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Emerging opportunities for nanotechnology to enhance water security

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No other resource is as necessary for life as water, and providing it universally in a safe, reliable and affordable manner is one of the greatest challenges of the twenty-first century. Here, we consider new opportunities and approaches for the application of nanotechnology to enhance the efficiency and affordability of water treatment and wastewater reuse. Potential development and implementation barriers are discussed along with research needs to overcome them and enhance water security.

The importance of clean water for global health and economic development cannot be overstated. Providing affordable water safely and universally is a grand challenge of mounting severity as the demand increases with a growing population[1]. Freshwater scarcity is exacerbated by climate change[2], with more frequent droughts and saline intrusion in coastal areas, and by water pollution, which is becoming more complex and more difficult and costly to treat[3–5]. Currently, over 650 million people worldwide lack access to safe water[6], and one child under the age of five dies every two minutes due to preventable diarrheal diseases caused by poor water quality and inadequate sanitation[7,8].

Public and environmental health are threatened by a wide variety of water pollutants, including naturally occurring contaminants and synthetic chemicals. Common 'natural' pollutants include pathogenic microorganisms and cyanotoxins produced by harmful algal blooms, as well as geogenic heavy metals and metalloids (for example, arsenic), which can be removed by some basic water treatment processes such as filtration/disinfection and precipitation, respectively (Fig. 1). More advanced treatment systems also target priority pollutants that are not easily detectable by our senses, but can cause chronic toxicity, ranging from disruption of fertility to cancer. These pollutants include pesticides, volatile organic compounds (for example, industrial solvents) and contaminants of emerging concern such as pharmaceuticals and personal care products that disrupt endocrine systems or cause other effects.

Priority pollutants and emerging contaminants are frequently detected in drinking water sources, sewage treatment plant effluents and natural waters at levels that may jeopardize public or ecosystem health. This fact underscores the need for technological innovation and capacity vitalization of marginally effective water treatment infrastructure. For example, multidrug-resistant bacteria (also known as superbugs) are breeding in (and being discharged from) some wastewater treatment plants[9], and a review on antimicrobial resistance (set up by UK Prime Minister David Cameron in 2014) found that by 2050, superbugs could claim the lives of 10 million people each year and cost the global economy hundreds of trillions of dollars in health care and reduced productivity[10]. Improved water treatment and pollution control can not only significantly mitigate health care costs and loss of productivity, but also go hand-in-hand with economic development and socioeconomic capacity[11,12] (Fig. 1). Technological innovation is also important to alleviate the financial burden of maintaining and operating aging drinking water and wastewater treatment plants.

In addition to regulatory mandates for water pollution control and economic drivers for reliable and inexpensive access to clean water, there is a growing need for more affordable desalination and wastewater reuse. This would enable utilization of a broader range of unconventional water sources (for example, brackish water, sea water, wastewater and stormwater) to enhance water security (which UN Water defines as "the capacity of a population to safeguard sustainable access to adequate quantities of and acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability"[13]).

The twenty-first century has brought to the water sector exciting new opportunities associated with nanotechnology. Through control over material size, morphology and chemical structure, nanotechnology offers novel materials that could endow some water treatment systems with exceptional catalytic, adsorptive, optical, quantum, electrical and/or antimicrobial properties that enhance treatment cost-efficiency. Though nanotechnology is unlikely to be a panacea for water purification, engineered nanomaterials (ENMs) may empower next-generation multifunctional distributed treatment systems that are relatively small and easy to deploy, while reducing water contamination, water losses and energy requirements associated with supplying water over long distances through large and leaky distribution systems[14]. Distributed nanotechnology-enabled treatment systems may also offer high capacity and flexibility to treat challenging waters that would otherwise require large and complex treatment trains.

ENMs may also facilitate the combination of multiple treatment functions (for example, adsorption, catalytic degradation and disinfection) in multifunctional advanced materials that simultaneously target a vast array of pollutants that require different removal processes because of their different physicochemical properties. This is important to simplify treatment trains, reduce their footprint and enhance treatment efficiency. Nanotechnology could also help transform some traditional energy-, chemical- and infrastructure-intensive technologies that currently treat municipal water to marginally safe levels (Fig. 1). A move towards more advanced catalytic and physical processes would decrease costs associated with energy requirements and waste residual management. Finally, ENMs can endow treatment systems with unprecedented selectivity to remove specific pollutants and help match the treated water quality to the intended use (for example, domestic use including drinking, landscape irrigation or industrial cooling).

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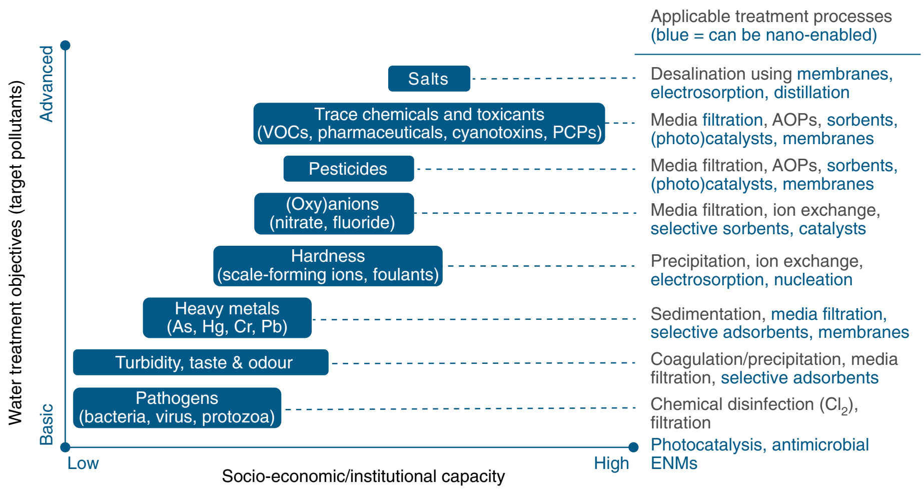

Fig. 1 | Water treatment priorities and processes that can be enhanced by nanotechnology. Water treatment generally requires removal of multiple pollutants, ranging from pathogens (basic treatment, bottom left) to trace chemicals and salts (advanced treatment, top right). The level of treatment generally increases with socioeconomic and institutional capacity. Basic treatment often relies on coagulation/precipitation and/or media filtration of colloidal and other suspended matter, followed by disinfection. Advanced technologies (for example, membrane filtration, adsorption, and catalytic or electrochemical oxidation) are increasingly used as polishing steps to remove carcinogenic and endocrine disrupting chemicals that may bypass traditional treatment processes, as well as other toxicants such as volatile organic compounds (VOCs), personal care products (PCPs) and cyanotoxins. Nanotechnology offers unprecedented opportunities to enhance a wide variety of existing treatment processes that occasionally are marginally effective (blue text), and create entirely new treatment processes for various niche applications. AOPs, advanced oxidation processes.

Such "fit-for-purpose treatment"[14] would avoid wastage of treatment capacity on non-problematic constituents, which is conducive to lower treatment costs.

In general, nanotechnology-enabled water or wastewater treatment should be considered when existing technologies do not meet current or future water-quality standards, when it enhances the cost-effectiveness of water purification (for example, faster pollutant removal with lower energy and treatment materials consumption), or when multifunctional high-performance treatment systems with small footprints (for example, at point-of-use or off-grid locations) are required. Here, we address emerging opportunities and sustainable approaches for the application of ENMs for water treatment and reuse. Potential opportune niches and development and implementation barriers are discussed along with research needs to overcome these barriers.

Opportunities for nanotechnology in water treatment

Several ENM properties can be tailored to enhance various water treatment processes. Examples include designing nanostructured photocatalysts with surface chemistries, band-edge energies and bandgaps that enable selective binding and degradation of targeted contaminants using sunlight[15,16] (though increasing quantum yields and catalyst stability while decreasing material costs is required to enable feasible application); using nanostructured carbons with high electronic conductivity and hierarchical porous structure as electrodes for electrosorption/capacitive deionization to enhance desalination performance[17,18]; engineering the morphology and surface area of electrodes through use of nanotube arrays[19] or three-dimensional macroporous structures[20] to improve kinetics and mass transfer in electrochemical oxidation[21]; and controlling the size of magnetic nanoparticles to enhance superparamagnetism for low-energy separation and recovery with magnets[22]. Both existing and next-generation water treatment processes could be enhanced by nanotechnology as discussed below.

Enhancing existing treatment processes. Nanotechnology offers new opportunities to enhance both basic and advanced water treatment processes (Fig. 1). For example, water filtration through sand beds is used worldwide as a cost-effective approach to remove colloids and other suspended solids (including bacteria). However, this process does not remove dissolved toxic metals and metalloids such as arsenic. A simple approach to overcome this limitation is to coat the sand with nanoscale magnetite[23], which enhances adsorption capacity for both As(III) and As(V) and facilitates efficient magnetic separation of any magnetite fines that elute during filter operation or regeneration[23]. Similarly, adsorbents such as activated carbon— which is commonly used to remove trace organic contaminants—are not efficient in removing polar organic pollutants (for example, pharmaceuticals and textile dyes) and (oxy)anions (for example, those from arsenic). However, incorporation of selective nanoadsorbents at small quantities in conventional adsorption media could significantly enhance performance and extend the range of contaminants removed by these units[24–27].

Another process that can be enhanced by nanotechnology is photocatalytic oxidation of priority organic pollutants, which also accomplishes disinfection. This advanced oxidation process suffers from inefficient utilization of photocatalytically generated reactive oxygen species (ROS, such as hydroxyl radicals, superoxide and singlet oxygen), which are rapidly scavenged by non-target water constituents (for example, natural organic matter). Through electrostatic attraction of pathogenic microorganisms (as shown with aminofullerenes)[28,29] or sorption of target organic pollutants near photocatalytic sites (as demonstrated with photocatalytic polymeric mats)[30], engineered nano-photocatalysts can significantly enhance treatment selectivity and ROS utilization efficiency. Selective adsorption of contaminants onto photocatalysts can be achieved by engineering nanoparticles with high-index crystal facets[31] or using surface-modification strategies[32].

Nanotechnology can also enhance membrane separation processes for water purification and desalination. One approach is to embed catalytic nanomaterials in the membrane selective layer to degrade organic foulants on light irradiation or applied voltage, thus reducing organic fouling[33]. Nanoparticles can also modify the surface wettability of membranes, altering the surface energy

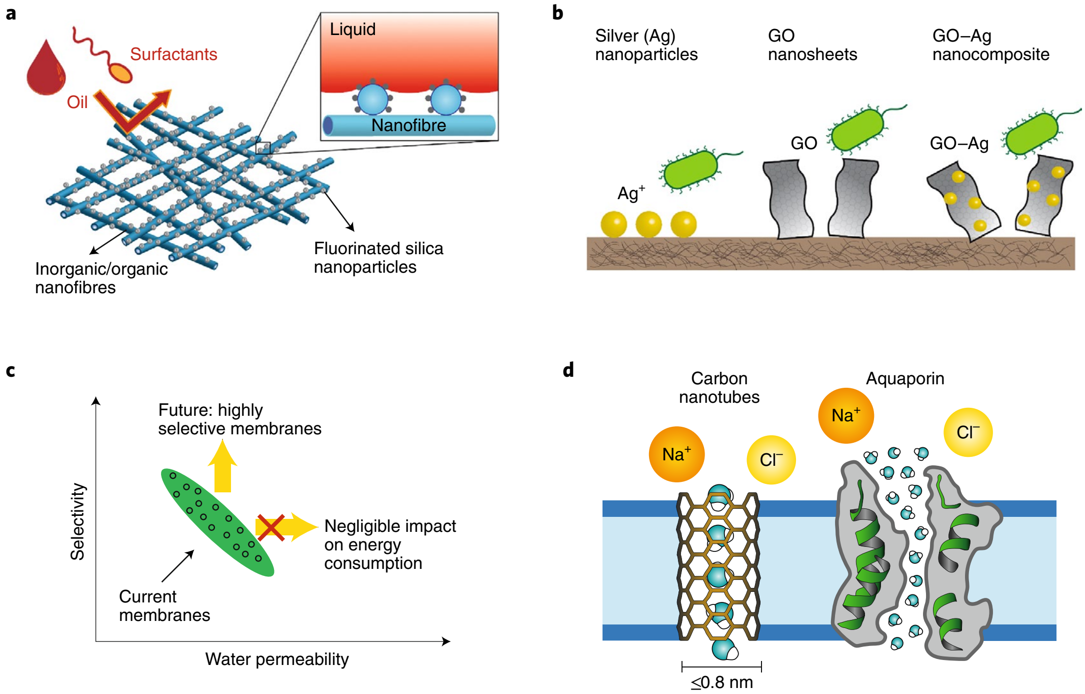

Fig. 2 | Nanotechnology-enabled membranes for water treatment. a, A microporous membrane featuring nanofibres coated with fluorinated nanoparticles to create a membrane with a multilevel, re-entrant structure and low surface energy. Membranes with such surface properties are suitable for membrane distillation desalination as they exhibit omniphobicity and resist wetting by both water and oil. **b**, Membranes with biocidal nanomaterials to control biofouling: silver nanoparticles that release silver ions for bacterial inactivation (left), graphene oxide nanosheets that inactivate microorganisms via direct contact (middle) and GO–Ag nanocomposites that combine both mechanisms for biofilm control (right). **c**, Current desalination membranes are constrained by the permeability–selectivity tradeoff: an increase in water permeability comes with an even greater increase in salt permeability. Next-generation desalination membranes will be highly selective (that is, low permeation of solutes) and will not benefit from water permeabilities higher than those of current desalination membranes. **d**, Next-generation highly selective membranes incorporating highly selective discrete channels (carbon nanotubes or aquaporins) in an impermeable thin film. Single-walled carbon nanotubes with diameters smaller than 0.8 nm or integral membrane proteins, aquaporins, can completely reject salt while enabling adequate water permeability. Panels adapted from: **c**, ref. [40], American Chemical Society; **d**, ref. [49], Springer Nature Ltd.

and enabling new applications. For example, coating the surface of hydrophobic microporous membranes with nanoparticles to form a re-entrant structure (that is, a nanoscale architecture with increased air to solid ratio) can result in an omniphobic surface (Fig. 2a)[34]. Such omniphobic membrane surfaces resist wetting by both water and low-surface tension contaminants (for example, surfactants and oil), and thus can be applied to treat challenging high-salinity wastewaters (for example, oil and gas produced water) by membrane distillation (MD).

Enabling next-generation treatment processes. Enhancing water security may require unprecedented versatility to tap unconventional sources of varying water quality and flow rate (for example, stormwater, brackish groundwater, grey water or sea water), as well as the flexibility to accommodate diverse treatment objectives for different intended uses. Next-generation water treatment systems will likely include interchangeable modules that are adaptive and highly efficient at removing priority pollutants. Several nanotechnology-enabled materials and technologies could be available for integration in such modules, including selective adsorbents[35], solar-thermal processes enabled by nanophotonics to desalinate water with MD[36], fouling-resistant membranes with embedded ENMs that allow for self-cleaning and self-repair[37]; capacitive deionization with highly conductive and selective electrodes to remove multivalent ions that precipitate or cause scaling[38]; rapid magnetic separation of heavy metals and other inorganic pollutants using superparamagnetic nanoparticles[22]; nanostructured surfaces that discourage microbial adhesion and protect infrastructure against biofouling and corrosion[39], and sensors to assess treatment performance and to trigger alarms if contaminant breakthrough occurs. Examples of such innovations are discussed below.

Fouling-resistant and highly selective membranes. Fouling is a major obstacle for efficient operation of membrane systems. Fouling increases energy consumption, requires the frequent use of chemicals for cleaning, shortens membrane life time and limits the water recovery of desalination processes[33,40]. The main types of membrane fouling encountered in membrane systems are organic fouling, biological fouling and inorganic scaling by sparingly soluble salts[33]. Some unique properties of nanomaterials (for example, reactivity, hydrophilicity and small size) can be used for membrane fouling control.

Desalination and water treatment membranes are relatively hydrophobic and thus are prone to fouling by adsorption of organic substances, which significantly hamper system performance[40]. Binding of superhydrophilic nanoparticles to the surface of polyamide desalination membranes or polyvinylidene fluoride ultrafiltration membranes can significantly reduce organic fouling by providing a thick hydration layer that resists the adsorption of organic foulants[33]. A recent study, however, shows that grafting a nanoscale brush layer of zwitterionic polymers to the polyamide selective layer of desalination membranes can achieve higher organic fouling resistance than membranes modified with superhydrophilic nanoparticles[41]. Similarly, for ultrafiltration membranes,

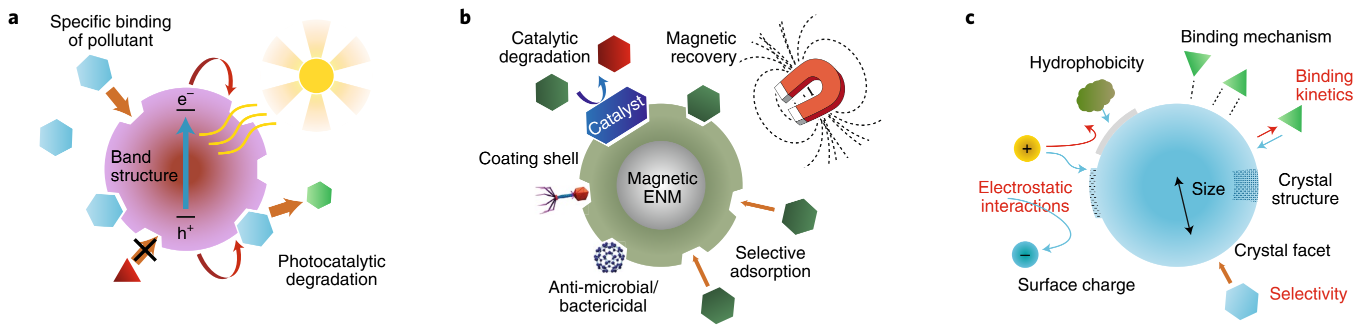

Fig. 3 | Multifunctional nanoparticles. a, Bait-hook-destroy concept for selective removal of pollutants via electrostatic or hydrophobic attraction which results in higher pollutant concentration for faster destruction by photocatalysis, for example by photo-oxidative degradation or by photoreduction. **b**, Superparamagnetic nanoparticles can be coated with a stabilizing shell and decorated with catalysts, antimicrobial or antibacterial particles, or selective adsorption binding sites for contaminant removal or degradation followed by facile ENM recovery using magnetic recovery. **c**, Selective sorbents depicting features that can be tuned to enhance water treatment, such as: (i) the nanoparticle size can be decreased to expose more surface area and sites for sorption; (ii) the nanoparticle crystal structure and exposed crystal facets can be controlled to improve selectivity for sorption; (iii) the surface structure and interfacial properties such as hydrophobicity/hydrophilicity or surface charge can be modulated to target specific contaminants or reject interfering species.

the addition of amphiphilic block copolymers during fabrication by the phase inversion process results in self-segregation of the hydrophilic segment of the block copolymer on the membrane surface and inside the membrane nanopores, thus imparting high organic fouling resistance[33,40]. In both cases, the highly uniform and dense hydrophilic polymer brush layers have superior organic fouling resistance compared to nanoparticle coatings.

Some ENMs can be used to control biofilm growth (that is, biofouling), a common limiting factor for membrane systems. Biofouling control is particularly important for polyamide desalination membranes because the selective polyamide layer is highly sensitive to oxidants (for example, free chlorine) that are commonly used for biofouling control[40]. One approach involves the binding or in situ formation of silver or copper nanoparticles on the polyamide membrane surface[42,43]. The continuous slow release of silver or copper ions inactivates bacteria attached to the membrane, slowing biofouling (Fig. 2b)[33]. Key to the long-term success of this approach is the ability to periodically regenerate the biocidal nanoparticles after their dissolution and depletion.

Other biofouling-control approaches involve the surface binding of non-depleting nanomaterials and nanostructures that inactivate bacteria by direct contact (Fig. 2b). Recent studies showed that graphene-oxide (GO) nanosheets are highly effective for inactivating bacteria on direct contact[44,45]. Application of this method to polyamide-based desalination membranes has shown significant inactivation of bacteria on the membrane surface without impacting the water permeability and salt rejection of the membranes[33,46].

Maintaining long-term biofouling resistance via non-depleting nanomaterials that act by direct contact is key to the success of biofouling control. ENMs on the membrane surface will likely be coated with dead bacteria and organic matter after long-term exposure, which reduces their antimicrobial efficacy. Combining GO nanosheets with silver nanoparticles to form GO–Ag nanocomposites can ensure inactivation of bacteria by both the GO nanosheets and the silver ions that diffuse through the organic deposits on the membrane surface (Fig. 2b)[47].

Nanotechnology-enabled desalination membranes with ultrahigh selectivity can significantly enhance seawater desalination and wastewater reuse by removing small molecules (for example, boron and 1,4-dioxane) that are not well rejected by current polyamide membranes. To achieve this goal, new paradigms for membrane design that overcome the permeability–selectivity trade-off of current membranes (Fig. 2c) are needed[40,48,49]. Novel membranes that incorporate aquaporin or narrow-diameter single-wall carbon nanotubes in the selective layer (Fig. 3d) could dramatically improve the rejection of small molecules while maintaining high water permeability. However, the major challenge of these next-generation desalination membranes is their large-scale, defect-free fabrication[48].

Multifunctional materials for selective removal of priority pollutants. Multifunctional treatment may be accomplished through combinations of high-capacity absorptive materials, magnetic materials and photocatalysts (Fig. 3). One example is the 'bait-hook-and-destroy' concept for selective adsorption and pre-concentration of high-priority pollutants on the surface of a photocatalyst (or its immobilization substrate) for more efficient degradation (Fig. 3a)[30,50]. In addition to oxidizing organic pollutants or fragmenting them into more biodegradable byproducts[51], photocatalysts may catalyse the conversion of undesirable forms of oxy(anions) (for example, hexavalent chromium, nitrate, selenate) to less toxic forms through photoreduction[52–55].

Another example is superparamagnetic nanoparticles (Fig. 3b) that can be decorated with selective sorption sites, catalysts or antimicrobial agents (including phages[56]) for multifunctional treatment and subsequent low-energy separation with magnets for nanoparticle recovery and reuse. Iron-based magnetic ENMs could be used in various applications ranging from the removal of pollutants from industrial water to drinking water treatment[22,57]. However, iron dissolution may require periodic replenishment of the superparamagnetic nanoparticles.

High-capacity sorbents (Fig. 3c) enabled by ENMs may be utilized in point-of-use drinking water applications to remove (oxy) anions of arsenic, selenium and chromium[22,58–60]. Selectivity may be achieved through manipulation of ENM physicochemical properties (for example, hydrophobicity, surface charge[20,49]). Synthetic control of the size, crystal structure or even crystal facet can yield different reactivity or kinetic control towards different pollutants.

Low-energy (solar-based) desalination. An important new breakthrough in nanoengineered water treatment is the direct solar-driven vaporization-based distillation process (Fig. 4). Conventional distillation is, in principle, an attractive approach for desalination, yielding highly purified water; however, the substantial energy requirement of heating all input (feed) water to vaporization temperatures by conventional sources is a critical limitation to its practical use. The discovery that optical absorption and scattering by nanoparticles (Fig. 4a,b)[61,62] or by nanostructured solid media (Fig. 4c)[63] can induce highly localized photothermal heating of fluids offers a new approach to energetically drive the distillation process. In contrast to conventional distillation, in the case

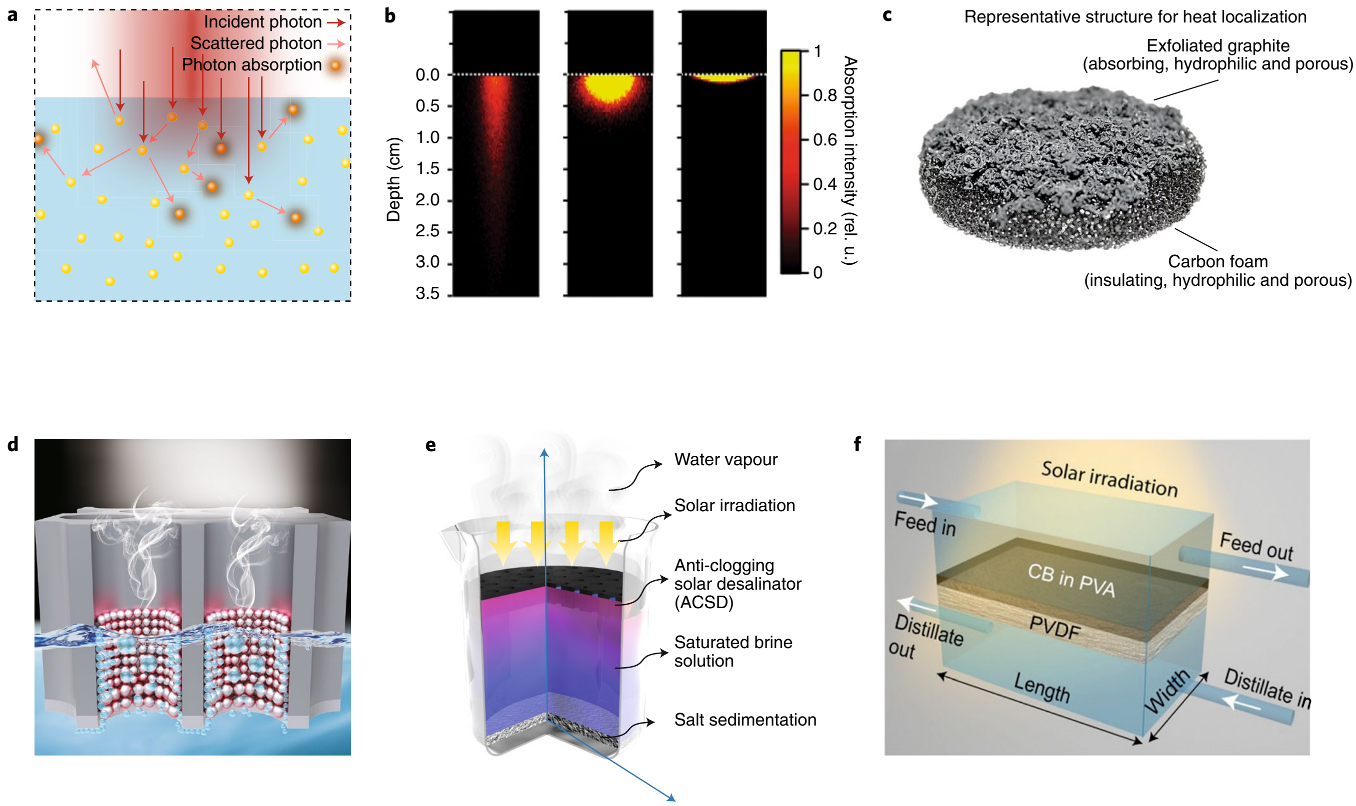

Fig. 4 | Direct solar-driven vaporization and distillation processes. a, For light-absorbing nanoparticles, the combination of absorption and scattering processes concentrates light energy in a compact region at the liquid–vapour interface, leading to steam generation. **b**, This process is controlled by the concentration of absorbers in the fluid: with increasing concentration, the active region where steam generation occurs is more compact. **c**, A bilayer geometry combining hydrophilic exfoliated graphite as optical absorber above an insulating layer of carbon foam also localizes light absorption at a liquid–vapour interface, facilitating solar vaporization. **d**, The nanovoids of an anodic aluminum oxide membrane also incorporating light-absorbing nanoparticles results in highly efficient solar vaporization. **e**, Schematic of a direct solar desalinator implemented using an anti-clogging graphite film. **f**, Illustration of NESMD geometry, where a photothermally coated membrane is illuminated by light, transforming MD into an all-solar process. CB, carbon black; PVA, polyvinyl alcohol; PVDF, polyvinylidene fluoride. Panels adapted from: **a**,**b**, ref. [62], American Chemical Society; **c**, ref. [63], Springer Nature Ltd; **d**, ref. [64], Springer Nature Ltd; **e**, ref. [65], RSC; **f**, ref. [66], PNAS.

of solar-driven vaporization, only the fluid within an optical path length of the suspended particles or the ENM is heated to the requisite vaporization temperature. A key requirement is the ability to absorb wavelengths of light that span a large fraction of the visible and infrared solar spectrum, resulting in the efficient coupling of the sun's emitted electromagnetic energy into a spatially compact region. In the case of particles, the solar photothermal fluid vaporization is related to light trapping by multiple scattering and absorption (Fig. 4b)[62]; in the case of ENMs such as exfoliated graphite (Fig. 4c)[63] or nanoparticle-functionalized nanovoids (Fig. 4c)[64], the light-absorbing region is typically decoupled from the remaining fluid volume by a region of low thermal conductivity, in a bilayer geometry, or with the optically absorbing region localized on the illuminated face of the material. For particles and the various media that have been used to demonstrate this effect, the results are remarkably similar: a large heating effect is established with a tight spatial temperature gradient between the heated fluid and the remainder of the fluid volume. Since there is no thermodynamic limit on the amount of light that can be absorbed by a particle or a material, over 99% of the light energy reaching the material can be utilized directly for heat production.

A key challenge is to develop geometries that harness the power of this approach. Initial experiments used solar vaporization directly, generating water vapour at the liquid–air interface, where the active material is floating (Fig. 4e)[65], or, alternatively, may be suspended by a buoyant support. While this approach allows for efficient illumination, the vapour stream could limit the efficiency of distillation by interfering with light collection or focusing optics, and by limiting the geometry of the condenser. These problems can be bypassed by implementing solar vaporization in the geometry of MD (Fig. 4f)[66]. In conventional MD, input water at an elevated temperature flows over a hydrophobic microporous membrane, where the distillate water, at a lower temperature, flows on the opposite side of the membrane. The temperature difference between the fluids on either side of the membrane establishes a vapour pressure difference, resulting in vapour transport across the membrane from the input (feed) side and condensation on the distillate side of the membrane. By coating the feed side of the membrane with broadband optically absorbing nanoparticles, one incorporates solar photothermal heating rather than conventional heating of the input fluid to drive this process. This modification, known as nanophotonics-enabled solar membrane distillation (NESMD), profoundly transforms the conventional MD process. Most importantly, the use of direct solar photothermal heating renders this approach scalable, with the efficiency of NESMD increasing with membrane size. NESMD is highly promising for off-grid, small-scale applications.

Implementation barriers and research needs

Nanotechnology could help overcome many water treatment challenges. Each group of ENM (for example, high capacity absorbents, photocatalysts, magnetic materials) has advantages and limitations regarding treatment capacity, scalability, regenerability and cost. For advanced materials selection and design, understanding how ENM functional properties are affected by their fundamental physicochemical characteristics (for example, morphology, crystal structure, facet-dependent adsorption) is a top priority.

While conventional sorbents face limitations on capacity and selectivity, nanosorbents with large specific surface area and tunable surface chemistry to minimize hindrance by interfering species could offer superior treatment capacity. Thus, a top research priority is to control pollutant–ENM interactions at the molecular level. Though nanosorbents offer a higher surface to volume ratio, which allows for higher sorption capacity than micron-scale or bulk counterparts[67], simply increasing the surface area does not always lead to an increase in removal capacity[68,69]. The adsorption ability of a nanosorbent is also determined by the structure and availability of favourable adsorption sites[70], and manipulating surface chemistry accordingly is a priority research area. Similar to conventional adsorbents, cost-effective regeneration of nanosorbents is also an important research challenge.

Improvements are needed to embed, secure or directly synthesize ENMs into substrates or scaffolds such as beads, polymers or commercial media (to minimize release and facilitate reuse) without losing their functionality. While magnetic immobilization and recovery may offer a solution to some of these issues, superparamagnetic ENMs must be designed to maintain their integrity in water while preventing loss of efficiency due to aggregation.

Photocatalytic processes that require ultraviolet (UV) irradiation suffer from limited light penetration and low quantum yields, which increases energy requirements (and associated cost) to power UV lamps and hinders treatment efficiency. Strategies such as bandgap engineering[71] and plasmonics[72] could circumvent these limitations and also enable the design of visible-light-active photocatalysts that are activated by sunlight to decrease electrical energy requirements.

Nanophotonics can overcome the severe energy consumption requirements and lack of scalability of conventional membrane distillation, but current membranes are not optimal for the integration of light-driven processes due to their inherent fragility. New nano-engineered composite materials are needed to further improve the robustness of optics-plus-membrane-based processes.

Also ripe for improvement are pressure-driven membranes for water purification and desalination, which face severe challenges associated with fouling and inefficient separation performance. These barriers can be overcome with antifouling coatings on the membrane surface that mitigate foulant attachment and inhibit biofilm formation, minimizing water pretreatment needs, as well as the use of novel membrane materials with ultrahigh selectivity. For antifouling coatings, it is imperative to select nanoscale coating materials that are irreversibly bound to the membrane surface and do not adversely impact the permeability and selectivity of the membranes. For next-generation highly-selective membranes incorporating nanochannels, such as carbon nanotubes, the critical challenges are the fabrication of defect-free membranes and the scaling-up of the membrane fabrication process to industrial scale[48].

The design and optimization of nanotechnology-enabled water treatment technologies will also require improved understanding of nanomaterial structure–activity relationships to inform material selection and enhance durability, structural integrity and process reliability. This includes developing green synthesis approaches to scale-up production of functional nanomaterials, and cost-effective strategies to regenerate or replenish functionality for nanomaterials that dissolve (for example, some metallic nanoparticles) or become passivated.

Outlook and conclusions

Nano-enabled treatment processes offer great potential to minimize energy requirements, chemical consumption and waste residuals associated with water treatment, and the associated costs and potential environmental impacts. For example, current energy-intensive distillation-based water desalination might take advantage of free energy sources (for example, sunlight, waste heat) through novel nanophotonic-based technologies. Furthermore, nanotechnology can enhance the selectivity of sorbents and photocatalysts to mitigate hindrance from interfering compounds and enhance their efficiency.

Membrane-based separation and desalination technologies will likely continue to be critical tools in water treatment in the foreseeable future, and nanotechnology will help overcome operational hindrances such as fouling and poor selectivity to separate specific ions or molecules. For example, membrane performance and reliability will be enhanced by preventing fouling through nanoscale grafting or doping, whereas highly-selective desalination membranes can be designed with the use of nanochannels. Next-generation desalination membranes will be fouling resistant, highly selective and chemically stable to oxidizing agents such as chlorine. To achieve this goal, there is a critical need for breakthrough developments in novel membrane nanomaterials and defect-free fabrication methods.

Overall, providing more reliable and affordable access to safer water will require technological innovation. Nanotechnology will likely play a critical role by providing a wide range of unprecedented opportunities to enhance some water treatment systems, including adaptable treatment technologies and materials that can be tuned to specific targets. In the near future, nanotechnology-enabled water treatment will likely be implemented mainly in niche applications (such as point-of-use devices) rather than in large municipal treatment plants that tend to be risk-averse to innovation and face a variety of limitations against system replacement. Nevertheless, this emerging innovation wave may eventually empower next-generation modular water treatment systems that significantly improve the safety and resiliency of water supply, while reducing the cost and energy use.

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Competing interests
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