Section 3

New Technologies for Water and Wastewater Treatment

INTRODUCTION

The global population is increasing steadily and is expected to be about 8.2 billion by 2025. To meet the requirements of the swelling consumer society, industrial activities and associated waste generation are increasing rapidly. Water consumption and used water generation have also gone up significantly. However, especially in the Global South, water resources are dwindling both in terms of quality and quantity. Only a fraction of the wastewater generated is getting treated for various reasons. A water-secure ecosystem needs to be prepared to address the impending challenges linked to water stress.

Though many technologies are available for water and wastewater treatment, there is a need to develop more efficient and affordable technologies, to meet the growing demands in developing countries. The increasing occurrence of various emerging pollutants in water environments is driving the development of new technologies capable of abating such pollutants. As the used water quantity is increasing and most of it is going untreated in emerging economies, it is advisable to adopt low-cost nature-based technologies instead of capital and energy-intensive technologies. Recovery and reuse of water, nutrients, carbon, etc., from wastewater are essential to achieve circularity. In the context of circularity in waste management, one must also investigate such circular systems' sustainability.

The seven chapters of Section 3 present the new technologies developed for water and wastewater treatment in recent years. The chapter on **New technologies for drinking water** focuses on the application of nanotechnologies to produce sustainable and affordable clean water. Recalcitrant and hazardous pollutants pose a severe challenge to conventional water treatment technologies. The chapter on **Pulse power technology for the removal of emerging contaminants from water and wastewater** gives an overview of the possible application of pulse power plasma technology (PPT) for efficient and rapid degradation of a wide range of emerging water pollutants, including dyes, pesticides, toxic solvents, pharmaceuticals, and so on for the disinfection of water and wastewater. Nature has a significant capability to abate many of the pollutants. The chapter on **Application of engineered natural treatment systems for the pollution abatement** focuses on emerging contaminants in various wastewater (greywater, blackwater, and domestic wastewater) and their fate in the CWs. It also attempts to discuss the factors affecting the removal of pharmaceuticals and personnel care products (PPCPs), such as flow configurations of CWs, choice of substrate materials and plant species, and operating conditions. Carbon is a unique material with extensive use in various fields of science and engineering. Purification of water and wastewater is an early application of carbon, and now it has become an integral part of most household and community-based water treatment units. The chapter on **Carbon-based filters for water and wastewater treatment** provides a review of the evolution and application of carbon-based materials in water and wastewater treatment. The synthesis, removal mechanism, and factors affecting purification by carbon filters, along with the challenges and prospects of carbon-based filtration technology, are also briefly discussed in this chapter.

The focus in the wastewater management sector has considerably shifted from conventional treatment processes to resource and nutrient recovery approaches in recent years to promote a circular economy. The recovery of nutrients such as nitrogen, phosphorus, and carbon from wastewater is a sustainable approach to wastewater management and increases ecological and economic sustainability. The chapter on **Nutrient recovery from wastewater for circular economy** provides a comprehensive overview of existing conventional technologies used to recover nutrients from different nutrient-rich wastewater generated from domestic, industrial, and agricultural sources from anaerobic digestate. The chapter on **Water pollution abatement using waste-derived materials: a sustainable approach** provides a holistic approach to solid waste management by generating value-added materials and their potential application for water pollution abatement. High-performance water and wastewater treatment has become feasible with the development of innovative and advanced technologies, with potential impact on health and the environment. At the same time, they can help protect the environment and meet specific social needs in a more sustainable way. Hence, there is a need to select sustainable technologies. The chapter on **Technology evaluation for sustainability** discusses the need of evaluating the sustainability of such technology and processes, ways to conduct such studies, and examples of sustainable technologies employed in India. In summary, this section focuses on the important aspects and concepts that form the basis for emerging technologies for water and wastewater treatment.

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Chapter 11

New technologies for drinking water

*Ankit Nagar, Md Rabiul Islam and Thalappil Pradeep**

DST Unit of Nanoscience (DST UNS), and Thematic Unit of Excellence (TUE), Department of Chemistry, Indian Institute of Technology Madras, Chennai, India
**Corresponding author: pradeep@iitm.ac.in*

ABSTRACT

The global population is expected to be about 8.2 billion by 2025. This suggests a dire need to prepare for the ongoing and impending challenges linked with water stress to create a water-secure ecosystem. Densely populated countries such as India and China are enhancing the production of semiconductor, petrochemical, automotive, chemical, and pharmaceutical products, which are materially enriching. Simultaneously, our quickly diminishing resources are being further stressed by unprocessed industrial waste. Therefore, to build a sustainable and hygienic livelihood for all, it is imperative to be able to remove conventional and emerging pollutants from water in an affordable and energy-efficient manner. Nanotechnology-based solutions have made substantial contributions towards offering sustainable solutions in the clean water space. Although nanotechnology-based water purification has been an active research area for decades, it is yet to occupy a significant market share because of irregularities in the context of sensitivity, efficient operation in the field, and higher cost in comparison to traditional technologies. This chapter will highlight emerging technologies for drinking water which have also reached society in the form of easily operable devices, such as nanomaterial-incorporated handpumps, desalination devices, and atmospheric water generators.

Keywords: water harvesting, water purification, membranes, capacitive deionization, commercialization

11.1 INTRODUCTION

Due to the growing population, climate change, decline in water quality, and inadequate management, there is a significant imbalance between the demand and availability of freshwater globally. There are three categories of water pollutants: organic, inorganic, and biological (Khalil *et al.*, 2016). Many of them are hazardous to humans and ecology. As an example, arsenic is among the most toxic elements, as it is prevalent in excess of its acceptable limits in numerous places. Heavy metals like mercury, uranium, lead, chromium, copper, nickel, cadmium, and zinc are also extremely hazardous. In addition, high levels of phosphates, selenides, chromates, nitrates, sulphates, and oxalates are

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harmful and may affect the taste of water. Toxic organic pollutants include detergents, hydrocarbons, phenols, pesticides, organochlorine chemicals, and phthalates. Emerging contaminants include non-biodegradable pharmaceutical and personal care products (PPCPs) (Carballa *et al.*, 2007; Eregowda & Mohapatra, 2020; Kunduru *et al.*, 2017). Their sources are domestic and hospital waters containing pharmaceuticals, their packaging, and detergent additives. PPCPs in water are found in the concentration range of 0.001 to 1 ppb (Kunduru *et al.*, 2017). Consequently, typical treatment technologies employed in wastewater treatment facilities are ineffective against such contaminants. The combustion of fossil fuels also generates polycyclic aromatic hydrocarbons (PAHs), which are another category of water contaminants. Due to their limited solubility and high affinity for particles, their concentration in water is low. The PAHs found in high amounts in drinking water are pyrene, phenanthrene, fluranthene, and anthracene (Mojiri *et al.*, 2019). Often, faeces are a source of microbial contamination of water. Water treatment plants, manufacturing facilities, and hospitals are the root drivers of such contamination. It has been demonstrated that urban activities increase the concentration of infections. Natural organic matter (NOM) is among the most important factors to comprehend water quality and select the treatment method in such circumstances.

The rapidly rising global population suggests a dire need to prepare for the ongoing and impending challenges linked with water stress to create a water-secure ecosystem. Densely populated countries like India and China are enhancing the production of semiconductor, petrochemical, automotive, chemical, and pharmaceutical products, which are materially enriching. Simultaneously, our quickly diminishing resources are being further stressed by unprocessed industrial waste. Therefore, to build a sustainable and hygienic livelihood for all, it is imperative to be able to remove conventional and emerging pollutants from water in an affordable and energy-efficient manner.

To ensure good public health and hygiene, it is important to remove both traditional and emerging toxins from water at a reasonable cost and with low energy input, ideally with no negative environmental impact. Conventional purification techniques include adsorption, filtration, ultraviolet irradiation, desalination, disinfection, and coagulation, whereas emerging nanotechnology-enabled purification techniques involve the use of carbon nanocomposites, metal or metal oxide nanoparticles (NPs), nanoporous ceramics, and other nanomaterials.

Although nanotechnology-based water purification has been an active research area for decades, it is yet to occupy a significant market share because of irregularities in the context of sensitivity, efficient operation in the field, and higher cost in comparison to traditional technologies. This chapter will highlight emerging technologies for purifying drinking water which have also reached the society in the form of easily operable devices, such as nanomaterial-incorporated handpumps, desalination devices, and atmospheric water generators (AWGs).

11.2 ADSORPTION-BASED PURIFICATION TECHNOLOGIES

The removal capacity of adsorbents is dependent on their density, porosity, external and internal surface area, pore-size distribution, surface structure, functionalization, and process variables such as temperature, pH, and contact time (Teodosiu *et al.*, 2018). Engineered nanomaterials (ENMs) have been used to generate diverse organic and inorganic adsorbents for the efficient remediation of environmental pollutants with varying molecular sizes, hydrophobicity, and speciation behaviour (Qu *et al.*, 2013). These ENMs consist of nanoscale metal and metal oxides of Fe, Ti, Ag, Zr, and Zn; carbonaceous materials such as carbon nanotubes and their derivatives, fullerenes, graphenic materials, and activated carbon; and magnetic nanoparticles involving Fe, Ni, Co, their oxides and alloys, and core–shell nanoparticles (Teodosiu *et al.*, 2018; van der Hoek *et al.*, 2014).

Composite materials are prepared by combining a matrix (the continuous phase) with reinforced materials (dispersed). Nanocomposites consist of nanoparticles integrated with a variety of functionalized materials, such as multiwall CNTs (MWCNTs), activated carbon, graphene oxide, polymeric or biopolymer fibres, clays, zeolites, and so on (Peng *et al.*, 2020). Their unique characteristics, such as high durability, high stiffness, high strength, corrosion resistance, low density, and heat resistance prove them advantageous over other materials. For instance, Al_2O_3/MWCNTs composite has been identified to remove Cd^{2+} and trichloroethylene from polluted water, whilst TiO_2-zeolite nanocomposites are known to remove industrial dyes from wastewater (Kamali *et al.*, 2019; Saini, 2015). AMRIT, which stands for Anion and Metal Removal by Indian Technology, is supplying arsenic-free water to more than 1.2 million people per day; it contains innovative nanostructured materials with high adsorption capacities for arsenite and arsenate ions in water in the field (Nagar & Pradeep, 2020). The composite's inherent structure with metastable 2-line ferrihydrite enclosed in chitosan biopolymer cages enables the formation of efficient adsorption sites, which are responsible for the composite's unprecedentedly high capacity (Kumar *et al.*, 2017). Similarly, nanochemistry is utilized by filters comprised of noble metal nanoparticle-coated metal oxides to remove pesticides from drinking water (Nair & Pradeep, 2003; Nair *et al.*, 2003). This technique had already reached more than 7.5 million people till 2016, the most recent year for which implementation data was obtained. It also led to a decrease in pesticide levels in certain regions of India from over 20 times above the safety standard to significantly below the prescribed limit (Sreeprasad *et al.*, 2011). In 2013, Sankar *et al.* developed an antibacterial composition comprised of a composite of aluminium oxyhydroxide and chitosan containing silver particles with a diameter of 10–20 nm (Sankar *et al.*, 2013). These solutions do not require energy and are affordable even in the poorest regions of the globe. The sustainability of sorbents was improved by constructing composites with reinforced micro- and nanocellulose, including active nanoscale adsorption sites that demonstrated greater absorption and excellent mechanical stability (Mukherjee *et al.*, 2018, 2019).

11.3 MEMBRANES

In comparison to traditional purification technologies such as coagulation and flocculation, membrane filtration is comparatively more robust and diverse, and provides crucial benefits in water and wastewater treatment applications. For instance, nano-TiO_2 filtration membranes do not undergo fouling and provide high filtration efficiency at high water flux (DelaiáSun, 2010). Nanoporous zeolites, nanoporous polymers, and attapulgite clays have a binding capacity 100,000 times more than that of typical activated carbon (Singer *et al.*, 2005). Pure silica particles coated with an active material are significantly more cost-effective at removing harmful compounds and microorganisms (Majewski & Chan, 2008). Conventional water treatment plants have been able to effectively remove biological pollutants with CNT-based technology, hence resolving the issue of maintaining the biostability of treated water in the distribution lines (Upadhyayula *et al.*, 2009). These membranes have been identified as promising replacements for RO membranes in the context of desalination. The large-scale fabrication of CNT membranes is becoming more cost-effective, and their entry into the desalination market is anticipated within the next five to six years, as scaling-related challenges are presently being addressed (Technology and Action for Rural Advancement (TARA), 2012). Numerous methods have been investigated as potential substitutes for traditional RO membranes in desalination and water recycling applications. Nanocomposite membranes have 1–3 times higher water permeability but the same rejection as commercial RO membranes, and the former are multifunctional with antibacterial and photoreactive properties (Technology and Action for Rural Advancement (TARA), 2012). The nanotechnology-based filtration devices are inexpensive, transportable, user-friendly, extremely effective, and have exceptionally large surface areas. Commercial applications of nanomaterials in the water industry include MoS_2 nanosheets for disinfection, CNF films for antimicrobial activity, silver nanobrushes for humidity harvesting, and ferrihydrite for heavy metal removal (Nagar & Pradeep, 2020). It is anticipated that the manufacturing of nanomaterials and their composites will increase, due to the growing need to generate clean water in a time- and energy-efficient manner.

11.4 CAPACITIVE DEIONIZATION

Capacitive deionization (CDI) is an emerging technology that involves the adsorption and desorption of ions on an electrode's surface by applying a DC low potential energy (1.2–1.8 V) across a pair of porous carbon electrodes. It is thus both cost-efficient and energy-efficient compared to other existing desalination methods. When a flowing water stream is passed across a CDI system, anions and cations are transported towards oppositely charged electrodes and get adsorbed on them. In this manner, deionized and 'potable' water is generated from saline or brackish water. The adsorbed ions are subsequently removed from the electrode by reversing the polarity, thereby regenerating the electrode surface for further reuse (Porada *et al.*, 2013). Thus, clean water can be generated by repeating the adsorption and desorption cycles continuously.

Numerous carbonaceous materials and their composites have been utilized as CDI electrodes due to their high surface area, suitable pore size, and high salt adsorption capacities (Porada *et al.*, 2013). Different graphenic materials, including activated carbon (AC), activated carbon nanofibre (ACF), graphene-like nanoflakes, reduced graphene oxide (rGO), carbon nanotubes (CNT), graphene–CNT composites, reduced graphene oxide-ACF, 3D-graphenic materials, sponge-templated graphene, graphene–Fe_3O_4, graphene chitosan-Mn_3O_4, rGO-activated carbon (AC) composites, functionalized graphene nanocomposite, and so on, have been used as CDI electrodes (Figure 11.1) (Islam *et al.*, 2021; Porada *et al.*, 2013). The adsorption capacities of the graphenic composites CO_2-activated rGO, graphene/carbon nanotubes, sulphonic functional graphite nanosheets, MgAl-Ox/graphene nanohybrids, SO_3H/NH_2 functionalized-graphene/AC, graphene sponges, and 3D-graphenic material were found to be 6.26, 1.4, 8.6, 13.6, 10.3, 14.9, and 14.7 mg/g, respectively, when given an input of 500 ppm NaCl solution (Gupta *et al.*, 2019; Islam *et al.*, 2021; Porada *et al.*, 2013). Emerging CDI electrode materials (i.e., activated carbon, ordered mesoporous carbon, carbon aerogel, other carbon

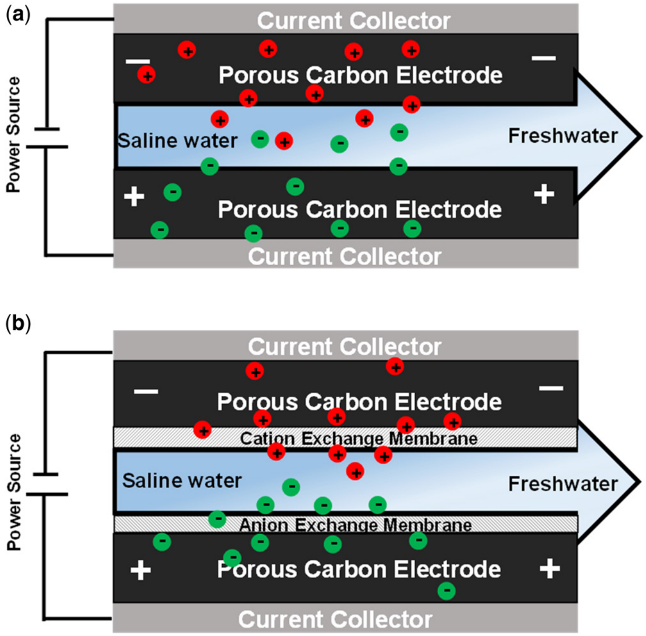

Figure 11.1 A schematic showing the working principle of (a) CDI and (b) MCDI during the electro-adsorption process. (*Source*: Modified and redrawn from Porada *et al.*, 2013).

derivatives, carbon nanotubes, graphene and graphene-based composites, and other two-dimensional materials such as MXenes, MOFs, COFs, MoS_2, etc.) have recently been studied in laboratories all over the world.

The main objective of CDI technology is to implement energy- and cost-efficient processes for water purification. Thus, the major tasks for the advancement of CDI technology are to improve the electrode architecture and synthesize suitable new electrode materials. The desalination capacity of the electrodes depends upon their material and the initial salt concentration. Mostly, carbon materials and other modified carbon materials integrated with novel materials have been used in electrode fabrication to enhance performance (Gupta *et al.*, 2019; Islam *et al.*, 2021). Electrode materials should have high electrical conductivity, high electrochemical stability over different pH, high specific surface area, and suitable voltage ranges (~1.2–1.8 V). Additionally, the pore size, total pore volume, and pore connectivity of the active electrode materials are the main parameters that affect electro-adsorption capacity. Furthermore, other electrode parameters, such as exceptional wetting behaviour, high bio-inertness to prevent bio-fouling, electrode stacks, input water flow rate, electrode characteristics, the lifetime of the electrodes, the process's cost-efficiency, and suitable porosity of the electrode materials, are significant factors to be considered while designing an efficient CDI technology (Gupta *et al.*, 2019; Porada *et al.*, 2013).

CDI has been extensively explored for brackish water desalination because it is considered to be energetically competitive with reverse osmosis (RO). The quanta of energy consumed by different CDI are less than those of a comparable RO in identical conditions. Energy consumed by MCDI could be lower than that of RO. It has been reported that the energy requirement of MCDI is 2–3 times lower than RO's for brackish water desalination (under the same conditions, i.e. flux (J_w) = 10.0 L/m^2/h, salt rejection (R_{salt}) = 80%, water recovery (WR) = 80%, and a feed salinity of 34.22 mM (2 g/L)). It was also observed that under the same conditions, the energy consumption of MCDI (~0.4 kWh/m^3) is less than that of CDI (~2.5 kWh/m^3) (Porada *et al.*, 2020). Furthermore, it was seen that for these desalination conditions (flux (J_w) = 11.9 L/m^2/h, salt rejection (R_{salt}) = 80%, water recovery (WR) = 93.5%, and a feed salinity of 40 mM), the energy consumption of RO (~0.5 kWh/m^3) is higher than of MCDI (~0.4 kWh/m^3) (Porada *et al.*, 2020). The cost of desalination using our CDI prototype was calculated to be approximately 3–4 paisa (US$0.00040 to 0.00054) per litre.

With regard to the commercialization of CDI technologies, Voltea was the first US-based recognized CDI Company founded in 2006. Ionic Engineering Technology Pvt. Ltd. in India, INNODI and NGen from India, Idropan Dell'Orto in Italy, and PowerTech Water in the United States have recently entered the CDI market. Atlantis Technologies claims that their product removes up to 99% of impurities and can reduce water salinity up to 100,000 ppm with reduced maintenance. Idropan Dell'Orto, founded by Tullio Servida, has products named Plimmer 4G Alpha and Delta, which claim to reduce total dissolved solids concentration (TDS) of 2000 μS by 70%–85% in a single pass and 85%–95% in a double pass. They have international partners including ECOWATER in the United States, EUROWATER in Denmark, AquaSphere in India, and others in Australia, Tunisia, Saudi Arabia, and Russia. INNODI is a new start-up from IIT Madras, which was established in 2017, and launched its first domestic CDI product in the market in 2017. Moreover, IIT Tirupati incubated a CDI company, NGen, which was established in 2022.

11.5 ATMOSPHERIC WATER HARVESTING

Atmospheric humidity is an abundant source of freshwater that can be easily harvested using a sustainable energy source such as solar, wind, or geothermal energy. This section provides a comprehensive and critical overview of current research and prospects in the area of atmospheric water harvesting (AWH). From an application standpoint, the greatest challenge is to build a humidity harvester that can produce sufficient freshwater across a wide range of weather conditions with minimal energy footprint. Therefore, several harvesting techniques, such as radiative cooling, solar distillation, and sorption-based water collection, are examined and explored in terms of their capture materials, system designs, and thermodynamic cycles. In addition, we comprehensively evaluate the performance of recently reported atmospheric water harvesters. We also explore four critical issues that limit cost-effectiveness and offer prospective solutions.

Over the past two decades, AWH technologies have made considerable advancements. However, broad-spectrum research on atmospheric water harvesters is limited and system integrations have been insufficiently studied. It is anticipated that additional research will address these challenges in order to facilitate efforts to translate decades of research on AWH into concrete benefits in our daily lives.

Despite the considerable value of the potentially recoverable freshwater globally, there are currently very few AWH devices in commercial operation. Any feasible AWH method must satisfy the following five key criteria: It must be efficient, inexpensive, scalable, operational in a broad range of weather conditions, and reliable enough to function for an entire year. At present, none of the commercially available AWGs meet all five of these criteria. As per thermodynamics, this is primarily due to the process's energy inefficiency.

The practise of collecting water from fog dates back millennia (Beysens & Mulumouk, 2000). Humans appear to have considered dew as a source of potable water since the beginning of time. Research on modern AWH technologies has continued, and a variety of atmospheric water-collection techniques, which are primarily utilized in arid and semi-arid regions, have been investigated. AWH technologies can be split into three distinct groups based on the type of airborne water: artificial rain collection (Bruintjes, 1999; DeFelice & Axisa, 2017; Wang *et al.*, 2016), fog water collection (Fessehaye *et al.*, 2014; Klemm *et al.*, 2012), and dew water collection (Khalil *et al.*, 2016). Weather manipulation, also referred to as cloud seeding, may produce large precipitation, but only in the troposphere, where clouds with high water content congregate. There is no proof that the same operation can be accomplished at ground level in a routine and controlled manner (Bruintjes, 1999; DeFelice & Axisa, 2017). In certain arid places, fog collecting, as opposed to weather modification, is a proven technology for obtaining considerable quantities of drinkable water. By blowing humid ambient air over a cooled surface, dew can be collected, and liquid water is produced if the surface temperature is below the dewpoint temperature of the air (Khalil *et al.*, 2016).

Fog harvesting technologies are viable and accessible, and can alleviate the dearth of potable water that often plagues arid coastal regions. Ordinarily, fog water is collected by installing a rectangular mesh orthogonal to the direction of wind flow, which captures fog droplets. When exposed to a foggy atmosphere, wind-borne water droplets push against the mesh and become trapped. The droplets grow by coalescence until they become large enough to drop by gravity, and a gutter carries the water to a storage tank. The greatest issue for fog collection today is its low efficiency, which is defined as the ratio of water that enters the collector's gutter to the liquid water flux perpendicular to the collector's mesh. The poor efficiency is primarily due to droplet pinning, which has been overcome at lab scale using superhydrophobic surfaces. However, such modified surfaces are yet to prove their durability by undergoing field tests.

While such 'passive' fog harvesters were effective, the amount of water they produced was insufficient in moderate-humidity weather. Therefore, active water harvesting was investigated, in which AWGs utilized the Peltier effect or a refrigeration cycle to lower the surrounding air's temperature below the dew point to facilitate condensation (Tu *et al.*, 2018). This permitted the collection of atmospheric water in water-scarce locations to overcome the limitations of long-distance freshwater transport and heavily polluted groundwater and surface water bodies. While several commercial devices are already available to consumers, research is ongoing to develop energy-efficient condensing surfaces for use in regions with relative humidity (RH) below 40%.

Adsorption-based harvesting has emerged as a viable alternative to systems that rely on condensation. In this technique, sorption of water vapour occurs during the night, followed by desorption in a closed chamber using sunlight in the daytime (Figure 11.2). During desorption, as soon as the enclosure

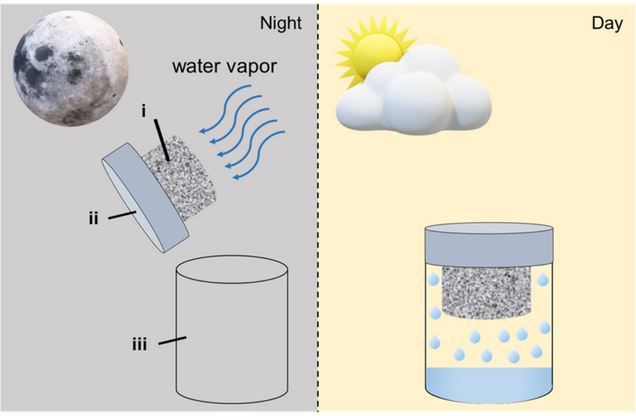

Figure 11.2 An illustration depicting the working of a sorption-based water harvesting device, wherein the material (i) integrated with the cap, (ii) of a container, (iii) is allowed to adsorb humidity at night (left panel), and desorb the humidity in the closed transparent container in the morning.

saturates with humidity, the desorbed vapour begins to condense on the chamber walls. Although typical desiccants such as zeolites and silica gel absorb humidity, their poor sorption kinetics, low absorption capacity, and high-energy requirement for regeneration prevent their practical application. Several intriguing alternatives, such as metal-organic frameworks (MOFs), have variable pore size and a high surface area. A kilogram of $Zr_6(OH)_4(fumarate)_6$, for instance, has the capacity to gather 2.8 L/day at 20% RH, thereby encouraging additional research on the development of molecular materials for water harvesting in deserts (Kim *et al.*, 2017). The incorporation of these MOF NPs into thermosensitive polymers, such as poly(N-isopropylacrylamide), has permitted harvesting at temperatures closer to the ambient temperature (Yilmaz *et al.*, 2020). Improving the absorption capacity by adding hydrophilic ligands into nanopores, minimizing the energy required for desorption, accelerating sorption kinetics, and maintaining cyclic stability for several hundreds of sorption cycles are current research priorities in the subject area.

11.6 EMERGING TECHNOLOGIES FOR WATER PURIFICATION

Carbon has been the primary component of water treatment materials since prehistoric times. In 3750 BC, Egyptians and Sumerians utilized wood charcoal to purify water (Patrick, 1995). Activated carbon has been a crucial component in water-cleaning applications since the 1940s. Carbon nanotubes (Liu *et al.*, 2013), carbon nanofibres (Shen *et al.*, 2016; Zhang *et al.*, 2022), and graphene-based materials (Jiang *et al.*, 2016; Li *et al.*, 2019), have been used in water treatment techniques like membrane-based separation, disinfection, and adsorption. Recent years have seen an influx of novel materials into water treatment, and their usage in combination with carbon will present fresh opportunities. The sensing and treatment applications of materials science for clean water technologies remain fascinating.

It is possible to incorporate developing nanomaterials-based purification methodologies into commercial water filtration systems and products present in the market. Several nanomaterials, such as carbon nanotubes, cellulose-based nanomaterials, aquaporins, and MXenes, have shown exceptional performance at the laboratory scale and have been effectively mass produced and incorporated into products as well (Nagar & Pradeep, 2020). CNTs, for instance, are among the most commonly used nanomaterials for purifying applications (Smith & Rodrigues, 2015). CNT-based purification is effective at eliminating inorganic, organic, and biological water pollutants. Nanomaterials-based membranes are currently manufactured by multinational corporations such as GEA Group ('GEA

Group,' n.d.), Applied Membranes ('Applied Membranes, Inc.,' n.d.), Inopor ('Inopor,' n.d.), Koch Separation Solutions ('Inopor,' n.d.), and Alfa Laval ('Alfa Laval India Pvt. Ltd.,' n.d.).

A future with clean water that is environmentally, socially, and economically sustainable would include the development and execution of water technologies, laws, and practices that ensure accessibility to clean and safe water for everyone. It is crucial to implement policies and practices that result in reduced water footprints and efficient water reuse. In addition, water resources must be coherently managed by establishing a balance between the consumption and reuse of groundwater, surface water, and recycled water. This is only possible with the involvement of local communities whose demands and perspectives are taken into account. Providing affordable clean water to marginalized communities can only happen with continuous investments on research and development in emerging water technologies.

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