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Nanotechnology in Water Purification

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Abstract: *The innovation of relevant nanotechnology and its significance in water purification is illustrated in this paper for broadening vision. Nanotechnology deals with understanding, controlling and manipulating matter at the level of individual atoms and molecules in the range of 0.1–100 nm. It creates materials, devices, and systems with new properties and functions.The adaptation of highly advanced nanotechnology to traditional process engineering offers new opportunities for development of advanced water and wastewater technology processes. Here, an overview of recent advances in nanotechnologies for water and wastewater processes is provided.*

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I. Introduction

Contemporary research in the area of Nanofiltration(NF) technology is primarily concerned with improving the performance of NF membranes, minimising membrane fouling and reducing energy requirements of already existing processes. Nanofiltration(NF) is a relatively recent membrane filtration process used most often with low total dissolved solids water such as surface water and fresh groundwater, with the purpose of softening (polyvalent cation removal) and removal of disinfection by-product precursors such as natural organic matter and synthetic organic matter. Nanomaterials have unique size-dependent properties related to their high specific surface area (fast dissolution, high reactivity, strong sorption) and discontinuous properties (such as superparamagnetism, localized surface plasmon resonance, and quantum confinement effect). These specific nanobased characteristics allow the development of novel high-tech materials for more efficient water and wastewater treatment processes, namely membranes, adsorption materials, nanocatalysts, functionalized surfaces, coatings, and reagents.

1.Nanofilteration:

It is a membrane filtration-based method that uses nanometer. Nanofiltration membranes have pore sizes from 1-10 nm, smaller than that used in microfiltration and ultrafiltration, but just larger than that in reverse osmosis. Membranes used are predominantly created from polymer thin films.The commonly used materials are polyethylene terephthalate or aluminum metal. Pore dimensions are controlled by pH, temperature and time during development with pore densities ranging from 1 to 106 pores per cm2. Membranes made from polyethylene terephthalate and other similar materials, are referred to as “track-etch” membranes. Membranes created from metal such as alumina membranes, are made by electrochemically growing a thin layer of aluminum oxide from aluminum metal in an acidic medium.

II. Adsorption

Adsorption is the capability of all solid substances to attract to their surfaces molecules of gases or solutions with which they are in close contact. Solids that are used to adsorb gases or dissolved substances are called adsorbents, and the adsorbed molecules are adsorbate. Due to their high specific surface area, nanoadsorbents show a considerably higher rate of adsorption for organic compounds. They have great potential for novel, more efficient, and faster decontamination processes aimed at removal of organic and inorganic pollutants like heavy metals and micropollutants. The superior process efficacy enables implementation of more compact water and wastewater treatment devices with smaller footprints, particularly for decentralized applications and point-of-use systems. The nano adsorbents are carbon-based nano adsorbents ie, carbonnanotubes (CNTs) , metal-based nanoadsorbents, polymeric nano adsorbents, zeolites.

2.1 Carbon Nano Tubes:

CNTs are allotropes of carbon with a cylindrical nanostructure. Based on their manufacturing CNTs are categorized as single-walled nanotubes and multiwalled nanotube. Besides having a high specific surface area, CNTs possess highly assessable adsorption sites and an adjustable surface chemistry. They can be used for adsorption of persistent contaminants as well as to preconcentrate and detect contaminants. Metal ions are adsorbable by CNTs through electrostatic attraction and chemical bonding.CNTs exhibit antimicrobial properties by causing oxidative stress in bacteria and destroying the cell membranes. Although chemical oxidation occurs, no toxic byproducts are produced, which is an important advantage over conventional disinfection processes like chlorination and ozonation. They can be simply regenerated through appropriate adjustments of operating conditions, like pH shift. Plasma-modified ultralong CNTs that feature an ultrahigh specific adsorption capacity for salt (exceeding 400% by weight) that is two orders of magnitude higher when compared with conventional carbon-based water treatment systems. These ultralong CNTs can be implemented in multifunctional membranes that are able to remove not only salt but also organic and metal contaminants. Next-generation potable water purification devices equipped with these novel CNTs are expected to have superior desalination, disinfection, and filtration properties.Sponge CNTs with a dash of boron that shows a remarkable ability to absorb oil from water. The oil can be stored in the sponge for later retrieval or burned off so the sponge can be reused. If they succeed in generating large sheets or find a way to weld the sheets, the sponge material can be applied in removing oil spills for oil remediation.Although CNTs have significant advantages over activated carbon, their use on an industrial scale for large municipal water and wastewater treatment plants is not expected in the midterm because of high production cost,for example: for the elimination of heavily degradable contaminants such as many antibiotics and pharmaceuticals.

2.2 Polymeric Nanoadsorbents:

Polymeric nanoadsorbents such as dendrimers (repetitively branched molecules) are utilizable for removing organics and heavy metals. Organic compounds can be adsorbed by the interior hydrophobic shells, whereas heavy metals can be adsorbed by the tailored exterior branches. Nearly all copper ions were recovered by use of this combined dendrimer-ultrafiltration system. The adsorbent is regenerated simply through a pH shift. The bioadsorbent for the removal of anionic compounds such as dye from textile wastewater by preparing a combined chitosan-dendrimer nanostructure. The bioadsorbent is biodegradable, biocompatible, and nontoxic. They achieve removal rates of certain dyes up to 99%.

2.3 Zeolites:

Zeolite has a very porous structure in which nanoparticles such as silver ions can be embedded. There they are released from the zeolite matrix by exchange with other cations in solution. When used for sanitary purposes, the silver attacks microbes and inhibits their growth. A small amount of silver ions is released from the metallic surface when placed in contact with liquids. For example, the Agion product line includes a compound made from zeolites and naturally occurring silver ions that exhibits antibacterial properties.

Properties, Applications, And Innovative Approaches Of Nanoadsorbents:

Both CNTs and nanometals are highly effective nanoadsorbents for the removal of heavy metals such as arsenic. With regard to this application field, nanometals and zeolites benefit from their cost-effectiveness and compatibility with existing water treatment systems since they can be implemented in pellets and beads for fixed absorbers. In contrast, the production of CNTs is very costly, and additional technical devices, for example, membrane filtration plants, have to be integrated in order to make absolutely sure that no nanoparticles are discharged into the aqueous environment. A major advantage of CNTs in terms of micropollutant removal is their strong adsorption capacity for polar organic compounds due to the diverse interactions between contaminants and CNTs. CNTs and nanometals are commercially available for diverse applications, market entry of polymeric nanoadsorbents is ongoing. From the point of view of process efficacy, polymeric nanoadsorbents are highly advanced materials allowing both removal of heavy metals as well as organic contaminants within one process step.In terms of ecotoxicity, the nanometals, CNTs, and zeolites described here consist of very well characterized basic materials that occur naturally in the environment and are classified as nontoxic. Thus, the potential toxic effect mainly depends on the size and shape of the respective nanoadsorbents, as well as chemical stabilizers and surface modifications.

III. Nanometals and nanometal oxides

Nanoscale metal oxides are promising alternatives to activated carbon and effective adsorbents to remove heavy metals and radionuclides. As well as having a high specific surface area, they feature a short intraparticle diffusion distance and are compressible without a significant reduction of surface area. Some of these nanoscale metal oxides are superparamagnetic, which facilitates separation and recovery by a low-gradient magnetic field. They can be employed for adsorptive media filters and slurry reactors. Nano iron hydroxide [α-FeO(OH)] is a robust abrasion-resistant adsorbent with a huge specific surface area that enables adsorption of arsenic from waste and drinking water. ArsenXnp is a commercially available hybrid ion exchange medium comprising iron oxide nanoparticles and polymers and is highly efficient in removing arsenic and requires little back wash. Usually, nanometals and nanometal oxides are compressed into porous pellets or used in powders for industrial use.

IV. Magnetic Nanoparticles

The use of magnetic nanoparticles (magnetite $Fe3O4$) for separation of water pollutants has already been established in ground water remediation, in particular for the removal of arsenic. The conventionally applied "pump-and-treat" technology for groundwater treatment comprises pumping up the groundwater to the surface and further treatment, usually by activated carbon for final purification. Magnetic nanoparticles can be injected directly into the contaminated ground, and loaded particles can be removed simply through a magnetic field. Besides ground water remediation, magnetic recovery makes such nanoparticles an ideal compound to increase the osmotic pressure of draw solutions used in forward osmosis. Forward osmosis as contrary process to reverse osmosis draws water from a low osmotic pressure to one with a higher osmotic pressure (draw solution) using the osmotic gradient. Another benefit of magnetic nanoparticles in terms of the removal and fate of nanoparticles in an aqueous environment is the fact that they can be simply recovered by applying a magnetic field.

V. Nanosilver and nano-titanium dioxide

Nanosilver has been registered with the Environmental Protection Agency for use in swimming pool algaecides since 1954 and drinking water filters since the 1970s. Although nanosilver exhibits a strong and broad-spectrum antimicrobial activity, it has hardly any harmful effects in humans. It is already applied to point-of-use water disinfection systems and antibiofouling surfaces. Nano-titanium dioxide (TiO2), featuring high chemical stability and low human toxicity at a cheap price, is utilizable in disinfection and decontamination processes. The main advantage of nano-TiO2 over nanosilver is the nearly endless life time of such coatings, since TiO2 as a catalyst remains unchanged during the degradation process of organic compounds and micro-organisms. The antimicrobial effect of nanosilver is based on the continuous release of silver ions. After a certain operation period, depending on the thickness and composition of the nanosilver layers, the coating has to be renewed or the complete device, including the bulk material, has to be disposed of, leading to significant replacement costs. However, compared with TiO2, which needs energy-consuming ultraviolet lamps for activation, nanosilver kills bacteria with no need of additional energy-consuming devices.

VI. Nano-zero valent iron

Nano-zero valent iron can be used for remediation of groundwater contaminated with chlorinated hydrocarbon fluids and perchlorates. A suspension of nano-zero valent iron can be injected into the groundwater, allowing in situ treatment of the ground water.Due to its high specific surface, nano-zero valent iron is much more reactive in comparison with conventional granular iron; on the other, as a result of its high reactivity, the life time of nano-zero valent iron is very low .

Properties, Applications, And Innovative Approaches For Nanometals And Nanometal Oxides:

Photocatalytic TiO2 benefits from its low price, high availability, inertness, and broad-spectrum effect on the chemical degradation of the majority of organic contaminants and micro-organisms. This makes it an ideal, robust, durable, and effective nanomaterial for chemical-free water and wastewater treatment processes in both large-scale and small-scale treatment plants.Nanosilver benefits from its low toxicity, high availability, and well proven bactericidal effect.If highly effective nano-TiO2 able to be activated by visible light can be developed successfully, photocatalysis will become one of the most promising water and wastewater treatment technologies due to its flexible and manifold implementation and easy scalability.Due to their magnetic recoverability, magnetic nanoparticles seem to be advantageous over nano-zero valent iron in the field of ground water remediation.

VII. Membranes and membrane processes

Membrane separation processes are rapidly advancing applications for water and wastewater treatment. Membranes provide a physical barrier for substances depending on their pore size and molecule size. Membrane technology is well established in the water and wastewater area as a reliable and largely automated process. The research activities with regard to nanotechnology focus on improving selectivity and flux efficiency, eg, by developing antifouling layers.

VIII. Nanocomposite membranes:

Nanocomposite membranes can be considered as a new group of filtration materials comprising mixed matrix membranes and surface-functionalized membranes. Mixed matrix membranes use nanofillers, which are added in a matrix material. In most cases, the nanofillers are inorganic and embedded in a polymeric or inorganic oxide matrix. These nanofillers feature a larger specific surface area leading to a higher surface-to-mass ratio. Metal oxide nanoparticles (Al2O3, TiO2) can help to increase the mechanical and thermal stability as well as permeate flux of polymeric membranes. The incorporation of zeolites improves the hydrophilicity of membranes resulting in raised water permeability. Thin film nanocomposite membranes are semipermeable membranes with a selective layer on the upper surface that is usually applied to reverse osmosis. The surface of the hydrophobic ordered mesoporous carbons is treated by applying atmospheric pressure plasma to achieve hydrophilized ordered mesoporous carbons with higher solubility. Only a small percentage of hydrophilized ordered mesoporous carbons (adding nanomaterial) is required to raise the hydrophilicity of the membrane surface, resulting in considerably increased pure water permeability. This membrane was generated by adding superhydrophilic nanoparticles to a polyamide thin film to form a thin film nanocomposite membrane with higher permeate efficiency and lower fouling potential. The nanoparticles are designed to attract water and are highly porous, soaking up water like a sponge while repelling dissolved salts and other impurities. The hydrophilic nanoparticles embedded in the membrane also repel organic compounds and bacteria, which tend to clog up conventional membranes over time.Another method used to prevent membrane clogging might be surface functionalization with chemical substances capable of oxidizing organic contaminants and thus prevent building up of fouling layers

IX. Self-assembling membranes:

Self-assembly is defined as the "autonomous organization of components into patterns or structures without human intervention". The structure of these membranes can be systematically controlled by the process parameters, so that the targeted membranes feature specific tailor-made characteristics eg, homogeneous nanopores. High-density cylindrical nanopores can be formed that way to be useful not only for micro/nanofluidic devices but also for water filtration. Such membranes belonging to the category of ultrafiltration provide enhanced selectivity and permeate efficiency. However, due to difficulties with adaption of the techniques to large-scale membrane areas, up until now self-assembling membranes have only been produced in small quantities in the laboratory.

X. Nanofiber membranes:

Electrospinning produces fibers by drawing very fine different materials like polymers or ceramics into an electric field. These so-called nanofibers are in the range of nanometers and are often used in separation and filtration processes. The technical process ensures a high specific surface porosityand thus a high surface to mass ratio. Another benefit of nanofibers is their capacity to be tailored to specifics such as membrane thickness and an interconnected open pore structure. The electrospinning process is a fully developed technology in air treatment, but nearly unknown in water and wastewater treatment. Thus, membranes made of these hydrophobic nanofiber materials might become very applicable for separation of organic solvents, leading to higher flux efficiency.

XI. Aquaporin-based membranes:

Aquaporins are pore-forming proteins and ubiquitous in living cells. Under certain conditions, they form highly selective water channels that are able to reject most ionic molecules. The combination of high water permeability and selective rejection make them an ideal material for creating novel high flux biomimetic membranes. To stabilize the aquaporins, they are incorporated in vesicles. Since stand-alone membranes based on these vesicles are too mechanically weak for their intended technical applications, like osmosis, they are embedded in a polymeric matrix or deposited onto polymeric substrates such as nanofiltration membranes.This kind of membrane is able to withstand pressures up to 10 bar and allow a water flux >100 L/(hm2) for example required for brackish water desalination.In order to enter the water and wastewater market, aquaporin-based membranes have to be competitive with conventional membranes in terms of stability and useful life. Currently, there exists no such membrane that can permanently withstand the operating pressures of reverse osmosis, the harsh cleaning conditions (high temperature, acidic and alkaline cleaners), and fouling-based corrosion.

XII. Photocatalysis

Photocatalysis is an advanced oxidation process that is employed in the field of water and wastewater treatment, in particular for oxidative elimination of micropollutants and microbial pathogens. Due to its high availability, low toxicity, cost efficiency, and well known material properties, TiO2 is widely utilized as a photocatalyst. When TiO2 is irradiated by ultraviolet light with an appropriate wavelength in the range of 200–400 nm, electrons will be photoexcited and move into the conduction band. As a result of photonic excitation, electron-hole pairs are created, leading to a complex chain of oxidative-reductive reactions. Hence, the biodegradability of heavily decomposable substances can be increased in a pretreatment step. Principally, persistent compounds like antibiotics or other micropollutants can be photocatalytically eliminated in polishing processes, such as tertiary clarification steps in municipal wastewater treatment plants. However, as the ultraviolet A radiation is only about 5% that of sunlight, the photon efficiency is quite low, limiting use on an industrial scale.

A solution for rejection of photocatalytic nanoparticles is their immobilization on defined materials by use of suitable coating processes, such as physical or chemical vapor deposition, as well as wet chemical coating processes. When using a microfilter material as a substrate, a beneficial multibarrier effect comprising mechanical filtration and chemical decontamination is obtained . Dirt particles and larger microorganisms are rejected by microfiltration membranes at the same time that viruses, spores, and contaminants are chemically eliminated and degraded.

XIII. Thin Film Composite Membranes (TFC):

It consist of a number of extremely thin selective layers interfacially polymerized over a microporous substrate, have had the most commercial success in industrial membrane applications due to the capability of optimizing the selectivity and permeability of each individual layer. Recent research has shown that the addition of nanotechnology materials such as electrospunnanofibrous membrane layers (ENMs) to conventional TFC membranes results in an enhanced permeate flux. This has been attributed to inherent properties of ENMs that favour flux, namely their interconnected pore structure, high porosity and low transmembrane pressure. This format has the advantage of requiring significantly less pre-treatment than spiral wound membranes, as solids introduced in the feed are displaced effectively during backwash or flushing. As a result, membrane fouling and pre-treatment energy costs are reduced. Extensive research has also been conducted on the potential use of Titanium Dioxide (TiO_2, titania) nanoparticles for membrane fouling reduction. This method involves applying a nonporous coating of titania onto the membrane surface.

XIV. Conclusion

There is a significant need for novel advanced water technologies, in particular to ensure a high quality of drinking water, eliminate micropollutants, and intensify industrial production processes by the use of flexibly adjustable water treatment systems. Nanoengineered materials, such as nanoadsorbents, nanometals, nanomembranes, and photocatalysts, offer the potential for novel water technologies that can be easily adapted to customer-specific applications. Most of them are compatible with existing treatment technologies and can be integrated simply in conventional modules. One of the most important advantages of nanomaterials when compared with conventional water technologies is their ability to integrate various properties, resulting in multifunctional systems such as nanocomposite membranes that enable both particle retention and elimination of contaminants. Further, nanomaterials enable higher process efficiency due to their unique characteristics, such as a high reaction rate.

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