fiber diameter of less than about 1.5 microns, each of the plurality of polyester fibers having grafted thereon a plurality of polymer segments constructed of a methacrylate polymer, each polymer segment carrying a functional group adapted for binding to a target molecule.

In certain embodiments, the nonwoven web comprises island fibers remaining after removal of sea component of islands-in-the-sea bicomponent fibers. The nonwoven web can have an exemplary specific BET surface area of at least about 1.5 m^2/g. Typically, the weight of the grafted polymer segments is about 2 to about 50% of the weight of the nonwoven web, most preferably between 5 and 25% weight gain.

In another embodiment, a method of bioseparation is provided, which comprises passing a solution comprising the target molecule, such as a protein, through the nonwoven membrane of the disclosure such that at least a portion of the target molecule in the solution binds to the nonwoven membrane.

In another aspect, there is provided a method of bioseparation comprising passing a solution comprising the target molecule through the nonwoven membrane as defined herein such that at least a portion of the target molecule in the solution binds to the nonwoven membrane.

In yet another aspect, the disclosure provides a method for preparing a polymer-grafted and functionalized nonwoven membrane adapted for use in bioseparation processes, comprising: receiving a nonwoven web comprising a plurality of islands-in-the-sea fibers or a plurality of island fibers remaining after removal of the sea component of bicomponent islands-in-the-sea fibers; optionally, removing the sea component of the bicomponent islands-in-the-sea fibers to expose the island fibers thereof; grafting a methacrylate polymer onto the surface of the island fibers to form a plurality of polymer segments

covalently attached thereto, thereby forming grafted island fibers, the grafting step comprising contacting the nonwoven web with a solution comprising an initiator and at least one methacrylate monomer and exposing the nonwoven web to ultraviolet light to initiate polymerization of the methacrylate monomer; and optionally, functionalizing the grafted island fibers to attach at least one functional group adapted for binding to a target molecule to each of the plurality of polymer segments of the grafted island fibers. The concentration of monomer in the grafting solution can vary, but is typically about 5 to about 50% v/v (most preferably 15 to 25% v/v) and the initiator, such as benzophenone, is typically present in a molar ratio of initiator to monomer of about 1:100 to about 1:5 (e.g., 1:20). The ultraviolet light source can have wavelengths ranging from 200 nm to 500 nm (most preferably 365 nm) to initiate polymerization. The specific wavelength to initiate polymerization depends on the photoinitiator used, as well as, the monomer that is to be grafted to the surface of the PBT. Additionally, the ultraviolet light source can have intensities between 1 and 30 mW/cm^2 (most preferably 5 mW/cm^2), depending on the energy required for grafting and the desired rate at which grafting is to be performed to achieve the desired degrees of polymerization.

The disclosure includes, without limitation, the following embodiments:

Embodiment 1: A polymer-grafted and functionalized nonwoven membrane adapted for use in bioseparation processes, comprising a nonwoven web comprising a plurality of polyester fibers having an average fiber diameter of less than about 1.5 microns, each of the plurality of polyester fibers having grafted thereon a plurality of polymer segments constructed of a methacrylate polymer, each polymer segment carrying a functional group adapted for binding to a target molecule.

Embodiment 2: The membrane of any preceding or subsequent embodiment, wherein the methacrylate polymer is constructed from one or more monomers selected from the group consisting of glycidyl methacrylate, methacrylic acid, 2-(diethylamino)ethyl methacrylate, [2-(methacryloyloxy)ethyl]trimethyl-ammonium chloride, 2-hydroxyethyl methacrylate, 2-acrylamido-2-methylpropane sulfonic acid, 2-(dimethylamino)ethyl methacrylate, butyl methacrylate, 3-chloro-2-hydroxypropyl methacrylate, 2-ethylhexyl methacrylate, and combinations thereof.

Embodiment 3: The membrane of any preceding or subsequent embodiment, wherein the polyester fibers are constructed of polybutylene terephthalate.

Embodiment 4: The membrane of any preceding or subsequent embodiment, wherein the average fiber diameter is about 1 micron or less.

Embodiment 5: The membrane of any preceding or subsequent embodiment, wherein the functional group is adapted for cation or anion exchange with the target molecule.

Embodiment 6: The membrane of any preceding or subsequent embodiment, wherein the nonwoven web comprises island fibers remaining after removal of the sea component of islands-in-the-sea bicomponent fibers.

Embodiment 7: The membrane of any preceding or subsequent embodiment, wherein the nonwoven web has a specific BET surface area of at least about 1.5 m^2/g.

Embodiment 8: The membrane of any preceding or subsequent embodiment, wherein the weight of the grafted polymer segments is about 2 to about 50% of the weight of the nonwoven web.

Embodiment 9: A method of bioseparation comprising passing a solution comprising the target molecule through the nonwoven membrane of any preceding or subsequent embodiment such that at least a portion of the target molecule in the solution binds to the nonwoven membrane.

Embodiment 10: The method of any preceding or subsequent embodiment, wherein the target molecule is a protein.

Embodiment 11: A method for preparing a polymer-grafted and functionalized nonwoven membrane adapted for use in bioseparation processes, comprising: i) receiving a nonwoven web comprising a plurality of islands-in-the-sea fibers or a plurality of island fibers remaining after removal of the sea component of bicomponent islands-in-the-sea fibers; ii) optionally, removing the sea component of the bicomponent islands-in-the-sea fibers to expose the island fibers thereof; iii) grafting a methacrylate polymer onto the surface of the island fibers to form a plurality of polymer segments covalently attached thereto, thereby forming grafted island fibers, the grafting step comprising contacting the nonwoven web with a solution comprising an initiator and at least one methacrylate monomer and exposing the nonwoven web to ultraviolet light or heat to initiate polymerization of the methacrylate monomer; and iv) optionally, functionalizing the grafted island fibers to attach at least one functional group adapted for binding to a target molecule to each of the plurality of polymer segments of the grafted island fibers.

Embodiment 12: The method of any preceding or subsequent embodiment, wherein the island fibers are constructed of polybutylene terephthalate and the methacrylate polymer is polyGMA.

Embodiment 13: The method of any preceding or subsequent embodiment, wherein the concentration of monomer in the solution is about 5 to about 50% v/v and the initiator is present in a molar ratio of initiator to monomer of about 1:100 to about 1:5.

Embodiment 14: The method of any preceding or subsequent embodiment, wherein the initiator is benzophenone.

These and other features, aspects, and advantages of the disclosure will be apparent from a reading of the following detailed description together with the accompanying drawings, which are briefly described below. The disclosure includes any combination of two, three, four, or more of the above-noted embodiments as well as combinations of any two, three, four, or more features or elements set forth in this disclosure, regardless of whether such features or elements are expressly combined in a specific embodiment description herein. This disclosure is intended to be read holistically such that any separable features or elements of the disclosed invention, in any of its various aspects and embodiments, should be viewed as intended to be combinable unless the context clearly dictates otherwise. Other aspects and advantages of the present disclosure will become apparent from the following.