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Introduction

1.1 Global Challenges

Water, food, and energy security represent major challenges to the stability and continuity of human populations. However, rapid population growth and steadily improving living standards place enormous pressures on already stressed water resource and agricultural systems. Large amounts of energy are consumed to produce clean water and to treat wastewaters prior to their return to the environment, which inevitably leads to a considerable amount of carbon dioxide (CO_2) emissions as well as releasing other environmental pollutants.

At the global scale, about 2600 km^3 of water are withdrawn to supply food-driven irrigation needs every year. Viewed another way, agriculture consumes nearly 70% of total human freshwater withdrawals. This number is to increase to more than 83% by 2050 to meet the growing food demand by the rapidly growing population.

In the last 25 years, access to water with potable quality has gone up from 75% to 90% of the world population, and, nevertheless, 884 million people nowadays still lack access to adequate drinking water in many geographical regions [1]. Thus, ensuring a stable and sustainable water, food, and energy supply into the future is a priority for all nations.

Adding to an already dreadful situation, water pollution is becoming a major global challenge [2, 3]. From the United Nations World Water Development Report in 2018, it is said that more than 2 billion people lack access to safe drinking water and more than double that number lack access to safe sanitation. With a rapidly growing global population, demand for water is expected to increase by nearly one-third by 2050 [4]. In addition, WHO estimated that 361 000 deaths in children under five years due to diarrhea, representing more than 5% of all deaths in this age group in low- and middle-income countries, could have been prevented through reduction of exposure to inadequate drinking water [5]. Thus, the ability to remove contaminants from these environments to a safe level and do it rapidly, efficiently, and with reasonable costs is important.

With the nonrenewable and pollutant-laden fossil fuels dominating the global energy supply, representing 78% of the world's primary energy, air pollution is worsening in many parts of the world especially where the economy is heavily dominated by low-tech manufacturing. Millions of people die every year from

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diseases caused by exposure to outdoor air pollution [6]. Ninety two percent of the global population, including billions of children, is exposed to hazardous effects of air pollution at which levels exceed WHO limits. Air pollution causes approximately 600 000 deaths in children under five years annually and increases the risk of respiratory infections, asthma, adverse neonatal conditions, and congenital anomalies.

1.2 Conventional Technologies in Environmental Science and Engineering

In the past century, the development in water and air treatment technologies by environmental engineers has significantly improved the quality of water and air. The research and relevant design of conventional water and air protection systems experienced its golden age in the first half of twentieth century and has gradually reached their steady states. At the same time, with the ever-growing population and ever-increasing life quality expectation, the demand for safe and clean water and air has never dwindled in the course of human existence and is gradually pushing existing technologies to their limits.

Conventional technologies, such as chemical coagulation [7], adsorptions [8, 9], chemical treatment (e.g. advanced oxidation process [AOP]) [10–12], membrane-based separation [13–15], and biological treatment [16, 17], are based on bulk water chemistry.

Coagulation, which involves adding chemical coagulants into bulk source water, is commonly used in drinking water plants. The particles in source water that cause turbidity (e.g. silt, clay) are generally negatively charged, while coagulant particles are positively charged. In coagulation and subsequent flocculation, the formed particles in the form of flocs are settled out or later removed by filtration. The effectiveness of the coagulation is controlled by bulk water chemistry, such as dose of the coagulants added and pH, among others.

AOP, as a type of chemical treatment, involves accelerated production of highly reactive hydroxyl free radical to degrade the organic pollutants [18–20]. The degradation rates can be affected by several factors from the bulk water chemistry [21]. Adsorption is a process in which pollutants are adsorbed on solid surfaces [9, 22]. Adsorption is a proven and much used water purification technique due to its low energy consumption and maintenance cost, as well as its simplicity and reliability. However, its performance relies on the concentration of the to-be-removed substances, the presence of other competing species, temperature, and pH of the bulk water.

Biological treatments rely on bacteria, nematodes, or other small organisms to break down organic wastes using normal cellular processes [23]. Biological wastewater treatment is often a secondary treatment process, used to remove remaining biodegradable organics after primary treatment. These processes can be either anaerobic or aerobic. “Aerobic” refers to the condition where oxygen is present, while “anaerobic” describes a biological process in which oxygen is absent. To obtain an aerobic condition, huge amount of electricity is typically consumed to re-aerate the bulk wastewater, which can be completely oxygen-depleted.

Membrane separation is a technology in which membrane acts as a selective barrier allowing water flowing through while it catches suspended solids and other substances. Membrane separation technology is commonly used for the creation of process water from groundwater, surface water, or wastewater, and it works without the addition of chemicals, with a relatively low energy use and experiencing simple bulk water separation process [24].

Although these conventional technologies are crucial at providing quality water especially at heavily populated areas, conventional water treatment and its infrastructure systems allow little flexibility in response to the changing demand for water quality or quantity, leading to significant energy consumption, water loss, and secondary contamination. For instance, coagulation itself results in the formation of flocs, and thus additional treatment process is required to help the floc to further aggregate and settle. Biological treatment method is at the cost of a long time due to the slow biodegradation process [10]. On the other hand, impurities and pollutants build up on the surface and clog the filtration membranes over extended periods of use, and thus the flux of the wastewater across the filters decreases, leading to higher energy requirements.

From air quality point of view, many prevention measures have been taken in addressing air pollution problems: source control, development of clean energy, filtration technologies, etc. [25] Among them, air filtration technology is of great interest due to low equipment cost and low energy consumption. The conventional fibrous membrane (e.g. glass, polyethylene [PE], polypropylene [PP], polyester, and aramid fibers), as a kind of porous media, has been widely applied in different filtration scenes, including disposable respirators, industrial gas cleaning equipment, cleanroom air purification systems, automotive cabin air filters, and indoor air purifiers [26]. Such fibrous media still suffer from some structural and performance disadvantages, such as large fiber diameter, nonuniform fiber diameter and pore size, relatively low filtration efficiency, high basis weight, and poor high-temperature resistance [27].

While the conventional technologies are being pushed toward their capacity limits, innovations in nanomaterials and more broadly nanotechnology have been fueling advances in environmental science and engineering [28].

1.3 Nanotechnology

1.3.1 History of Nanotechnology Evolution

The term "nanotechnology" can be traced back in 1959 when it was first used by Richard Feynman in his famous lecture entitled "There's Plenty of Room at the Bottom," which is hailed by many as the herald of the era of nano [29]. Starting 1980s, two major breakthroughs sparked the growth of nanotechnology in the modern era. First, in 1981, the invention of the scanning tunneling microscope provided unprecedented visualization of individual atoms and bonds. Second, fullerenes were discovered in 1985 by Harry Kroto, Richard Smalley, and Robert

Curl, who together won the 1996 Nobel Prize in Chemistry [30, 31]. Initially, C_{60} was not described as nanotechnology while the term was used regarding subsequent work with related graphene tubes (called carbon nanotubes), which suggested potential applications for nanoscale electronics and devices.

In the beginning of 2000s, there were commercial applications of nanotechnology, although these were limited to the bulk application of nanomaterials and do not involve atomic control of matter, such as using silver nanoparticles as antibacterial agent, nanoparticle-based transparent sunscreens, and carbon nanotubes for stain-resistant textiles [32–34].

Nanotechnology is developing at a very fast rate, and its development is regarded as another industrial revolution. It is anticipated that increasing integration of nanoscale science and engineering knowledge promises mass applications of nanotechnology in all fields of the industry [35].

1.3.2 Concept and Definition

Overall, nanotechnology is the manipulation of matter at an atomic, molecular, and supramolecular scale. It is naturally very broad, including fields of science as diverse as surface science, organic chemistry, molecular biology, semiconductor physics, energy storage, microfabrication, molecular engineering, etc. [36–39] The associated research and applications are equally diverse, ranging from extensions of conventional device physics to completely new approaches based upon molecular self-assembly [40], from developing new materials with dimensions on the nanoscale to direct control of matter on the atomic scale.

Nanomaterials are defined as the structures that can be produced in a controlled manner in a size ranging from 1 to 100 nm in one, two, or three dimensions [41]. Materials reduced to the nanoscale can show different properties compared with what they exhibit on a macroscale, enabling unique applications. For instance, opaque substances can become transparent (copper); stable materials, combustible (aluminum); and insoluble materials, soluble (gold). A material such as gold, which is chemically inert at normal scales, can serve as a potent chemical catalyst at nanoscales.

1.3.3 Fields of Current Applications

Nanotechnology is widely regarded as a powerful enabling platform, and it has created many new materials and devices with a vast range of applications [42, 43]. The nanotechnology research has produced many scientific breakthroughs and is fostering potentially endless possibilities. Some applications of nanotechnology in the fields of nanomedicine, energy, and environment are briefed as follows.

Nanotechnology provides new options for drug delivery and disease therapies. Nanosized drug carrier enables drugs to be precisely delivered to the right location in the body and release drug doses on a predetermined schedule for optimal treatment. The surgical nanorobot, programmed or guided by a human surgeon, can act as a semiautonomous on-site surgeon inside the human body when introduced into the body through vascular system or cavities [44, 45]. Moreover, the integration of nanotechnology with molecular imaging provides a versatile platform for novel design of nano-probes that have tremendous potential to enhance the sensitivity, specificity, and signaling capabilities of various biomarkers in human diseases.

Nanotechnology has potential in securing new sustainable energy sources and in effective use of existing energy resources. It has reduced cost both of solar cells and the equipment needed to produce and deploy them, making solar power economical and hence a more useable alternative to fossil fuels. There is a potential for nanotechnology to cut down on energy consumption through lighter materials for vehicles, smart materials that lead to more effective temperature control, advanced materials that increase the efficiency of electrical components and transmission lines, and materials that could contribute to a new generation of fuel cells and a step closer toward a hydrogen economy, among numerous others [46, 47].

From an environmental engineering point of view, nanotechnology presents new opportunities to improve how contaminants in the environment are measured, monitored, managed, and minimized, which will be discussed heavily in the rest of the chapters.

Overall, nanomaterials have two primary advantages over conventional bulk materials: (i) they have small size and thus big specific surface area, which are beneficial to many interface-related applications, and (ii) their properties, including chemical, physical, optical, electronic, mechanical, and magnetic properties, can be judiciously tuned by controlling their size, surface morphology, shape and crystal orientation, etc. As a result, going to nanoscale has opened up numerous new avenues that would otherwise be impossible with conventional bulk materials.

1.3.4 Nanotechnology in Environmental Engineering

Applications of nanotechnology in environmental science and engineering mainly include a high surface area for adsorption (nanoadsorbents), unique surface functionalization properties, high activity for (photo)catalysis (environmental catalytic materials), nanofiltration for wastewater treatment, nanofibrous air filter, water purification and desalination membranes, and sensors for water quality monitoring (Figure 1.1) [15, 48–52].

For example, nanoadsorbents offer significant improvements over conventional adsorbents with their extremely high specific surface area and tunable pore size and surface chemistry. The high surface area and size-dependent surface structure at the nanoscale could create highly active adsorption sites [53], resulting in higher adsorption capacity. Meanwhile, the surface of many nanomaterials can be functionalized to target specific contaminants, achieving high selectivity.

As for environmental sensors, the integration of nanomaterials and recognition agents could yield fast, sensitive, and selective sensors for water quality

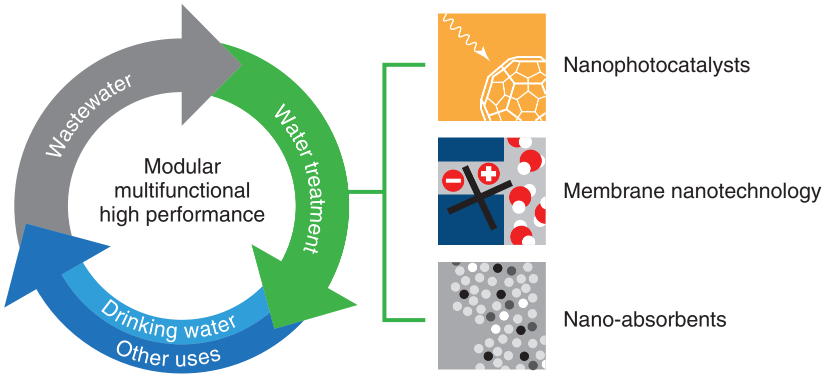

Figure 1.1 Nanotechnology applications involving nanophotocatalysts, membrane nanotechnology, and nanoadsorbents for a safe and sustainable water supply. Source: Qu et al. 2012 [48]. Reprinted with permission of American Chemical Society.

monitoring [54]. Effective nanomaterials can improve sensor sensitivity and speed and achieve multiplex target detection by utilizing their unique electrochemical, optical, or magnetic properties.

Membrane technology is a key component of an integrated water treatment and reuse paradigm. However, current materials and fabrication methods for membranes are largely based on empirical approaches and lack molecular-level design, thus hampering membrane performance and increasing the cost of water treatment [55]. A nanoscale membrane with molecular-level design can potentially overcome some limitations in conventional membranes especially permeability–selectivity trade-off and high fouling propensity [56].

Photocatalysis is the phenomenon of overcoming the activation energy or temperature of a chemical reaction by light. AOPs paired with sunlight present an attractive option for water treatment by the generation of OH radical [57]. Nanophotocatalysts can be used to break down a wide variety of organic materials, organic acids, estrogens, pesticides, dyes, crude oil, microbes, and inorganic molecules such as nitrous oxides. In combination with precipitation or filtration, photocatalysis can also remove metals like mercury [58]. Photocatalytic oxidation used in water treatment has an obvious advantage of high reaction rates due to high specific surface areas and low mass-transfer restrictions unmatched by other conventional methods, especially when there are high concentrations of organic pollutants in water [59].

Overall, nanotechnology is actively pursued to both enhance the performance of existing treatment processes and develop new processes. It is now a popular belief that many of the solutions to the existing and even future environmental challenges are most likely to come from nanotechnology and especially novel nanomaterials with increased affinity, capacity, and selectivity for environmental contaminants. The field of rational design of nanomaterials for environmental engineering has grown significantly in the past two decades and is poised to make its contribution to creating next-generation environmental technologies in the years to come [7, 50, 60–64].

1.4 Artificially Intelligent Materials

1.4.1 Artificial Intelligence (AI) and Nanotechnology

The first work that is now generally recognized as artificial intelligence (AI) was McCullouch and Pitts' 1943 formal design for Turing-complete "artificial neurons" [65] The AI concept emphasizes the capability of manmade machines to imitate intelligent human behavior to perform tasks normally requiring human intelligence but without humanlike intervention [66]. Thus, the design of AI machine necessitates proactive, instead of reactive, functionality, which endows the machine with anticipatory, change-oriented, and self-initiated behavior.

As a matter of fact, AI entered the general field of nanotechnology in the 1990s. Nanomaterials with certain level of AI are entrusted with multiple, synergistic, and proactive functionalities so that these "nanomachines" perceive their environment and subsequently take automated actions or make self-adjustments for the purpose of maximizing their possibility to achieve their desired goal [67].

For practical applications, it is desired to rationally integrate multiple synergistic and advanced functions into one single material and to design the responsive functions that can switch to a desirable function in a controlled fashion in response to the external environmental stimuli. Following this line of thought, the AI materials could provide unprecedented advantages over traditional materials.

Recently, there have been significant developments in the materials that are integrated with "artificial intelligence." These intelligent nanomaterials typically have one or more of their properties (e.g. mechanical, thermal, optical, or electromagnetic properties) able to vary in a predictable or controllable way in response to external stimuli, such as stress, light, temperature, moisture, pH, electric or magnetic fields, etc.

1.4.2 Examples of Artificially Intelligent Nanomaterials

Generally, the response mechanism of intelligent nanomaterials lies in the change in molecular movement in response to external stimuli, which brings about the macroscopic property change of the materials. Some artificially intelligent nanomaterials in engineering fields including energy nanogenerator/nanosensor, shape-memory materials, and artificial muscles are presented as follows.

1.4.2.1 Energy Nanogenerator/Nanosensor (Piezoelectric/Triboelectric Materials)

Piezoelectric materials are crystalline materials exhibiting piezoelectric effect [68–70] and mainly include inorganic semiconducting piezoelectric ZnO nanowires, GaN nanowires, and lead-based and lead-free perovskite materials (e.g. $Pb(Zr,Ti)O_3$, $NaNbO_3$, $KNbO_3$, $BaTiO_3$, and $ZnSnO_3$ [71–77]) and piezoelectric polymer (e.g. polyvinylidene difluoride [PVDF] and poly(vinylidenefluoride-co-trifluoroethylene) [P(VDF-TrFE)]) [78–80]. Piezoelectric materials have been integrated along with sensors and actuators to

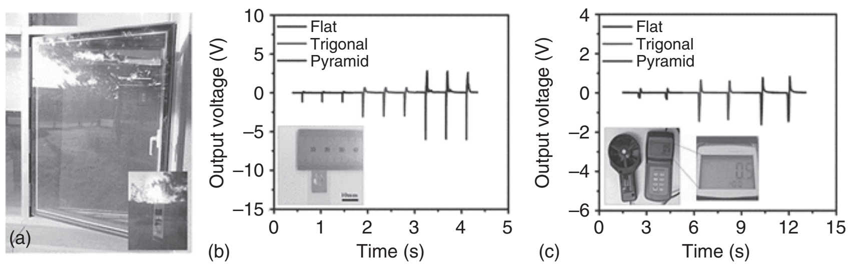

Figure 1.2 (a) Climate sensor is situated onto the window outward. *Inset:* Enlarged illustration of the rain sensor. (b) The output voltage generated from different types of sensors with respect to patterns on the surface as dropping water droplet. *Inset:* Water droplets staying at the sensor surface (scale bar: 10 mm). (c) Output voltage generated from sensors with respect to patterns on the surface as stirring up the wind using an air gun. *Inset:* Wind speed was recorded by an anemometer. Source: Lee et al. 2015 [85]. Reprinted with permission of John Wiley and Sons.

make intelligent materials. For example, piezoelectric materials have been used to capture and harvest mechanical energy wasted in nature (e.g. airflow, raindrop, sound, human motion, and ocean waves) that can later be used as portable, lightweight, and sustainable power sources [81–84]. Figure 1.2 presents a self-powered pressure sensor based on piezoelectric effect to detect water droplet and wind flow [85].

Triboelectric nanogenerator (TENG) has been produced to collect energy from common environmental sources [86–88]. When contacting and separating two different materials with oppositely charged surfaces, there is surface electron transfer, which in turn creates an electric potential difference. By repeating the contact and separation in a cyclic manner, electrons can be driven to flow through external load, generating a continuous output. Wang's group pioneered and demonstrated many TENG designs that harvested multiple types of environmental energy [89]. For example, a superhydrophobic and self-cleaning PTFE-based TENG could harvest the water-related energy in the environment [90]. The power generated from water drop could power 20 light-emitting diodes (LEDs) (Figure 1.3). Such water-TENG can also serve as a sensor to detect water/liquid leakage from a container/pipe [91, 92].

1.4.2.2 Shape-Memory Materials

Shape-memory materials are featured by their ability to recover their original shape from a significant and seemingly plastic deformation when a particular stimulus is applied [93–95]. Shape-memory materials can be inorganic or organic materials [96]. Shape-memory metal alloys can change their shape through microstructural transformation induced by temperature or magnetic fields. On the other hand, shape-memory polymers are intelligent as they have the ability to return from a temporary deformed shape to a memorized permanent shape upon external stimuli, including heat [97–100], light irradiation [101, 102], solvent [103, 104], electrical current [105], and magnetic fields [106]. Representative shape-memory polymers contain polyurethanes [107], cellulose [103, 104], block copolymer of polyethylene terephthalate (PET) and

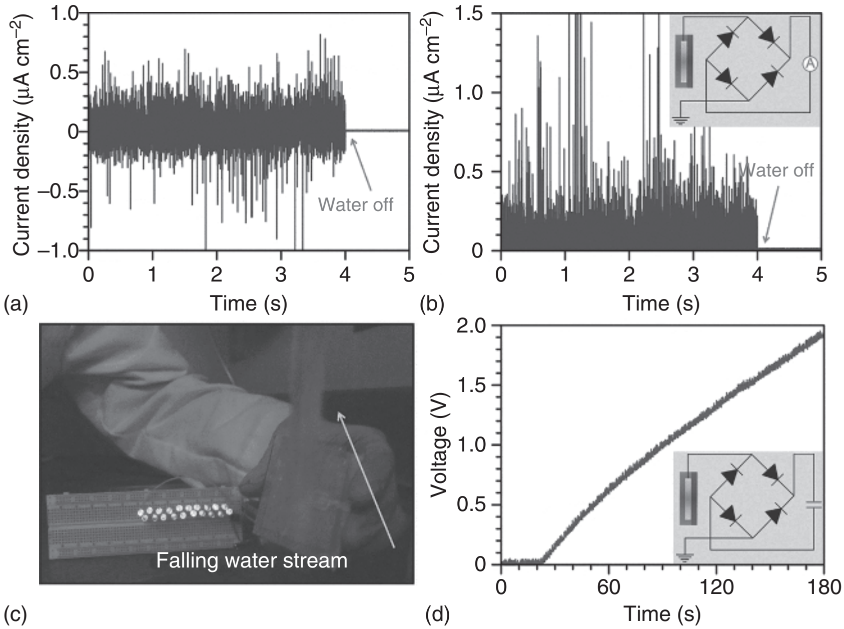

Figure 1.3 (a) Output current density of the water-TENG generated from flowing tap water. (b) The alternating current (ac) output transformed to unidirectional pulse output by a full-wave rectifying bridge. (c) The image of the water-TENG used as a power source to light up 20 LEDs. (d) The rectified output used to charge a commercial capacitor of 33 μF. Insets of (b) and (d) are the sketches of the corresponding circuit connection polarities. Source: Lin et al. 2014 [90]. Reprinted with permission of John Wiley and Sons.

polyethylene oxide (PEO) [108], block copolymers containing polystyrene and poly(butadiene) [101, 109], polynorbornene or hybrid polymers consisting of polynorbornene units substituted by polyhedral oligosilsesquioxane (POSS) [110], etc. Shape-memory polymers have several advantages over inorganic materials. They have higher deformation strain, lower stiffness, density and manufacturing cost, potential biodegradability and healability, and the capability to be activated by various stimuli [111, 112]. Therefore, they have diverse promising applications in areas of biomedical devices, the aerospace industry, textiles, flexible electronics, and so forth [113–117]. Figure 1.4 presents a healable shape-memory polymeric films that can heal the mechanical damage and the fatigued shape-memory function [118].

1.4.2.3 Actuator

Intelligent actuators is a generic term for a class of materials and devices that can offer controllable mechanical responses (contract, expand, or rotate) toward external stimuli, such as electric fields [119, 120], temperature [121, 122], solvent [123], humidity [124–126], and light [127, 128],, and convert those input energies into 2D or 3D movements. As energy transducers, actuators have numerous promising applications, involving switches [129], microrobotics [126], artificial muscles [130, 131], etc. Therefore, the fabrication of various actuators with

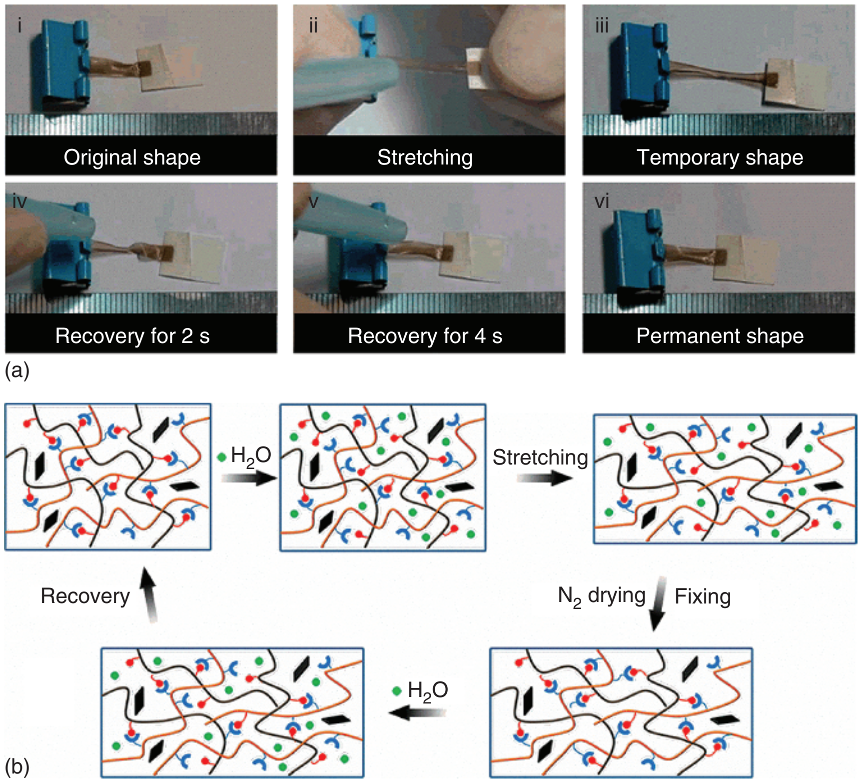

Figure 1.4 (a) Polymeric films are fabricated by layer-by-layer assembly of branched poly(ethylenimine) (bPEI)-graphene oxide (GO) complexes with poly(acrylic acid) (PAA). As-prepared films exhibited the shape-memory function. The small piece of paper stuck on the right side of the film was used to stretch the film during the shape-memory process. (b) Schematic illustration of the shape-memory mechanism of the PAA/bPEI-GO film. The humidity-induced healing and shape-memory behavior are due to the electrostatic and hydrogen-bonding interactions induced by water between PAA and bPEI-GO complexes. Source: Xiang et al. 2017 [118]. Reprinted with permission of American Chemical Society.

intelligent response has become a heated topic in scientific and engineering fields.

In 2013, Ma et al. prepared a water-responsive artificial actuator that combined both a rigid matrix (polypyrrole) and a dynamic network (polyol–borate). The actuator could exchange water with the environment to induce its structural expansion and contraction, resulting in rapid and continuous locomotion [125]. The film actuator of this type as an artificial muscle could generate contractile stress up to 27 MPa, lift objects 380 times heavier than itself, and transport cargo 10 times heavier than itself. Meanwhile, by associating with a piezoelectric element, this film can be used as an energy generator driven by water gradients, capable of outputting alternating electricity with a peak voltage of ~1.0 V. Actuator driven by light possesses distinctive advantages, involving remote control, non-contact actuation, and high-level integration with other components as no

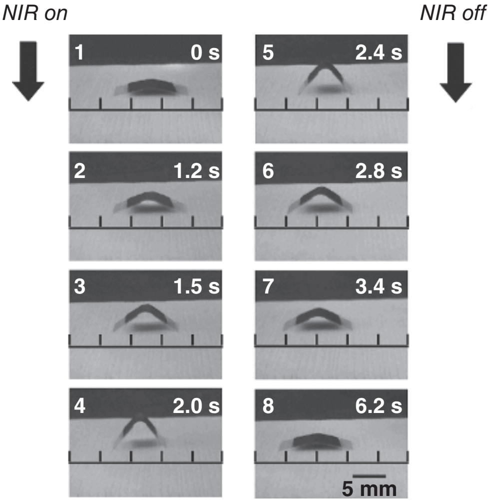

Figure 1.5 The bilayer actuator was fabricated by exploiting the photothermal conversion and humidity-sensitive properties of polydopamine-modified reduced graphene oxide (PDA-RGO). Therefore, an NIR light-driven walking device capable of performing quick wormlike motion on a ratchet substrate was built by connecting two polyethylene terephthalate plates as claws on opposite ends of the bilayer actuator. Locomotion of a walking device on a ratchet substrate when NIR light is periodically turned on (1–4) and off (5–8). The walking device moves from right to left. Source: Ji et al. 2014 [134]. Reprinted with permission of John Wiley and Sons.

wires or connections are required [132, 133]. Figure 1.5 presents a near-infrared (NIR) light-driven bilayer actuator capable of reversible bending/unbending motions [134].

1.5 Intelligent Environmental Nanomaterials

1.5.1 Overview

Given that there are inherent complexity and unpredictability and more particularly varying and even quite contrasting application scenarios in environmental problems, an ideal design of environmental nanomaterials should be proactive with AI.

These nanomaterials work as "nanomachines" that, based on their environmental conditions, make self-adjustments to maximize their possibility to achieve their desired goals [67]. Thus, these nanomaterials are "intelligent" based on the previous definition. The key to a successful design of intelligent nanomaterials is endowing the nanomaterials with proactive functionality that would lead to their change-oriented and self-initiated behaviors during their applications. Given the inherent complexity and stochastic nature of environmental problems, environmental nanomaterials can greatly benefit from an intelligent design, i.e. the ability to change its properties depending on the environmental conditions.

However, the development and application of intelligent nanomaterials in the environmental field is comparatively sluggish and still at a very nascent stage, although its popularity is growing. However, over the years, there are indeed some exciting exploratory works done in the intelligent environmental nanomaterials, many of which seemingly offer innovative and disruptive technologies.

1.5.2 Self-Propelled Nanomotors

Self-propulsion at nanoscale always represents a challenge. The latest self-propelled nanomotors can draw in fuel from surrounding medium and generate remarkable thrust and force through the ejection of gas bubbles from chemical reactions or fuel-free stimuli response like light [135–137], magnetic fields [138–140], electric fields [141–143], ultrasound [144, 145], etc. The self-propelled nanomotors that are able to autonomously transport remediation agent throughout polluted samples/media with ultrahigh speed and to penetrate inaccessible locations [146–148] have potential such environmental applications as water quality screening [149–154], removal and degradation of pollutants [155–158], removal of spilled oil [159–161], CO_2 scrubbing [162], etc.

1.5.3 Intelligent Gating Membrane

Conventional filtration membranes can be imparted with responsive gates that could self-regulate their permeation and species selectivity by intelligently switching their on/off states, which offer certain hope toward differential water quality or fit-for-purpose separation using the same separation membranes [163]. A number of photothermal materials, when combined with membrane distillation (MD), can harvest solar energy, generate heat locally only at the membrane and bulk water interface, and thus lead to considerably improved energy efficiency when compared with the conventional bulk water heating scheme of the conventional MD processes [164–168].

1.5.4 Switchable Oil/Water Separation

In the field of oil spill cleanup, intelligent materials show tremendous advantages over conventional methods. A bio-inspired intelligent membrane with super-wetting behavior can easily realize gravity-driven oil/water separation, which is of great importance to facilitate the oil spill cleanup, contributing to reduced response time and operation cost [169–171]. Moreover, the intelligent materials could be made to switch their oil and water wettability between two opposite sides in response to external stimuli and offer self-controlled, on-demand, and selective oil/water separation. The intelligent materials would allow for the recovery of the collected oils as well as the reuse of the separating materials, which the conventional materials largely fail to [170, 171].

1.5.5 Self-Healing Environmental Materials

Self-healing materials can self-recover their physical damages, self-restore their lost functions, and self-clean their contaminated surfaces. The healing property effectively expands the lifetime of the materials and reduces the overall operational cost. Recently, the self-healing materials have been preliminarily extended into environmental areas of water filtration membranes and to fouling resistance of oil/water separation materials with confirmed results at lab scales [172–175].

1.5.6 Molecular Imprinting

Imprinting has always been seen as the nature of some intelligent animals, which are capable to learn or "imprint" the characteristics of some external stimulus. However, the artificial materials can be also imparted into such an exciting gift to selectively recognize specific molecule, which is called "molecular imprinting." Molecular imprinting technique is to create the tailor-made and template-shaped binding sites with the memory of the shape, size, and functional groups of the specific template molecules. Molecularly imprinted materials can be prepared by self-assembly of the functional monomers around the template, followed by cross-linking them in the presence of template molecules. After removing the template molecules, the formed cavities complementary in size, shape, and chemical functionality to the template can selectively rebind the template molecules, just like the model of key and lock. In the environmental area, molecularly imprinted materials can selectively recognize and remove specific pollutants from contaminated water [176–184].

1.5.7 Nanofibrous Membrane Air Filters

The nanofibrous membranes offer a multitude of attractive features such as high specific surface area, high porosity, interconnected porous structure, more active sites, easy functionalization ability, and good mechanical behavior [26, 185–189]. Therefore, the nanofibrous membranes have great potential in air filters that are capable of $PM_{2.5}$ removal. The intelligently designed nanofibrous membrane air filters can have multifunctions, such as high filtration capacity, high transparency, large-scale production, high thermal stability, toxic gases removal, and even self-powering capability, which have an eminent application as personal protective equipment.

From these examples, it is clear that the design of intelligent environmental nanomaterials is meant to create things. Therefore, it is expected that new designs of intelligent environmental nanomaterials will continue to be produced.

1.6 Introduction to the Book Chapters

The purpose of this book is to provide a comprehensive review of the state-of-the-art intelligent environmental nanomaterials, with a particular focus on the design concepts and responsiveness of the materials.

We will present a broad collection of artificially intelligent materials and systems that are used in environmental problem solving. The book covers the following topics: (i) intelligent functional materials and responsive mechanisms (Chapter 2), (ii) designing filtration membranes with responsive gates

(Chapter 3), (iii) switchable wettability materials for controllable oil/water separation (Chapter 4), (iv) self-healing materials for environmental applications (Chapter 5), (v) emerging nanofibrous air filters for $PM_{2.5}$ removal (Chapter 6), (vi) self-propelled nanomotor for environmental applications (Chapter 7), (vii) molecular imprinting in wastewater treatment (Chapter 8), and (viii) emerging synergistically multifunctional and all-in-one nanomaterials and nanodevices in advanced environmental applications (Chapter 9). We hope this book would provide an inspiration for readers to further explore intelligent materials to solve environmental problems.

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