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FEATURE ARTICLE

Nanotechnology in a world out of balance

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INTRODUCTION

As the world population marches towards the 9 billion mark by 2050, factors critical for the sustenance of the ecosystems will come under increasing stress. Having crossed the 7 billion figure in 2011, the 9 billion mark may well be reached much earlier based on population predictions depending on advances in science and behavioural changes. How humanity will address the depletion of resources crucial to our survival will have a bearing on life style, societal values and peace on the planet. Mankind appears to have tipped the scale in favour of population versus resources, probably for all time, and the balance of resources and their use is no longer in our favour (United Nations, 2005). In April 2005, the Millennium Ecosystem Assessment carried out by the United Nations (2005) indicated that "*...the ability of ecosystems to sustain future generations can no longer be taken for granted* ". In the same year, in a significant development, the United Nations in its Millennium Project Report (2005) addressed the potential of nanotechnology for sustainable development. Salamanca-Buentello *et al*. (2005) in their assessment of nanotechnology for developing the world have listed 10 areas for nanotechnology development, aligned with the Millenium Development Goals (MDGs).

As science and technology are crucial to development (von Weizsäcker *et al*., 1997), nanotechnology as an emerging technology must inevitably address problems of sustainable development created by earlier technologies in the past two hundred years, on one hand, and those that the new technology will generate on the other. This article highlights some critical issues and prioritizes applications of nanotechnology, which can contribute to sustainable development, in the light of particular problems faced by the emerging economies.

Nanotechnology and sustainability

Nanotechnology can be defined as research and development at the atomic or molecular scale and involves manipulating and manufacturing structures less than 100 nm across (Bleeker *et al.*, 2004). If nanotechnology is to lead the way to sustainable development, then it must fulfill the needs of the current generation without depleting the opportunities of the future generations (Fleisher & Grunwald, 2007). Currently there is increasing awareness of the role of nanotechnology as an enabling technology rather than an original technology. Thus, in many examples the nano-component will be a crucial part of a more complex product. Therefore, nano-enabled components will continue to arise in energy technology, information and communication technology and biotechnology. Importantly, according to Fleisher and Grunwald (2007) all these technologies with their own sustainability issues make cross connections, facing head on societal acceptance or rejection. There is a prevailing consensus among scientists and engineers that nanotechnology applications will consume less energy and material, generate less waste and pollution while giving the same or even more benefits - the classical situation of more from less. In addition, there is reasonable potential on the one hand for more advanced countries to reduce the environmental footprints of their industrial processes and for the developing countries to address their critical sustainability issues on the other (Salamanca-Buentello *et al*., 2005).

In this backdrop it is crucial for the developing world to ask how nanotechnology can address the areas

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identified by the United Nations Report of the World Summit on Sustainable Development (2002), which need, urgent attention: water, agriculture, nutrition, health, energy and the environment.

***Water*:** Oceans, saline ground water and saline lakes, contain 97.5 % of the total amount of water of the planet (Shiklomanov, 1993). Of the remaining 2.5 % of fresh water, only 1.3 % is available as surface fresh water, the rest being hidden away in ground water, glaciers and ice caps. Of this meager amount of fresh water, nearly 74% is present as ice or snow. Thus, understanding how little is available for human consumption, places pollution of water bodies in a catastrophic perspective. Highlighting the seriousness of the water shortage issue, some have predicted that "*by 2025 more than half of the world population will be facing water-based vulnerability*" (Kulshreshtha, 1998). The three major types of contaminants in drinking water are halogenated organics including pesticides, heavy metals and microorganisms (Pradeep & Anshup, 2009). The high surface area to volume ratio of nanoparticles increases the availability of atoms and molecules for adsorption of pollutants. Some notable applications are, magnetic nanoparticles (Yavuz *et al*., 2006) and titania nanoparticles for removal of arsenic, silver nanoparticles supported on alumina for removal of pesticides and halogenated organics, hydrous polymer based iron oxide nanoparticles for removal of arsenic, chromium, vanadium and uranium and more recently the use of heavy metals for the removal of organic pollutants (Pradeep & Anshup, 2009).

***Energy*:** If new oil supplies are not harnessed, by 2020 the Middle East will control 83% of global oil supplies, and by 2070, there may be no more cost effective oil supplies available (United Nations, 2005). On the other hand, worldwide energy demand is expected to increase by 2% per year until 2035 (Fabricant & Farnsworth, 2001). Ironically over 2 billion people in the developing world have limited access to energy. In addition, since the highest growth rates are also in regions of high fossil fuel usage, the carbon dioxide emissions are expected to outpace energy consumption (Flieisher & Grunwald, 2008). The climate watchers constantly worry about what the tipping point of atmospheric carbon dioxide concentration is. In harnessing sunlight for electric power, the currently used photovoltaic technologies are of limited use because of low conversion and high cost (Serrano *et al.*, 2009). Nanostructured photovoltaic devices using quantum dots, which allow sunlight to be harnessed from a broader range of wave lengths can dramatically reduce cost (Ross & Nozik, 1982). Though highlighted early, these processes are yet to show promise in scaled up systems.

Although hydrogen is an alternative to fossil fuels, its formation, storage and conversion to electricity are facing technological challenges. However, in the use of water as a renewable resource to produce hydrogen, the use of nanophoto catalysts have shown promise. It is estimated that such new processes cannot be expected to be in operation until about 2035 (Ni *et al.*, 2007).

***Agriculture and nutrition*:** The neglect by governments and international agencies of agriculture relevant to the poor, the current worldwide economic crisis, and the significant increase of food prices in the last several years have made close to a billion people, mostly in the developing world suffer due to malnutrition. One of the major problems in agriculture is the loss of the macronutrient nitrogen to the environment from urea used in fertilizer applications. This loss of nitrogen, exceeding 50 – 60% in the form of urea, is due to the conversion to water soluble nitrates, gaseous ammonia and incorporation into the soil by microorganisms (Monreal *et al.*, 1986). Mitigating the loss of nitrogen is one way of reducing the cost of food production. However, there has been little research into increasing the efficiency of nitrogen use. Owing to the high surface area to volume ratio of nanoparticles, nanofertilizers (Kottegoda *et al.*, 2011) will enable the uptake of fertilizer by plants in a slow and sustained manner, which would be more efficient, lead to cost savings and less environmental damage than even polymer-coated conventional slow release fertilizers (De Rosa *et al.*, 2010).

In other applications, pesticides bound to nanoparticles effect timed-release (Lauderwasser, 2008). Nanobiosensors are being developed for detecting harmful pathogens such as *E. coli* (Majid *et al.*, 2008). Bionanocomposites, which are hybrids between a biopolymer such as cellulose, clays such as montmorillonite and a plasticizer such as glycerol, when used in packaging increases the shelflife and protects food as well (Sozer & Kokini, 2009). Bioactive food additives such as probiotics, prebiotics, vitamins and flavanoids can be encapsulated in bioactive packaging and released when needed, into the food products (Lopez-Rubio *et al.*, 2004).

***Environment*:** Having altered one half of the planet's land surface, humanity is in dire straits (Vitousek *et al.*, 1997). According to the United Nations estimates, the amount of wastewater produced annually is about six times more than what is available in all the rivers of the world (UNWWAP, 2003). Pollution of rivers and lakes from chemical substances (including agricultural chemicals) and eutrophication (including abnormal

growth of toxic algae) coupled with water shortages and tropical forest destruction is more widespread now; recently the United Nations Environmental Programme stated that "*the human population is living far beyond its means and inflicting damage on the environment that could pass points of no return"* (UNEP, 2007). In addition, air pollution due to increased levels of SO_2 and suspended particulate matter is rising in urban areas of the developing world. It has been predicted that to reverse climate change, greenhouse gas emissions must be reduced by 50% by 2050 (UNEP, 2007). On the other hand, it has been hypothesized that while air pollution levels might go up as a developing country undergoes industrialization while increasing its agricultural production, this trend will be mitigated as the gross domestic product (GDP) increases (Selden & Song, 1994).

The promise of nanotechnology in addressing environmental pollution related problems is predominantly in the area of nanosensors. A variety of nanomaterials such as gold nanoparticles (Pan *et al.*, 2007), carbon nanotubes (Cui *et al.*, 2007), magnetic nanoparticles (Pan *et al.*, 2007) and quantum dots (You *et al.*, 2007) are increasingly been used as biosensors to detect pollutants because of the unique physical, chemical, mechanical, magnetic and optical properties, which aid in the enhancement of selectivity and sensitivity of detection. In another noteworthy application, liposome based biosensors have been successfully employed for the detection of organophosporous pesticides such as dichlorvos and paraoxon at very low concentrations (Vamvakaki & Chaniotakis, 2007). A key thrust area of nanomaterial based biosensors is the development of single molecule biosensors and high throughput biosensor arrays (Kerman *et al.*, 2008). It is reasonable to assume that such biosensors will be broadly applied to environmental monitoring in the near future (Zhang *et al.*, 2009).

***Medicine*:** In the United States, about 75% of the manufactured prescription drugs are synthetic (Cordell & Colvard, 2007). The remaining 25% are derived from natural sources and they rely on organic solvents for extraction and purification. Therefore, the entire global pharmaceutical industry is dependent on the petrochemical industry and when the global competition for oil increases, healthcare for the majority of the developing world will be undermined (Cordell & Colvard, 2007). Nanotechnology has shown promise in making medicines more effective and low cost, by assembly and immobilization of biomolecules in a synergistic manner (Zampa *et al.*, 2007). Nanomedicine is defined broadly as either "*use of molecular tools and knowledge of the human body for medical diagnosis and treatment*" (Royal Society & Royal Academy of Engineering, 2004) or "*one that makes use of physical effects occurring in nanoscale objects that exist at the interface between the molecular and macroscopic world in which quantum mechanics still reigns* "(Sato & Webster, 2004).

The areas where there is active research and development in nanomedicine are theranostics, targeted drug delivery and regenerative medicine. Theranostics, is a fusion of diagnosis and therapy, which leads to better treatment of disease. Nanoparticle-based imaging and therapy are on the verge of entering clinical trials (Xie *et al.*, 2010). In a recent finding, gold nanoparticles were delivered to target cells and intracellular plasmonic nanobubbles were optically generated and controlled through laser fluence (Lukianova-Helb *et al.*, 2010); significantly, the plasmonic nanobubbles were tuned in within cells for non-invasive high-sensitive imaging at lower fluence and disruption of cellular membrane at higher fluence. In targeted drug delivery, the pharmaceutical agent is delivered specifically to the diseased cell (Kim & Dobson, 2009). Thus, small doses of medicine can be used at just the right place leading to potential cost reductions and fewer side effects. Regenerative medicine uses nanoparticles containing gene transcription factors and other modulating molecules that carry out the reprogramming of cells *in vivo* (Zarbin *et al.*, 2010).

Specific to the developing world, nanobiotechnology has the capability to address three of the United Nations Millennium Development Goals (UNESCO, 2006): reducing child mortality, improving mental health and combating HIV/AIDS (das Neves *et al.*, 2010), malaria and other diseases. However, in comparison to the the total pharmaceutical and medical device market, nanomedicines are just emerging and research into the modification of nanoscale carriers remains to be done in order to know more about circulation lifetime, biodistribution and penetration of biological tissues (Wagner *et al.*, 2006).

Life cycle assessment of the potential benefits of nanomaterials and health, safety, and environmental risks

As is seen from the foregoing, nanotechnology can make a paradigm shift to make a difference in solving problems created by previous technologies. However, as a new technology, nanotechnology must become sustainable for it to reach the society at large. Therefore, life cycle assessment (LCA) of nanoparticles and nano-enabled products are important in finding answers to issues such

as: (a) How do life cycles of products/devices using nanomaterials compare to those made by conventional materials particularly in the area of energy consumption; (b) What particular phase in the life cycle use the highest amount of energy; (c) Identification of particular end-of-life management issues specific to nanomaterials such as recovery, reuse and recycling; (d) Identification eco-toxicity and human toxicity of nanomaterials (Bauer *et al.*, 2008).

We must come to terms with the inevitability that manufactured nanomaterials and nanostructures will enter our natural world sooner or later, where several types of nanoparticles have shown unintended consequences. For example, silver nanoparticles, which are bacteriostatic, may destroy beneficial bacteria important for breaking down organic matter in waste treatment plants or farms (Murray, 1993). Similar concerns have been expressed about TiO_2 and carbon nanotubes (Donaldson *et al.*, 2004; Schilling *et al.*, 2010). Aerosols resulting from nanoparticles and their manipulation, the resulting agglomerates and their degradation aerosols and suspensions should be cleared of any potential harm to humans and the ecosystem. If we rely only on exposure controls, such attempts will fail in the long term. Therefore, research must strive for performance without toxicity with the implicit assumption that innovation is not attractive enough until we reach that point. The recent announcement that the Continental Western Group "*will no longer issue insurance coverage for research and development work on carbon nanotubes until their toxicity has been determined*" is noteworthy (Barnard, 2009). Because of the complex and emerging nature with high social cost, nanotechnology must employ a holistic model where risk based and application based research must be integrated, proactively minimizing health and ecological risks.

It has been recommended that public participation with nanotechnology should be 'upstream' in nature (Rogers-Hayden, 2007), reflecting its occurrence before commercialization in real-world applications and undoubtedly before significant social controversy, as was the case in genetically modified foods. Significantly, for the first time in the history of science, with respect to nanotechnology, scientists and citizens are engaged in healthy public debates over the new technology. Risk perception analysis indicates that the technology's acceptability will depend upon people's perceptions of both benefit and risk, with the balance between the two depending upon the particular technology or the context within which judgments are formed (Pidgen *et al.*, 2009). Interestingly, nanotechnology surveys in the United States and United Kingdom show two clear findings. The first is that most people know little or nothing about nanotechnologies. Second, notwithstanding this, many feel that nanotechnology's future benefits will outweigh its risks (Pidgen *et al.*, 2009).

CONCLUSION

Nanotechnology, as it forges ahead, can make a significant impact on addressing the sustainability crises faced by the emerging economies. In addition, it is highly conceivable that the large majority of nanomaterials containing products that reach the market will fulfill the standards of efficacy and safety, assuring that toxicity assessment and environmental impact audits will closely follow innovation. In the end, scientists and engineers who envision and practice nanotechnology must charter a course, which leads both to technological advancement and sustainability. Through these exciting yet challenging times, the developing world must prioritize the application of nanotechnologies, which lead to sustainability, halting further erosion of the ecosystem.

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