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Nanoparticles for environmental clean-up: A review of potential risks and emerging solutions

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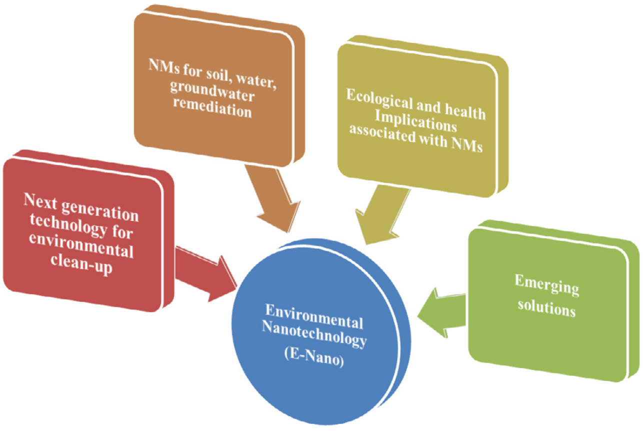
HIGHLIGHTS

- Current status of nanotechnology for environmental clean-up.
- Ecological and human health risks associated with the use of nanomaterials.
- Sustainable, advanced engineered and regulatory measures for existing problems.
- Emerging trends and prospects of nanoremediation.

GRAPHICAL ABSTRACT



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ABSTRACT

Nanotechnology is playing an increasingly important role in addressing innovative and effective solutions to a vast range of environmental challenges. In recent years, nanoscale zero valent iron (nZVI), carbon nanotubes and nano-fibers have been applied for the remediation of a variety of contaminants including chlorinated compounds, hydrocarbons, organic compounds and heavy metals. The use and development of nanomaterials (NMs) are understandably heralded as an environmentally beneficial technology; however the ecological risks associated with their use have only begun to be assessed. This critical review highlights (i) the successful applications of nanotechnology for environmental clean-up,

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Nanomaterials
Risks and recommendations of E-Nano

(ii) the potential ecological implications of environmental nanotechnology (E-Nano) involving use of nanomaterials and (iii) the potential solutions to current E-Nano related implications. Although there is undoubtedly cause for concerns among the scientific community over nanotechnology risk management, the efficacy of E-Nano is unquestionable. Hence, to advance this field in a rational manner without causing further environmental damage, we suggest an integrated preventive approach. This includes innovative greener routes for nanoparticle synthesis; advanced engineering ways for manufacturing smarter and more degradable NMs; and governing local and international legislations to monitor nanoparticles released into the environment. The aims of these recommendations is to promote the responsible innovation of NMs and its cautious use in order to take optimal advantage of E-Nano, minimizing potential risks which is a crucial aspect to improve environmental quality rather than to cause additional damage.

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1. Nanotechnology: the next generation technology

'Nanotechnology' as a field has emerged in 1980s through convergence of K.E. Drexler's theoretical and public work has now gained a worldwide attention among both the scientific and public community. Nanotechnology is defined as "the understanding and control of matter at dimensions between 1 and 100 nm, where unique phenomena enable novel applications" (National Nanotechnology Initiative, 2009). As of 2012, it is estimated that over 1300 manufacturer-identified nanotech products are publicly available with new products hitting the market at a pace of 3–4 per week (Bondarenko et al., 2013). In recent years, nanotechnology has spread through all sectors of science and technology including engineering, medical, pharmaceutical, agriculture, environment and many more. Among several general applications of nanotechnology, the use of nanomaterials (NMs) like titanium dioxide and zinc oxide in the production of cosmetics, sunscreens, surface coatings and some food products represent successful applications of this technology. Silver nanoparticles are getting widely used in food packing, clothing, disinfectants, household appliances, bandages and water purification systems. In addition, the use of carbon nanotubes in solar panels (Royal Society and Royal Academy of Engineering, 2004) provides further evidence of the commercial impact of nanotechnology. The worldwide investment in nanotechnology research and development has been reported to be increased approximately nine-fold from $US 432 million in 1997 to about $US 4100 million in 2005 (Roco, 2005). $US 1 trillion worth of products worldwide are expected to incorporate nanotechnology in key functional components by the year 2015 (Roco, 2005), of which high end estimates suggest that 17% may end to soils, 21% to water and 2.5% to air, with balance entering landfills (Keller and Lazareva, 2013). These estimates were based on a broad industry survey in America, Europe, Asia and Australia. The numbers of patents have also increased worldwide rapidly from 224 in 1991 to 12,776 by 2008, with the United States leading the nanotechnology patents with more than 5000 from 1990 to 2009 (Dang et al., 2010; Roco et al., 2011). The number of US patents issued in nanotechnology was more than 6000 in 2013, a 17% increase over 2012 (Jordan et al., 2012). The top five countries which published nanotechnology patent literature in United States Patent and Trade Office (USPTO) by 2013 in the major sectors of electronics, automotive, healthcare, energy and consumer products are presented in Fig. 1 (McDermott Will and Emery, 2013). The lack of data on patents applications in environmental sector, gives a clear indication that environmental nano-remediation needs a major boost to conduct innovative research.

There are currently increasing efforts to use nanotechnology in the environmental sector (Environmental nanotechnology, E-Nano), which improves the overall effectiveness of remediation methods through the application of nanoscale particles. Several studies and commercial reports presented so far have highlighted the benefits of nanotechnology for environmental clean-up (Cao et al., 2005; Continental Remediation LLC, 2009; Gavaskar et al., 2005; Ghasemzadeh et al., 2014;

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