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EDITORIAL FOR SPECIAL ISSUE ON NANO-SUSTAINABILITY

Nanotechnology for sustainable development: retrospective and outlook

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Abstract The world is facing great challenges in meeting rising demands for basic commodities (e.g., food, water and energy), finished goods (e.g., cell phones, cars and airplanes) and services (e.g., shelter, healthcare and employment) while reducing and minimizing the impact of human activities on Earth's global environment and climate. Nanotechnology has emerged as a versatile platform that could provide efficient, cost-effective and environmentally acceptable solutions to the global sustainability challenges facing society. This special issue of the *Journal of Nanoparticle Research* is devoted to the utilization of nanotechnology to improve or achieve sustainable development. We highlight recent advances and discuss opportunities of utilizing nanotechnology to address global challenges in (1) water purification, (2) clean energy technologies, (3) greenhouse gases management, (4) materials supply and utilization, and (5) green manufacturing and chemistry. In addition to the technical challenges listed above, we also discuss societal perspectives and provide an outlook of the role of nanotechnology in the convergence of knowledge, technology and society for achieving sustainable development.

Keywords Nanotechnology · Sustainability · Natural resources · Manufacturing · Societal needs

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Introduction

Every human being needs food, water, energy, shelter, clothing, healthcare, employment, etc., to live and prosper on Earth. One of the greatest challenges facing society in the twenty-first century is providing better living standards to all people while minimizing the impact of human activities on the global environment and climate as the world population reaches 8–10 billion by 2050 (Diallo et al. 2013). The Brundtland

Commission of the United Nations defined "sustainable development" as "that which meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland 1987). Currently, the world is facing great challenges to meet rising demands for basic commodities (e.g., food, water and energy), finished goods (e.g., cars, airplanes and cell phones) and services (e.g., shelter, healthcare and employment) while reducing the emission of greenhouse gases and the environmental footprint of agriculture and industry (Godfray et al. 2010; Diallo and Brinker 2011; Brinker and Ginger 2011; Diallo et al. 2013). Soon after the inception of the National Nanotechnology Initiative (NNI), it was envisioned that nanotechnology could provide more sustainable solutions to the global challenges facing society. During a presentation made at the Cornell Nanofabrication Center on September 15, 2000, Roco (2001) discussed how nanotechnology could help improve agricultural yields, provide more efficient and cost-effective water treatment and desalination technologies, and enable the development of clean and renewable energy sources including highly efficient solar photovoltaic cells. As nanotechnology continues to advance, the research agenda is increasingly focused on addressing two key questions related to sustainability over the next 10–20 years:

- Can nanotechnology help address the challenges of improving global sustainability in energy, water, food, shelter, transportation, healthcare and employment?
- Can nanotechnology be developed in a sustainable manner with maximum societal benefits and minimum impact on Earth's global environment and climate?

In this special issue of the *Journal of Nanoparticle Research* (JNR), we highlight and discuss the utilization of nanotechnology to advance and achieve sustainable development. Two key goals of this special issue are to:

1. Provide a retrospective and an outlook of the state-of-the-field for interested scientists, engineers, policy makers and business leaders.
2. Bring into focus crosscutting scientific, technological and societal issues associated with the development and implementation of nanotechnology-based solutions for societal challenges in clean water and energy supplies, greenhouse gases management and materials and manufacturing.

The content of this JNR special issue is based on invited article from the presentations and discussions during two international meetings that were held at the California Institute of Technology in 2011: the *Eighth US-Korea Forum on Nanotechnology* (http://www.andrew.cmu.edu/org/nanotechnologyforum/Forum8/GeneralInfo.htm) and the *Resnick Sustainability Institute Workshop on Critical Materials for Energy Generation and Storage* (http://resnick.caltech.edu/e-critical-materials.php). In addition, the editors of this special issue have included selected articles published by JNR during 2012 and 2013 to provide a broader discussion of the contributions of nanotechnology to sustainable development. Table 1 provides a list of the thirty (30) core articles that are featured in this JNR special issue. Building upon the research findings and perspectives of selected articles listed in Table 1, this editorial provides a retrospective and outlook of nanotechnology for sustainable development. Following the "Introduction" section, "Nanotechnology for sustainable development: overview of recent advances" section highlights recent advances in the utilization of nanotechnology to address global challenges in water purification, clean energy technologies, greenhouse gases management, materials supply and utilization, and green manufacturing and chemistry. "Nanotechnology for sustainable development: Societal perspectives and outlook" section discusses key societal perspectives and provides an outlook of the role of nanotechnology in the convergence of knowledge, technology and society (CKTS) for achieving sustainable development.

Nanotechnology for sustainable development: overview of recent advances

As noted above, nanotechnology has emerged as a versatile platform for addressing global sustainability challenges facing the world (Diallo and Brinker 2011; Brinker and Ginger 2011). Nanomaterials exhibit key physicochemical properties that make them particularly attractive as functional materials for sustainable technologies. On a mass basis, they have much larger and more active surface areas than bulk materials. Nanomaterials can be functionalized with various

Table 1 List of thirty (30) core research, review and perspectives articles that are highlighted in this JNR Special Issue

Title	Authors	Citation
Water purification		
1. Ionic transport in nanocapillary membrane systems	Vikhram V. Swaminathan, Larry R. Gibson II, Marie Pinti, Shaurya Prakash, Paul W. Bohn and Mark A. Shannon	J Nanopart Res (2012) 14:951
2. Nanofiltration membranes based on polyvinylidene fluoride nanofibrous scaffolds and crosslinked polyethyleneimine networks	Seong-Jik Park, Ravi Kumar Cheedrala, Mamadou S. Diallo, Changmin Kim, In S. Kim and William A. Goddard III	J Nanopart Res (2012) 14:884
3. Composite polyester membranes with embedded dendrimer hosts and bimetallic Fe/Ni nanoparticles: synthesis, characterization and application to water treatment	Soraya P. Malinga, Omotayo A. Arotiba, Rui W. Krause, Selweyn F. Mapolie, Mamadou S. Diallo and Bhekie B. Mamba	J Nanopart Res (2013) 15:1698
4. A new approach for determination of fouling potential by colloidal nanoparticles during reverse osmosis (RO) membrane filtration of seawater	Ji Yeon Park, Sungil Lim and Kihong Park	J Nanopart Res (2013) 15:1548
5. Multiwalled carbon nanotubes decorated with nitrogen, palladium co-doped TiO_2 (MWCNT/N, Pd co-doped TiO_2) for visible light photocatalytic degradation of Eosin Yellow in water	Alex T. Kuvarega, Rui W. M. Krause and Bhekie B. Mamba	J Nanopart Res (2012) 14:776
6. Synthesis and characterization of carbon-covered alumina (CCA) supported TiO_2 nanocatalysts with enhanced visible light photodegradation of Rhodamine B	Mphilisi M. Mahlambi, Aay K. Mishra, Shivani B. Mishra, Rui W. Krause, Bhekie B. Mamba and Ashok M. Raichur	J Nanopart Res (2012) 14:790
7. Improvement of the structural, morphology and optical properties of TiO_2 for solar treatment of industrial wastewater	Mona Saif, Sameh Mohammed Aboul-Fotouh, Sahar A. El-Molla, Marwa M. Ibrahim and Laila F. M. Ismail	J Nanopart Res (2012) 14:1227
8. Shape-controlled synthesis of α-Fe_2O_3 nanostructures: engineering their surface properties for improved photocatalytic degradation efficiency	Subramaniasiva Bharathi, Devaraj Nataraj, Karuppanan Senthil and Yoshitake Masuda	J Nanopart Res (2012) 15:1346
9. Protein-functionalized magnetic iron oxide nanoparticles: time efficient potential water treatment	Chuka Okoli, Magali Boutonnet, Sven Järås and Gunaratna Rajarao-Kuttuva	J Nanopart Res (2012) 14:1194
10. Fabrication of amine functionalized magnetite nanoparticles for water treatment processes	Candace C. P. Chan, Hervé Gallard and Peter Majewski	J Nanopart Res (2012) 14:828
11. Manganese-incorporated iron(III) oxide–graphene magnetic nanocomposite: synthesis, characterization and application for the arsenic(III)-sorption from aqueous solution	Debabrata Nandi, Kaushik Gupta, Arup Kumar Ghosh, Amitabha De, Sangam Banerjee and Uday Chand Ghosh	J Nanopart Res (2012) 14:1272
12. Arsenic removal by magnetic nanocrystalline barium hexaferrite	Hasmukh A. Patel, Jeehye Byun and Cafer T. Yavuz	J Nanopart Res (2012) 14:881
13. Removal of heavy metals from aqueous solutions using Fe_3O_4, ZnO and CuO nanoparticles	Shahriar Mahdavi, Mohsen Jalali and Abbas Afkhami	J Nanopart Res (2012) 14:846
14. Kaolin-supported nanoscale zero-valent iron for removing cationic dye-crystal violet in aqueous solution	Zheng-xian Chen, Ying Cheng, Zuliang Chen' Mallavarapu Megharaj and Ravendra Naidu	J Nanopart Res (2012) 14:899
15. Aqueous phosphate removal using nanoscale zero-valent iron	Talal Almeelbi and Achintya Bezbaruah	J Nanopart Res (2012) 14:900

Table 1 continued

Title	Authors	Citation
Clean energy and greenhouse gas management		
16. Poly(vinyl chloride)-g-poly(2-(dimethylamino ethyl methacrylate) graft copolymer templated synthesis of mesoporous TiO_2 thin films for dye-sensitized solar cells	Rajkumar Patel, Sung Hoon Ahn, Jin Ah Seo, Sang Jin Kim and Jong Hak Kim	J Nanopart Res (2012) 14:845
17. SnO_2, IrO_2, Ta_2O_5, Bi_2O_3 and TiO_2 nanoparticle anodes: electrochemical oxidation coupled with the cathodic reduction of water to yield molecular H_2	Jina Choi, Yan Qu and Michael R. Hoffmann	J Nanopart Res (2012) 14:983
18. Preparation of proton conducting membranes containing bifunctional titania nanoparticles	Ayse Aslan and Ayhan Bozkurt	J Nanopart Res (2013) 15:1781
19. Nanotechnology convergence and modeling paradigm of sustainable energy system using polymer electrolyte membrane fuel cell as a benchmark example	Pil Seung Chung, Dae Sup So, Lorenz T. Biegler and Myung S. Jhon	J Nanopart Res (2012) 14:853
20. Thermally rearranged (TR) polymer membranes with nanoengineered cavities tuned for CO_2 separation	Seungju Kim and Young Moo Lee	J Nanopart Res (2012) 14:949
21. Local intermolecular interactions for selective CO_2 capture by zeolitic imidazole frameworks: energy decomposition analysis	Ji Young Park, Yoon Sup Lee and Yousung Jung	J Nanopart Res (2012) 14:793
Materials, manufacturing and green chemistry		
22. Nanotechnology and clean energy: sustainable utilization and supply of critical materials	Neil Fromer and Mamadou S. Diallo	J Nanopart Res (2013) XXX
23. Recovery of silica from electronic waste for the synthesis of cubic MCM-48 and its application in preparing ordered mesoporous carbon molecular sieves using a green approach	Tzong-Horng Liou	J Nanopart Res (2012) 14:869
24. Sustained release of fungicide metalaxyl by mesoporous silica nanospheres	Harrison Wanyika	J Nanopart Res (2013) 15:1831
25. Nanomanufacturing and sustainability: opportunities and challenges	Ahmed Busnaina, Joey Mead, Jacqueline Isaacs, and Sivasubramanian Somu	J Nanopart Res (2013) 15:1984
26. Synthesis, characterization and mechanistic insights of mycogenic iron oxide nanoparticles	Arpit Bhargava, Navin Jain, Manju Barathi L, Mohd S Akhtar, Yeoung-Sang Yun and Jitendra Panwar	J Nanopart Res (2013) 15:2031
27. Electrochemical synthesis of gold nanorods in track-etched polycarbonate membrane using removable mercury cathode	Manoj K. Sharma, Arvind S. Ambolikar and Suresh K. Aggarwal	J Nanopart Res (2012) 14:1094
28. Filtration behavior of silver nanoparticle agglomerates and effects of the agglomerate model in data analysis	Jelena Buha, Heinz Fissan and Jing Wang	J Nanopart Res (2013) 15:1709
Societal perspectives		
29. Nanotechnology for sustainability: what does nanotechnology offer to mitigate complex sustainability problems?	Arnim Wiek, RiderFoley and David Guston	J Nanopart Res (2012) 14:1093
30. Nanotechnology policy in Korea for sustainable growth	Dae Sup So, Chang Woo Kim, Pil Seung Chung and Myung S. Jhon	J Nanopart Res (2012) 14:854

chemical groups to increase their affinity toward a given compound including dissolved solutes and gases. They can also be functionalized with chemical groups that selectively target key biochemical constituents and metabolic/signaling networks of waterborne bacteria and viruses. Nanomaterials are also providing unprecedented opportunities to develop functional materials with superior electronic, optical, catalytic and magnetic properties. These novel functional materials can be processed into various form factors including water-soluble supramolecular hosts, particles, fibers and membranes. Figures 1, 2 and 3 show selected classes of nanomaterials, nanotechnology-based processes/systems and multi-scale modeling tools that are, respectively, being employed/developed to design and build the next generation of sustainable products and technologies. Below, we provide an overview of recent progress in the utilization of nanotechnology to address global challenges in (1) water purification, (2) clean energy technologies, (3) greenhouse gases management, (4) materials supply and utilization and (5) green manufacturing and chemistry.

Water purification

The availability of clean water has emerged as one of the most critical problems facing society and the global economy in the twenty-first century (Savage and Diallo 2005; Shannon et al. 2008; Diallo and Brinker 2011). Many regions of the world face multiple challenges in sustainably supplying potable water for human use and clean water for agriculture, food processing, energy generation, mineral extraction, chemical processing, and industrial manufacturing (Shannon et al. 2008; Diallo and Brinker 2011). Demand for water is increasing due to population growth at the same time as water supplies are being stressed by the increasing contamination and salinization of freshwater sources including lakes, rivers and groundwater aquifers. A report published by the Intergovernmental Panel on Climate Change (Bates et al. 2008) suggests that global climate change will adversely impact the world's freshwater resources in several ways: (1) increase the frequency of droughts and floods; (2) decrease the amount of water stored in snowpack and glaciers; and (3) decrease the overall water quality due to salinity increase and enhanced sediment, nutrient, and pollutant transport in many watersheds throughout the world. Thus, a significantly larger amount of clean water needs to be produced from impaired water (e.g., wastewater, brackish water and seawater) to meet the growing demand throughout the world in the next decade and beyond. The convergence between nanotechnology and water science and technology is leading to revolutionary advances in water treatment, desalination and reuse technologies (Savage and Diallo 2005; Shannon et al. 2008; Diallo and Brinker 2011). In this special issue, we have selected fifteen (15) published JNR articles (Table 1) to highlight significant advances that have resulted from the application of nanotechnology to water purification.

Pressure-driven membrane processes such as reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF) and microfiltration (MF) are becoming the key components of advanced water treatment, reuse and desalination systems worldwide (Savage and Diallo 2005; Shannon et al. 2008). Four (4) articles of this JNR special issue are devoted to fundamental investigations of membrane processes, materials and systems. The article *Ionic transport in nanocapillary membrane systems* by Swaminathan et al. (2012) reviews the state-of-the-art of nanocapillary array membranes (NCAMs) as model systems for probing ion and particle transport in nanopores of characteristic length scales ranging from 1 to 100 nm. NCAMs consist of nanoporous membranes with tunable pore sizes that are fabricated by track etching using base polymers such as polycarbonate. The authors reported that pore geometry, surface charge and nonlinear electrokinetic effects arising from the interplay between surface charge density and surface energy control the transport of ions and charged particles in nanopores with diameters below 100 nm. They also discussed how basic knowledge derived from fundamental studies of NCAMs is providing new opportunities to design (1) biomimetic membranes for water desalination and (2) 3D micro-/nanofluidic systems for sustainability applications including chemical separations, analysis sensing and energy conversion. The article *Nanofiltration membranes based on polyvinylidene fluoride nanofibrous scaffolds and crosslinked polyethyleneimine networks* by Park et al. (2012a) describes the preparation, characterization and evaluation of a new family ion-selective nanofiltration (NF) membranes using polyvinylidene fluoride (PVDF) and hyperbranched polyethylenimine (PEI) as building

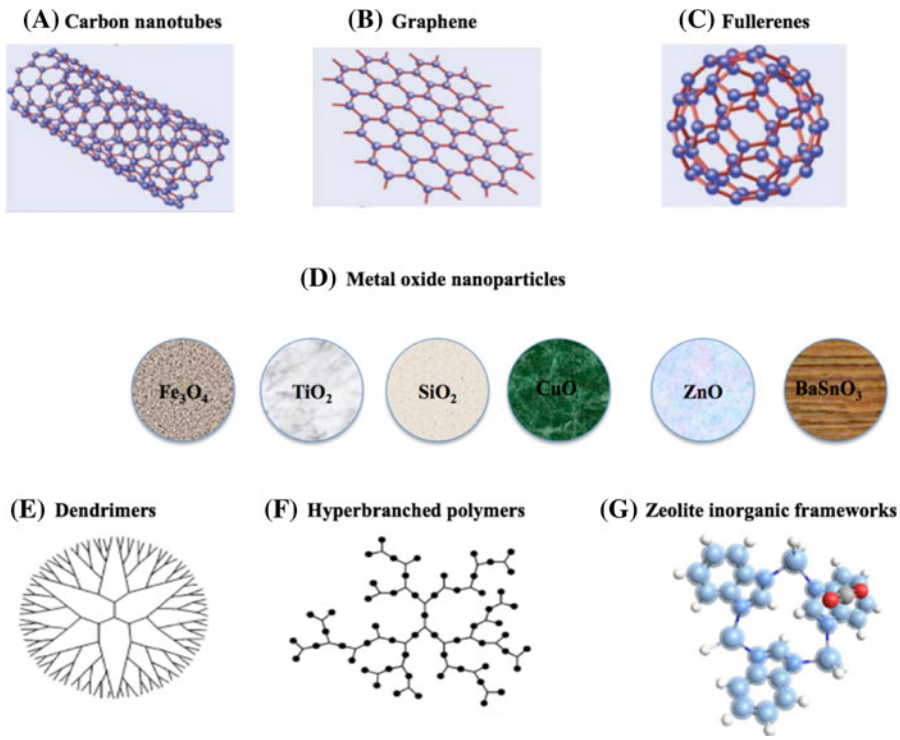

Fig. 1 Selected nanomaterials that are currently being utilized as building blocks to develop the next generation of sustainable products and technologies in water purification, energy generation, conversion and storage, greenhouse gas management, materials supply and utilization and green manufacturing and chemistry

blocks. These new nanofibrous composite (NFC) membranes consist of crosslinked hyperbranched PEI networks supported by PVDF nanofibrous scaffolds that are electrospun onto commercial PVDF microfiltration (MF) membranes. A major objective of this work was to develop positively charged NF membranes that can be operated at low pressure (i.e., less than 10 bar) with high water flux and improved rejection for monovalent salts such as NaCl, compared to the commercially available membranes. The proof-of-concept experiments show that the NFC–PVDF membrane with crosslinked PEI/trimesoyl chloride networks has a high water flux ($\sim$30 L m^{-2} h^{-1}) and high rejections for $MgCl_2$ (88 %) and NaCl (65 %) at pH 6 and pressure of 7 bar. The overall results of this study suggest that PVDF nanofibers and hyperbranched PEI are promising building blocks for the fabrication of a new generation of high performance NF membranes for (1) water purification Park et al. (2012a) and (2) metal extraction from non-traditional sources including mine tailings and industrial wastewater (Fromer and Diallo 2013).

Metal oxide nanoparticles (Fig. 1D) have great potential as catalyst materials for water purification due their large surface areas and superior optical/electronic properties (Savage and Diallo 2005). During the last decade, titanium dioxide (TiO_2) nanoparticles have emerged as promising photocatalysts for water treatment. TiO_2 nanoparticles are versatile and can serve both as oxidative and reductive catalysts for organic and inorganic pollutants. Three (3) articles of this JNR special issue are devoted to the synthesis, characterization and evaluation of TiO_2-based photocatalysts for water treatment. The article *Multiwalled carbon nanotubes decorated with nitrogen, palladium co-doped TiO_2 (MWCNT/N, Pd co-doped TiO_2) for visible light photocatalytic degradation of Eosin Yellow in water* by Kuvarega et al. (2012) investigates the photocatalytic activity of MWCNT/N, Pd co-doped TiO_2 nanocomposites. To probe catalyst reactivity, the authors measured the photodegradation of Eosin Yellow under simulated solar and visible light irradiation. They reported that the 0.5 wt% MWCNT/N, Pd co-doped TiO_2 composite gave high degradation rate constants of 3.42×10^{-2} and 5.18×10^{-3} min^{-1} using simulated solar light and visible light, respectively. The article *Synthesis and characterization of carbon covered alumina (CCA) supported TiO_2 nanocatalysts with enhanced visible light photodegradation of Rhodamine B* by Mahlambi et al. (2012)

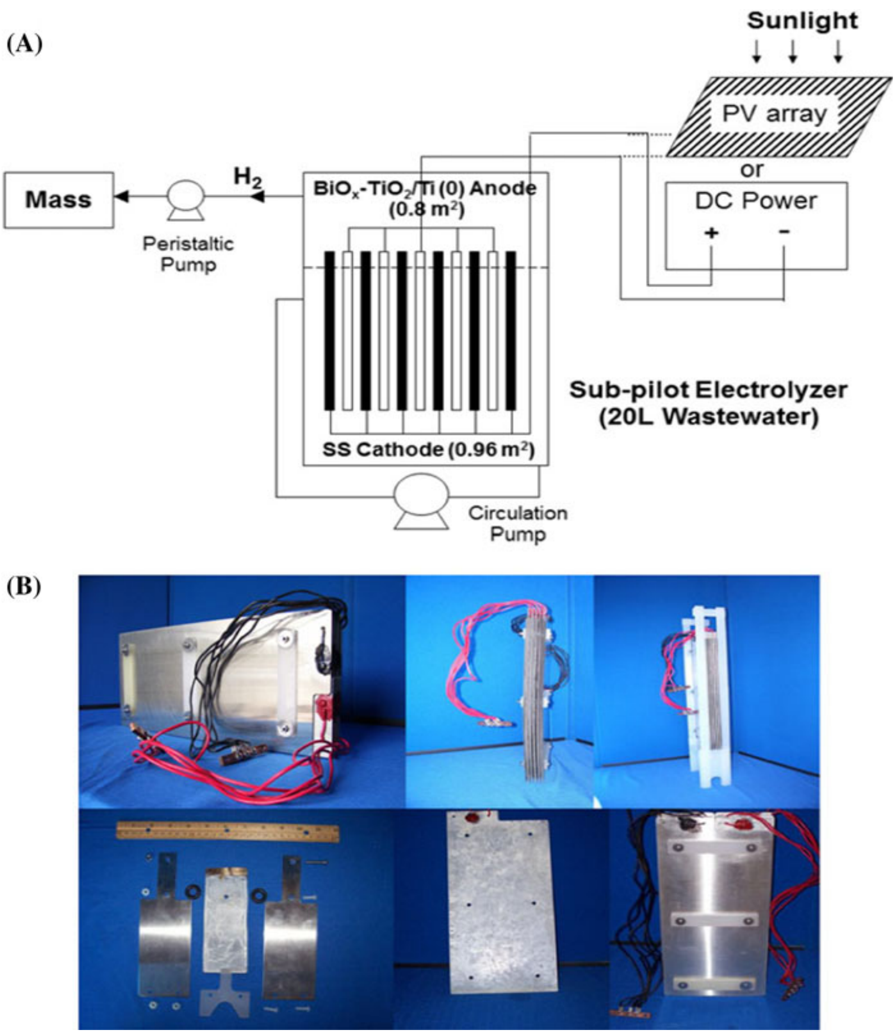

Fig. 2 **A** Schematic diagram of a hybrid photovoltaic–electrochemical system, which utilizes semiconductor nanoparticles coated on to metal substrates as electrodes for the generation of hydrogen coupled with the oxidation of wastewater. **B** Photographs of the electrode arrays showing the anodic semiconductor coatings on the Ti-metal base support [Choi et al. J Nanopart Res (2012) 14:983]

illustrates the preparation of TiO_2 nanocatalysts on CCA supports. The authors reported that the CCA-TiO_2 photocatalysts show higher reactivity under visible light compared to their unsupported counterparts. Metal oxide nanoparticles are also providing new opportunities to leverage the efficiency of magnetic separations technology in water purification (Ge et al. 2011; Ling and Chung 2011). Four (4) articles of this JNR special issue are devoted to the synthesis, characterization and evaluation of MNPs for water treatment. The article *Protein-functionalized magnetic iron oxide nanoparticles: time efficient potential-water treatment* by Okoli et al. (2012) discusses the synthesis, characterization and evaluation of composite magnetic nanoparticles (MNPs) with an iron oxide core and a shell consisting of sorbed *Moringa oleifera* proteins. The authors reported that their protein-stabilized MNPs could be utilized as recyclable media in water treatment to remove turbidity (i.e., suspended solids) from surface water. Okoli et al. (2012) also showed that the MNPs could be combined with magnetic separations to remove more 90 % of the turbidity from a test surface water sample within 12 min. In contrast, only 70 % of turbidity removal was achieved within 60 min using conventional gravity separation with a synthetic and non-recyclable coagulant such as alum.

Clean energy technologies

Global climate change is one of the greatest challenges facing the twenty-first century (Solomon et al. 2007). During the last two decades, a consensus has gradually

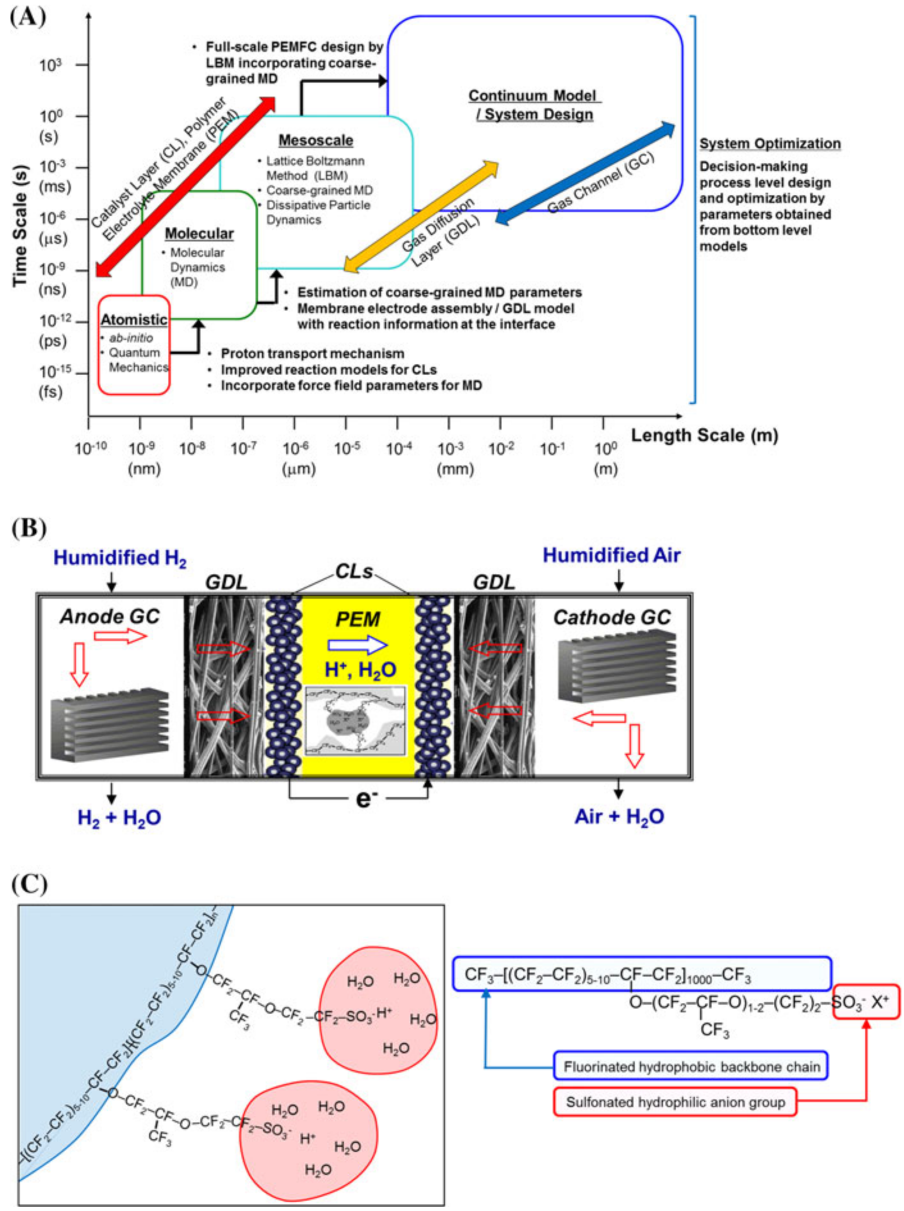

Fig. 3 **A** Multi-scale modeling strategy for designing and optimizing polymer electrolyte membrane fuel cells (PEMFC). **B** Components of a single stack hydrogen PEMFC. **C** Structure a polymer electrolyte membrane (Nafion) [Chung et al. J Nanopart Res (2012) 14:853]

emerged that increasing emissions of greenhouse gases such as carbon dioxide (CO_2) from the combustion of fossil fuels (e.g., coal and petroleum) are the key drivers of global climate change (Solomon et al. 2007). Meeting the growing demand for energy while significantly reducing CO_2 emissions will require the deployment of orders of magnitude more clean and renewable energy systems than what is now in place as the world population reaches 8–10 billion by 2050 (Brinker and Ginger 2011; Fromer et al. 2011; Diallo et al. 2013). Nanotechnology provides unprecedented opportunities to advance the development of clean and renewable energy technologies (Fromer and Diallo 2013). Four (4) articles of this JNR special issue are devoted to clean energy technologies. Solar photovoltaics has emerged the most attractive source of renewable electrical energy due to its abundance, versatility, and ease of implementation with minimum environmental impact in terms of water consumption and land usage (Lewis 2007; Brinker and Ginger 2011). The article *Poly(vinyl chloride)-g-poly(2-(dimethylamino ethyl methacrylate) (PVC-g-PDMAEMA) graft copolymer templated synthesis of mesoporous* TiO_2 *thin films for dye-sensitized solar* *cells* by Patel et al. (2012b) investigates the utilization of graft copolymers as structure-directing agents for the fabrication of mesoporous thin films containing titanium dioxide (TiO_2) layers used as anodes. The authors subsequently employed these new mesoporous TiO_2 films to fabricate a photoanode for a dye-sensitized solar cell (DSSC) that achieved an energy conversion efficiency of 3.2 % at 100 mW/cm^2. This performance was higher when using a TiO_2 film with a higher porosity and lower interfacial resistance between the anode and the electrolyte. According to the authors, they achieved one of the highest reported energy conversion efficiency for a quasi-solid-state DSSC with a 600-nm-thick TiO_2 film. The article *SnO_2, IrO_2, Ta_2O_5, Bi_2O_3, and TiO_2 nanoparticle anodes: electrochemical oxidation coupled with the cathodic reduction of water to yield molecular H_2* by Choi et al. (2012) discusses hydrogen generation by solar water splitting using organic contaminants in wastewater as sacrificial electron donors. This work is potentially important since solar radiation is intermittent and the large-scale implementation of solar power will require efficient systems that convert solar energy into high-density chemical fuels. The authors demonstrated the feasibility of a scaled-up rooftop prototype of a hybrid photovoltaic electrolysis system (Fig. 2), which utilizes semiconductor nanoparticles coated onto metal substrates as electrodes for the generation of hydrogen coupled with the oxidation of organic compounds in wastewater.

In industrialized countries such as the USA, transportation is responsible for approximately 66 % of oil consumption and 33 % of CO_2 emissions (Davis et al. 2008; EPA 2008). Thus, fuel cell cars could meet the world's growing demand for transportation vehicles while significantly reducing CO_2 emissions. Polymer electrolyte membrane fuel cells (PEMFCs) have emerged as the most promising energy conversion devices for automotive applications (http://www.nextgreencar.com/fuelcellcars.php). Two (2) articles of this JNR special issue are devoted to PEMFCs. The article *Preparation of proton conducting membranes containing bifunctional titania nanoparticles* by Aslan and Bozkurt (2013) discusses the preparation and characterization of novel proton conducting nanocomposite membranes. These new polymer electrolyte (PE) membranes consisted of poly(vinyl alcohol) (PVA) membrane matrices that are embedded with sulfated TiO_2 nanoparticles (TS) and nitrilotri(methyl phosphonic acid) (NMPA). The authors reported that one of their new PE membranes [PVA–TS–$(NMPA)_3$] achieved a proton conductivity of 0.003 S cm^{-1} at 150 °C. This membrane also showed improved mechanical strength, which is critical for applications such as PEMFCs. The article *Nanotechnology convergence and modeling paradigm of sustainable energy system using polymer electrolyte membrane fuel cell as a benchmark example* by Chung et al. (2012) discusses nanotechnology convergence for clean energy generation and novel multi-scale modeling paradigms using the fuel cell system as a benchmark example (Fig. 3). This approach includes understanding and modeling complex multi-physics phenomena at different time and length scales along with the introduction of an optimization framework for application-driven nanotechnology research trends. The new modeling paradigm introduced by the authors covers the novel holistic integration from atomistic/molecular phenomena to meso-/continuum scales. The authors also discuss system optimization with respect to the reduced order parameters for a coarse-graining procedure in multi-scale model integration as well as system design.

Greenhouse gases management

Currently, fossil fuels provide approximately 80 % of the energy used worldwide (IPCC 2005). Although many non-CO_2-emitting energy sources are being developed, the world will continue to burn significant amounts of fossil fuels in the foreseeable future. Thus, carbon capture and storage is emerging as a viable short-to-medium term alternative for reducing the amounts of anthropogenic CO_2 released into the atmosphere (IPCC 2005). Nanotechnology has the potential to provide efficient, cost-effective and environmentally acceptable solutions for CO_2 separation, capture and storage (Diallo and Brinker 2011). Two (2) articles of this JNR special issue are devoted to CO_2 separation and storage. The article *Thermally rearranged (TR) polymer membranes with nanoengineered cavities tuned for CO_2 separation* by Kim and Lee (2012) reviews recent developments in CO_2 separation technologies utilizing various membranes including thermally rearranged (TR) polymeric membranes with CO_2 selective nanocavities. The authors reported that these new TR polymeric membranes show high gas permeability as well as good selectivity, especially in CO_2 separation from post-combustion flue gases. Zeolitic imidazolate frameworks (ZIFs) have emerged as promising building blocks for high capacity and selective CO_2 capture and storage media (Wang et al. 2008; Banerjee et al. 2008). The article *Local intermolecular interactions for selective CO_2 capture by zeolitic imidazole frameworks: energy decomposition analysis* by Park et al. (2012b) utilizes density functional theory (DFT) calculations to investigate the binding of CO_2 with ZIFs. The overall objective of this work was to provide a molecular level interpretation of experimental measurements of CO_2 uptake (capacity and selectivity) by ZIFs. The DFT calculations suggest that the local electronic interactions of CO_2 and the substituent groups of ZIFs, which is mainly characterized by frozen density and polarization interactions with little charge transfer, are the primary binding interaction. Park et al. (2012b) also reported that electron correlation effects are also important depending on the binding geometry and functional groups.

Materials supply and utilization

Innovations in the sustainable supply and utilization of materials will also be critical to developing the next generation of sustainable technologies and products (Diallo et al. 2013). Metals are used to fabricate the critical components of numerous products and finished goods, including airplanes, automobiles, cell/smart phones and biomedical devices (NRC 2008; Diallo and Brinker 2011). Carbon-based materials derived from petroleum are also the building blocks of a broad range of essential products and finished goods, including plastics, solvents, adhesives, fibers, resins, gels, and pharmaceuticals (Diallo et al. 2013). Four (4) articles of this JNR special issue are devoted to materials supply and utilization. The article *Nanotechnology and clean energy: sustainable utilization and supply of critical materials* by Fromer and Diallo (2013) discusses the utilization of nanotechnology to improve or achieve materials sustainability for energy generation, conversion and storage. There is a growing realization that the development and large-scale implementation of clean energy technologies will also require sizeable amounts of technology metals (Diallo and Brinker 2011; Fromer et al. 2011; Diallo et al. 2013). In their perspectives article, the authors argue that many current problems involving the sustainable utilization and supply of *critical materials* in clean/renewable energy technologies could be addressed using (1) nanostructured materials with enhanced electronic, optical, magnetic and catalytic properties (Table 2) and (2) nanotechnology-based separation materials and systems that can recover *critical materials* from non-traditional sources including mine tailings, industrial wastewater and electronic wastes with minimum environmental impact.

The article *Recovery of silica from electronic waste for the synthesis of cubic MCM-48 and its application in preparing ordered mesoporous carbon molecular sieves using a green approach* by Liou (2012) deals with the recovery of valuable elements/materials from electronic wastes (e-wastes) consisting of mixtures of epoxy resin, phenolic resin, silica and additives. In this case, the author utilized resin ash from electronic packaging wastes to synthesize mesoporous silica (MCM-48) with high purity (99.87 wt%), high surface area (1 317 m^2/g) and mean pore size of 3.0 nm. Converting e-wastes into mesoporous materials (e.g., MCM-48) could help alleviate waste disposal problems associated with the use of consumer electronics products. Nanotechnology has also emerged as a versatile platform for addressing materials sustainability in agriculture through the development of smart systems for controlled/precision release of nutrients, fertilizers and pesticides (Scott and Chen 2003; Diallo and Brinker 2011). The article *Sustained release of fungicide metalaxyl by mesoporous silica nanospheres* by Wanyika (2013) discusses the utilization of silica nanoparticles for the storage and controlled release of the pesticide metalaxyl. The author found that the silica (SiO_2) nanoparticles (average particle diameters of 162 nm and mean pore sizes of 3.2 nm) could load about 14 wt% of metalaxyl. He also reported a "sustained release behavior" in water-saturated soil columns over a period of 30 days with a release into the soil media of 11.5 wt% of the metalaxyl trapped into the SiO_2 nanoparticles compared to 76 wt% when metalaxyl is used without initial storage into the nanoparticles.

Green manufacturing and chemistry

Manufacturing is critical to a sustainable world economy. It is the key engine that drives innovation and creates higher value jobs in both developed and developing countries (Liveris 2012). Industrial manufacturing has a heavy environmental footprint. First, it requires a significant amount of materials, energy and water. Second, it generates a lot of wastes (gaseous, liquid and solid) and toxic by-products that need to be disposed of or converted into harmless products. Nanotechnology is emerging as an enabling platform

Table 2 Nanotechnology and materials criticality reduction strategies in clean and renewable energy systems (Fromer and Diallo, J Nanopart Res (2013) 15:2011)

Systems	Components	Critical materials	Materials criticality reduction strategies
Wind turbines	Generators	Neodymium dysprosium	Develop nanostructured REPMs that utilize less amounts of neodymium and dysprosium
			Use non-critical materials and earth-abundant elements to develop nanocomposite "exchange spring magnets" by coupling nanoparticles with s hard and soft magnetic domains to achieve high energy density and coercivity
Electric vehicles	Motors	Neodymium, dysprosium	Same strategy as above
	Li-ion batteries	Lithium, cobalt	Use electrospun nanofibers of earth-abundant elements to prepare more efficient anodes, cathodes and separators for Li-ion batteries
	NiMH batteries	REEs, cobalt	Develop magnesium batteries and new batteries using nanomaterials based on earth-abundant elements
Solar cells	Thin film	Tellurium, gallium, germanium, indium, silver, cadmium	Find new nanostructured and absorbing materials that match the solar spectrum without using critical materials
			Exploit quantum confinement to tune and improve the optical properties of solar cells materials built using non-critical materials
			Exploit advances in nanophotonics and plasmonics to build thin-film solar cells that utilize orders of magnitude less active materials
Solid state lighting devices	LED devices	Gallium, indium	See strategy as above
			Utilize nanoparticles and quantum confinement to improve light emitting efficiency throughout the visible spectrum
	Phosphors	Yttrium, europium, terbium, other REEs	Switch from fluorescent lights to LED lights to decrease the use of phosphors (REEs) by an order of magnitude
			Utilize nanoparticle light emitters to reduce or replace REEs in phosphors
Solar fuel generators	Catalysts	Platinum, palladium, iridium, yttrium	Develop hydrogen/oxygen evolution catalysts using nanomaterials based on earth-abundant elements
			Optimize grain size and exploit quantum size effects to tune band energies/surface states/thermal properties to increase catalyst activity and reactivity

for green manufacturing and chemistry in the semiconductor, chemical, petrochemical, materials processing, pharmaceutical and many other industries (Schmidt 2007; Diallo and Brinker 2011). The article *Nanomanufacturing and sustainability: opportunities and challenges* by Busnaina et al. (2013) discusses the state-of-the-art of nanomanufacturing. The authors argue that rapid and directed assembly based processes (Fig. 4), which are carried out at room temperature and ambient pressure, could significantly decrease the cost of manufacturing equipment and tools and achieve "long-term sustainability" by reducing the consumption of materials, water, energy and the generation of wastes. The convergence between nanotechnology and biotechnology is also providing new opportunities to develop non-toxic and environmentally acceptable "green chemistry" routes for the synthesis of functional nanomaterials using bacteria, fungi and plants (Mohanpuria et al. 2008). The article *Synthesis, characterization and mechanistic insights of mycogenic iron oxide nanoparticle*s by Bhargava et al. (2013) discusses the biosynthesis of ion oxide nanoparticles (IONPs) using an *Aspergillus japonicus* fungus (AJP01) that was isolated from an iron-rich soil. The authors reported that the AJP01 fungus isolate could utilize a mixture of potassium ferricyanide and ferrocyanide as precursor salt solution to synthesize IONPs with size raging from 60 to 70 nm. They showed that extracellular proteins play a key role in the synthesis and stabilization of the IONPs (Fig. 5). The authors believe that their approach could be utilized to synthesize other classes of nanomaterials.

Nanotechnology for sustainable development: societal perspectives and outlook

Societal perspectives

Brundtland's Commission called the three pillars of sustainability social, economic and environment—suggesting that sustainability requires convergence of all three (Brundtland 1987). Thus, two important goals of global sustainability are to achieve inclusive economic and societal development, which benefits all people while minimizing the impact of human activities on Earth's climate and ecosystems (UN 2012; Diallo et al. 2013). Two articles of this JNR special issue are devoted to societal perspectives associated with the utilization of nanotechnology to advance sustainable development. The article *Nanotechnology for sustainability—what does nanotechnology offer to mitigate complex sustainability problems?* by Wiek et al. (2012) argues that the current research on nanotechnology for sustainable development narrowly "focuses on end-of-pipe applications" such as water purification and energy efficiency. The authors make the case that nanotechnology-based solutions are often proposed without seriously considering other alternatives and/or negative side effects of these technologies. To support their arguments, Wiek et al. (2012) combined the results of discussions form focused interdisciplinary workshops and literature reviews to evaluate the utilization of nanotechnology to address three urban sustainability problems in the Gateway Corridor Community of Phoenix in Arizona (USA): (1) water contamination, (2) energy utilization and (3) childhood obesity. The authors reported that "there is potential for nanotechnology to contribute to a sustainable future, but those

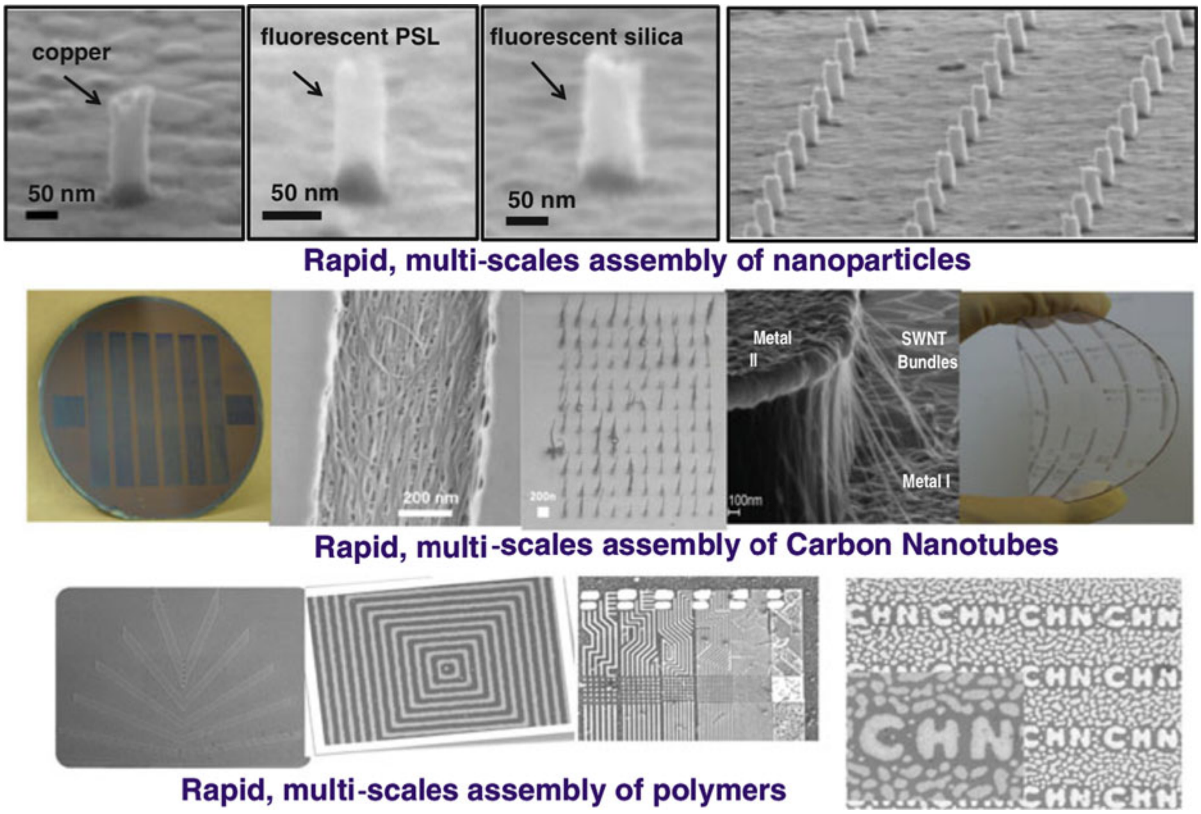

Fig. 4 Sustainable nanomanufacturing processes: rapid assembly of nanoparticles, carbon nanotubes, and polymers in various configurations and orientations [Busnaina et al. J Nanopart Res (2013) 15:1984]

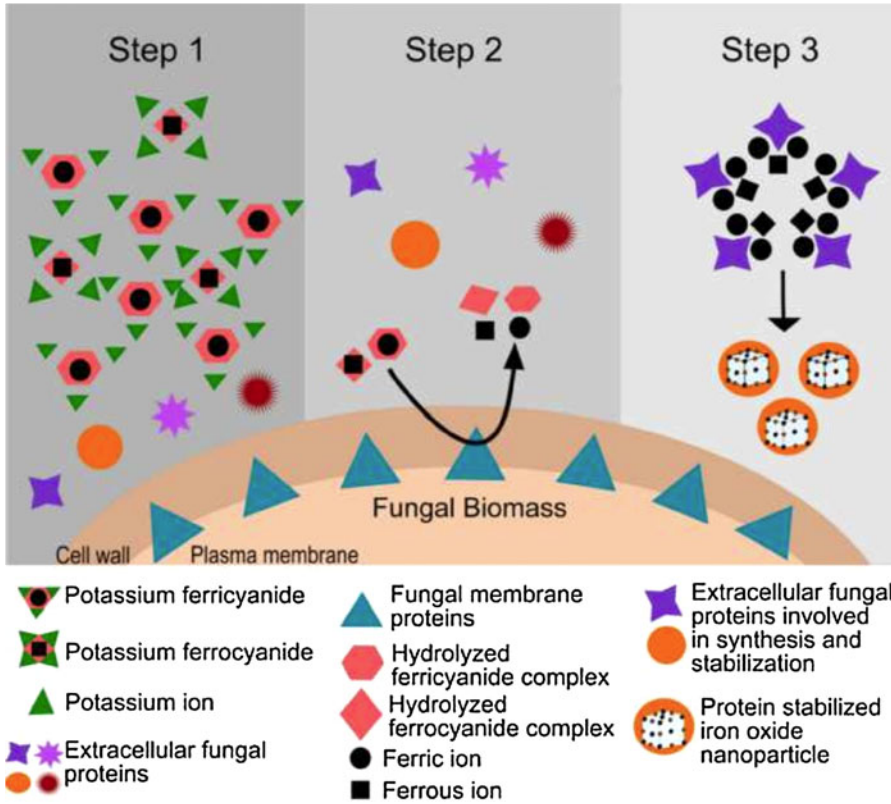

Fig. 5 Biosynthesis of iron oxide nanoparticles using an *Aspergillus japonicus* fungal isolate [Bhargawa et al. J Nanopart Res (2013). In press]

interventions must be coupled with and embedded in systemic intervention strategies, which are not solely reliant on nanotechnology as the silver bullet."

Because sustainability entails considering social, economic and environmental factors, it is critical in all cases to integrate fundamental science (e.g., materials synthesis, characterization and modeling) with engineering research (e.g., system design, fabrication and testing), commercialization (e.g., new products) and societal benefits (e.g., new jobs and cleaner environment) (Diallo and Brinker 2011; Diallo et al. 2013). Thus, nanotechnology solutions for sustainable development cannot simply be addressed at the level of small- and single-investigator funded research grants. Sustainability R&D has to be integrated with broader research goals and included from the beginning in large interdisciplinary programs to be carried out by interdisciplinary teams of investigators and/or dedicated government funded research and development centers (Diallo and Brinker 2011; Diallo et al. 2013). The article *Nanotechnology policy in Korea for sustainable growth* by So et al. (2012) reviews nanotechnology policy for sustainability in South Korea over the past decade. The authors reported that several key policy enactments fostering both fundamental and application-driven research have helped South Korea become one of the leading countries in nanotechnology R&D along with the USA, Japan and Germany. The authors also discuss the current (Third Phase) of Korea's nanotechnology program (2011–2020), which focuses on nanotechnology convergence and integration with the information technology, energy and environmental sectors.

Outlook

The global sustainability challenges facing the world are complex and involve multiple interdependent areas. Nanotechnology has emerged as a versatile platform for the development of technical solutions to global sustainability challenges facing the world. In this JNR special issue, we provided a retrospective of the utilization of nanotechnology to advance sustainable development. More specifically, we discussed the results/findings of selected articles from this special issue to highlight key advances in the following topical areas of global sustainability: (1) water purification, (2) clean energy technologies, (3) greenhouse gases management, (4) materials supply and utilization, (5) green manufacturing and chemistry and (6) societal perspectives. Our retrospective confirms that nanotechnology continues to provide unprecedented opportunities to develop functional materials for sustainable technologies/products with superior electronic, optical, catalytic and magnetic properties. These novel nanomaterials can be processed into various form factors including water-soluble supramolecular hosts, particles, fibers and membranes. Thus, they have emerged as promising building blocks for a broad range of sustainability applications including (1) water treatment, reuse and desalination, (1) energy generation, conversion and storage, (3) CO_2 capture, storage and conversion, (4) environmental monitoring and remediation, (5) material extraction, purification and recovery and (6) manufacturing (Diallo and Brinker 2011; Diallo et al. 2013).

Because sustainability is determined by the coupled interactions between (1) population growth and human needs, (2) societal and cultural values and (3) the human-built environment and Earth system's boundaries (Diallo et al. 2013; Tonn et al. 2013), it is vital to take into account the complex linkages between the "social system" (i.e., the institutions that support human existence on Earth), the "global system" (i.e., the Earth's ecosystems that support human life) and the "human system" (i.e., all the other factors that impact the health and well being of humans) to achieve global sustainability (Rapport 2007; Diallo et al. 2013). Following the June 2012 Rio Conference on Sustainable Development, the United Nations began developing its post-2015 development agenda (UN System Task Team 2012). Three guiding principles of this new agenda are (1) human rights, (2) equality, and (3) sustainability. The implementation of the post-2015 UN development agenda will require transformative changes in the ways we produce and consume goods, manage our natural resources, and govern our society. In addition, the convergence of knowledge, technology and society (CKTS) will also be required to produce the transformative advances and revolutionary technology/products critical to realizing a sustainable, healthy, secure, and peaceful world (Diallo et al. 2013). We expect that nanotechnology to continue to be a critical component of CKTS as its offers the potential to expand the limits of sustainability and address all critical needs of human development on Earth including basic commodities (e.g., energy, water and food), finished goods (e.g., cell phones, cars and airplanes) and services (e.g., shelter, healthcare and employment). However, it is critical to make sure that any potential adverse effects of nanotechnology on human health and the environment are effectively assessed and addressed before the large-scale deployment of nanotechnology-based solutions and products for the global sustainability challenges facing the world in the next 10–20 years.

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