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Green Nanotechnology

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Abstract

Nanotechnology has been defined as the understanding and control of matter at dimensions of roughly 1 - 100 nanometers. Nanotechnology is still in its infancy but some of its potential health and safety hazards have been with us for a long time since extremely small particles can pose threats to health and the environment. Due to widespread use in consumer products it is expected that nanomaterials will find their way into aquatic, terrestrial and atmosphere environments. The chemical and physical methods for production of nanomaterials are expensive, labor-intensive, and potentially hazardous to the environment. There is an urgent need to develop environmentally friendly methods of synthesis of nanoparticles through techniques that are not only safe for the environment but cost effective as well. Green nanotechnology aims to not only contribute nanoproducts that provide solutions to environmental challenges, but also to produce nanomaterials without deteriorating the environment or human health.

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Introduction

Technology refers to the application of knowledge for human benefits. Nanotechnology has been defined as 'the understanding and control of matter at dimensions of roughly 1 - 100 nanometers, where unique phenomena enable novel applications'[1]. Nanotechnology is unique in the sense that it enables us to observe, synthesize and manipulate things at the nanometer scale[2]. The word *nano* is derived from the Greek word meaning 'dwarf' and a Nanometer (nm) is an SI (Système International d'Unités) unit of length. In dimension terms nanometer is 10^{-9} or a distance of one-billionth of a meter[3,4]. Nanotechnology is not restricted to one specific area, but represents a variety of disciplines ranging from basic material science to personal care applications. Nanotechnology is a techno-scientific platform, whereby a range of existing techno-scientific disciplines like physics, chemistry, biology, biotechnology, information technology and engineering are able to shift down to the molecular level[5]. Nanobiotechnology is the combination of nanotechnology with biotechnology which helps us to design and produce biological materials or devices with specific function by modifying processes occurring at the nanoscale level[6]. The expanding potential of nanotechnology stems from its interdisciplinary nature, cutting across fields of science, engineering, technology, and their potential applications[4,7]. Nanotechnology has stimulated new research and innovative thinking throughout the scientific world. The rapid rise of nanotechnology has led some technologists to call it the next industrial revolution.

Although nanoparticles have been used since a very long time, the primary concept of nanotechnology was presented on December 29, 1959 by Richard Feynman during the annual meeting of the American Physical Society in a lecture entitled 'There's Plenty of Room at the Bottom'. The term nanotechnology was coined in the year 1974 by Norio Tanigutchi, professor at Tokyo Science University, who referred first used this term while describing precision manufacturing at the scale of nanometers. Nanomaterials are of great scientific interest as they bridge the gap between bulk materials and atomic or molecular structures.

Imaging Techniques

A number of techniques are available for detecting, measuring and characterizing nanoparticles. Different techniques will require different types of sample like an aerosol, a suspension or liquid sample. Microscopes are instruments designed to produce magnified images (visual or photographic) of small objects. A modern light microscope had a magnification of about 1000x and enabled the eye to resolve objects separated by 200 nm. With the popularization of nanotechnology, an urgent need arose for the development of tools dedicated to the characterization of the nano-objects and nano structured materials[8]. Advances in various imaging technologies in the past decades enabled researchers to study biological processes at different levels of resolution. It was discovered in the 1920s that accelerated electrons travel in straight lines and have wave like properties, with a wavelength that is about 100,000 times shorter than that of visible light. It was realized that electric and magnetic fields could be used to shape the paths followed by electrons. Ernst Ruska and Max Knoll combined these characteristics and built the first Transmission Electron Microscope (TEM) in 1931. TEM enabled the instrument's user to examine fine detail of objects which were tens of thousands times smaller than the smallest resolvable object in a light microscope. Electron Microscopy (EM) is capable of visualizing whole cells as well as individual biomolecules, their sub-molecular structure, and individual atoms, but is limited by the high vacuum inside the EM instrument which causes the biological specimen to dehydrate[9].

Solid-state Nuclear Magnetic Resonance (NMR) spectroscopy and X-ray crystallography have been developed to have a greater structural insight into molecules and better understanding of non-covalent interactions and atomic bonds[7]. X-ray crystallography, the first method for structure determination of single biomolecules, has become the most popular method for characterizing atomic structure of bio-macromolecules, ranging from proteins to entire virus entities and has the sensitivity down to 1 nm[10]. However, for both NMR and X-ray crystallography there is a theoretical size limit for the sample to be studied, which renders the structure determination of large supramolecular assemblies unlikely[7]. Recently, the Scanning Probe Microscope (SPM) has opened completely new avenues for analyzing biological material in its aqueous environment and at a resolution comparable to that achieved by electron microscopy[11,12]. The two major kinds are the Atomic Force Microscope (AFM) and the Scanning Tunneling Microscope (STM). SPM enables resolution of features down to about 1 nanometer in height, allowing imaging of single atoms[13]. The SPM has several advantages such as the ability to measure small local differences in object height and no requirement of a partial vacuum. Specimens can be observed in air at standard temperature and pressure, or while submerged in a liquid medium. Hence, the SPM has become a method of choice for directly correlating structural and functional states of biological matter at sub-molecular resolution[14-16].

Hazards of Nanotechnology

Nanotechnology is still in its infancy but some of the potential health and safety hazards have been with us for a long time since extremely small particles can pose threats to health and the environment. There are numerous exposure pathways (both primary and secondary) stemming from greater use of nanotechnology in different sectors that lead to occupational exposure[17]. Depending on the nanomaterial and its specific application, the exposure can occur via inhalation, dermal, oral and parenteral routes[18,19]. The toxicity of nanoparticles is mass-dependent and also dependent on its physical and chemical properties that are not routinely accounted for in toxicity studies[17,20-22]. However, despite significant progress in recent years, the biological and environmental pathways taken by nanomaterials remain largely unexplored[17-20,23]. The potential health impact of a material is gauged by its toxicity and by the amount of material that is able to reach the target organs within the body[24]. There is a big perception that increased exposure of nanotechnology researchers, workers, and consumers to potentially hazardous materials could cause adverse health effects. Research on the biological impacts of nanomaterials is primarily based on information obtained from controlled lab studies of cell cultures and model organisms exposed to high concentrations of nanomaterials in the culture media. However, these studies are of only limited utility in predicting the impacts of engineered nanoparticles under likely environmental exposure scenarios since exposure in an ecosystem occurs at a much lower concentration that is both physically and chemically more complex than a flask or petri dish[25]. Although there are no confirmed reports of human ailments ascribed to nanomaterials till now, experimental evidences indicate that nanomaterials have the potential to initiate adverse biological responses which can lead to toxicological outcome[26].

Experiments at cellular levels and in animal models have shown that some types of nanoparticles are capable of generating pro-inflammatory and pro-oxidative effects that could lead to respiratory pathology[27-32]. Several studies are available that point towards the pulmonary toxicity of metal nanoparticles[33], cationic nanoparticles[34,35] and carbon nanotubes[36,37]. Although adverse cardiovascular effects of engineered nanomaterials in humans have not been reported, some experimental studies have shown that nanomaterials could produce adverse cardiovascular impacts. Engineered nanoparticles may penetrate the pulmonary epithelial cell barrier, enter the systemic circulation, and gain access to the cardiovascular system[30]. Carbon nanoparticles like single walled nanotubes, multi walled nanotubes, and carbon black nanoparticles have been reported to induce human platelet aggregation *in vitro* and promote arterial thrombosis in rodents[38]. Ferric oxide nanoparticles could also exert anticoagulant effects by lengthening of prothrombin time and activation of partial thromboplastin time in rats[39].

Nanomaterials also present a significant problem due to their chemistry, size, and possible non-biodegradable composition due to which they will rapidly distribute throughout the environment and bioaccumulate with consequences that are unknown today. Due to widespread use in various consumer products like creams, sunscreens and lotions it is expected that nanomaterials will find their way into the biosphere where their fate and behaviour are largely unknown[40]. There is still very little research into the potential negative impacts of nanotechnology on the environment. There are ample opportunities for nanomaterials to interact with the environment from their initial production to final disposal[41]. There is a possibility that interaction of nanoparticles with the environment will have deleterious effects. Preliminary investigations on environmental concerns with respect to nanoparticles have primarily revolved around fullerenes which have been reported to be toxic to aquatic life forms[42], leading to speculation that nanomaterials may disrupt ecosystems[40-43]. However, several researchers have debated these results.

The Need for Green Nanotechnology

The nanomaterials have high surface volume ratio due to their extremely small size which makes the physicochemical properties of nanoparticles containing materials quite different to those of the bulk materials. Also, the optical, electronic, and catalytic properties of nanoparticles are greatly influenced by their size, shape, and crystal structure[44]. Due to immense demand, there is an accelerated development of nanomaterials by various methods. From inception nanoparticle synthesis has been done through two approaches[45] (Figure 1):

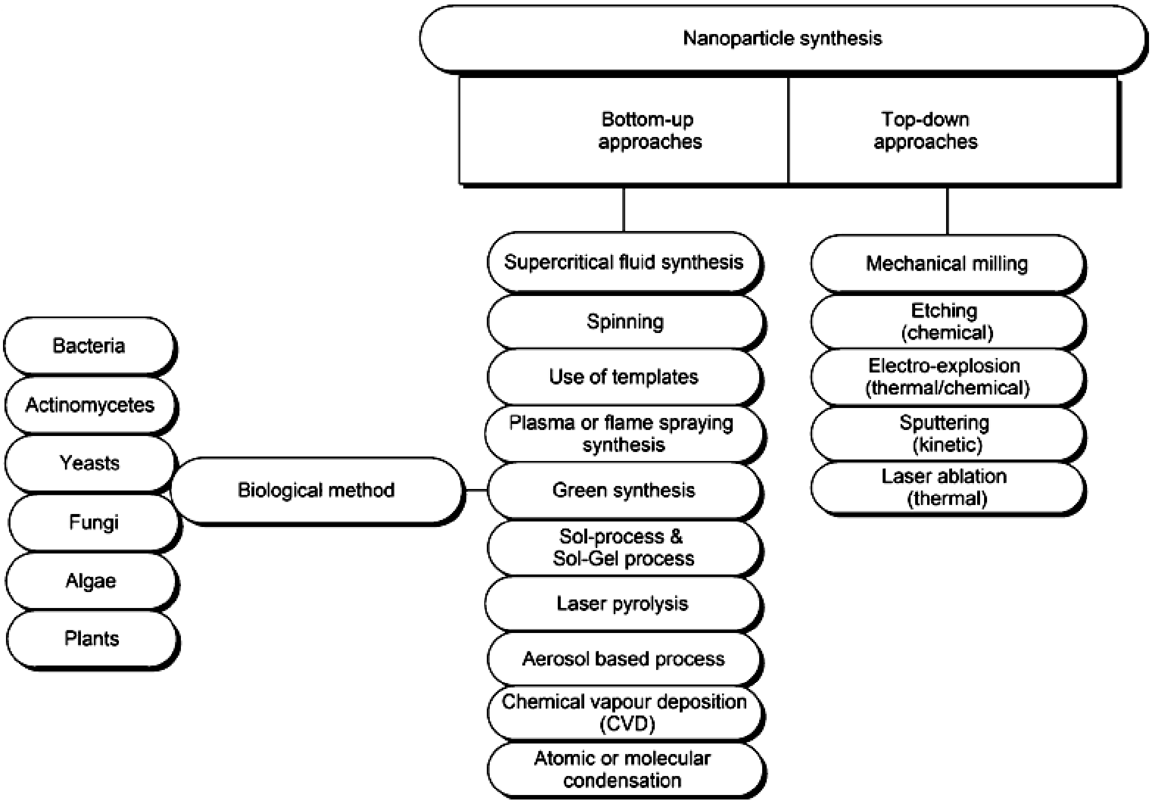

Figure 1: Bottom-up and top-down approaches for nanoparticle production (Iravani 2011)[45].
(A) Top down approach- breakdown method by which a big component is broken down into smaller ones of desired size, and
(B) Bottom up approach- buildup method that starts from atoms and is based on atomic transformations and molecular condensation.

The bottom up approach is mainly divided into gaseous phase methods and liquid phase methods. The top down method is further subdivided into the wet and dry (grinding) methods. The dry method is cost effective but mono-dispersity and surface chemistry control remains a drawback. Using the wet process it is possible to prevent condensation of nanoparticles and we can obtain highly dispersed nanoparticles. However, both the wet and dry methods of nanoparticle production are not environmentally friendly. Their drawbacks include contamination from precursor chemicals, use of toxic solvents, and generation of hazardous by-products. Thus, these production methods are expensive, labor-intensive, and are potentially hazardous to the environment and living organisms. There is an urgent need to develop environmentally friendly methods of synthesis of nanoparticles through techniques that are not only safe for the environment but cost effective as well.

Green Nanotechnology

Green nanotechnology refers to the application of green chemistry and green engineering principles to nanotechnology to evolve methods, materials and techniques for diverse applications like generating energy to non-toxic cleaning products. Green nanotechnology aims to not only contribute nanoproducts that provide solutions to environmental challenges, but also to produce nanomaterials without deteriorating the environment or human health. Green nanotechnology is likely to result in manufacturing processes that are more environmentally friendly and more energy efficient.

There are two key aspects to green nanotechnology[46].
(i) Involves nano products that provide solutions to environmental challenges, and
(ii) Involves producing nanomaterials and products containing nanomaterials with a view toward minimizing harm to human health or the environment.

Green nanotechnology aims to develop sustainable environmentally-sustainable manufacturing processes and solutions to address burning issues like contamination of aquatic bodies, energy shortages and other areas of environmental concern[47]. Green nanotechnology 'sustains' the fourth goal of the National Nanotechnology Initiative[1] i.e. 'supporting the responsible development of nanotechnology' by following existing principles of green chemistry and green engineering. It enables nanotechnology to develop in a more responsible and sustainable manner by minimization or elimination of harmful materials used in the synthesis of nanomaterials or by using the products of nanotechnology to regulate these pollutants in the environment[48]. Green nanotechnology is a sustainable approach to nanotechnology from design to production and product use to disposal or recycling. Thus, the eco friendly approach of green nanotechnology limits the risk of producing nanomaterials and minimizes the production of toxic intermediates and end-products[48]. Green nanotechnology also aims to make current manufacturing processes for non-nano materials and products more environmentally friendly.

Components of Green Nanotechnology

[A] Synthesis of nanoparticles

This forms the most important component of green nanotechnology. As described previously, synthesis of nanoparticles is carried out by several physical and chemical methods. Although chemical and physical methods may successfully produce pure, well-defined nanoparticles, these are quite expensive and potentially dangerous to the environment[49]. There is an urgent need to develop environmentally benign processes in place of synthetic protocols involving toxic ingredients. Use of biological organisms or their biomass could be an alternative to chemical and physical methods for the production of nanoparticles in an eco-friendly manner[49-51]. Moreover, the coating of biological molecules on the surface of nanoparticles makes them biocompatible in comparison with the nanoparticles obtained by chemical methods[52-54]. The biocompatibility of biologically synthesized nanoparticles offers very interesting applications in biomedicine and related fields[55].

A great deal of effort has been put into the biosynthesis of metal nanoparticles using different microbes primarily bacteria and fungi (Table 1). However, green synthesis of various nanoparticles has also been achieved using lower plant forms like algae (Table 2) as well as angiosperms (Table 3). Considering the vast potentiality of microbes and plants as sources, the biological synthesis can serve as a green technique for the synthesis of nanoparticles as an alternative to conventional methods.

Table 1: List of nanoparticles synthesized by microorganisms

Microbes	Nanoparticle	Reference
Bacteria		
Aeromonas hydrophila	Zinc oxide	Jayaseelana et al. (2012)[56]
Bacillus mycoides	Titanium dioxide	Aenishanslins et al. (2014)[57]
Geobacillus sp.	Gold	Correa-Llantén et al. (2013)[58]
Klebsiella pneumonia	Selenium	Fesharaki et al. (2010)[59]
Fungi		
Alternaria alternata	Gold	Sarkar et al. (2012)[60]
Aspergillus flavus	Titanium dioxide	Rajakumara et al. (2012)[61]
Fusarium oxysporum	Cadmium-selenide	Kumar et al. (2007)[62]
Neurospora crassa	Platinum	Castro-Longoria et al. (2012)[63]

Table 2: List of nanoparticles synthesized by algae

Algae	Type of nanoparticle	Reference
Bifurcaria bifurcata	Copper oxide	Abboud et al. (2014)[64]
Caulerpa racemosa	Silver	Kathiraven et al. (2015)[65]
Chlorella vulgaris	Gold	Annamalai and Nallamuthu (2015)[66]
Padina gymnospora	Gold	Singh et al. (2013)[67]
Sargassum muticum	Gold	Namvar et al. (2015)[68]

Table 3: List of nanoparticles synthesized by angiosperms

Angiosperm	Type of nanoparticle	Reference
Aloe vera	Gold, Silver	Chandran et al. (2006)[69]
Azadirachta indica	Gold, Silver	Shankar et al. (2004a)[70]
Eucalyptus oleosa	Silver	Mahdi et al. (2015)[71]
Murraya koenigii	Silver	Christensen et al. (2011)[72]
Sesuvium portulacastrum	Silver	Nabikhan et al. (2010)[73]

[B] Solar cells and nanotechnology

There has been a gradual shift towards development of renewable energy since current fossil fuel usage is unsustainable and associated with greenhouse gas production. Nanoscale systems have allowed new ways of approaching solar energy conversion for electricity generation or production of fuels[74]. Nanotechnology is being used to provide improved performance coatings for solar thermal and photovoltaic panels. Features like hydrophobic and self-cleaning properties create more efficient solar panels, especially during inclement weather. Nanoscale objects have immense potential to revolutionize the conversion of solar energy by enabling highly efficient and low-cost devices[74]. Quantum dot solar cell, nano wire solar cell and mesoscopic solar cell are some types of cells that are being explored. Nanostructured solar cells having long-term stability and low cost can go a long way in promoting human welfare in the coming decades.

[C] Environment remediation

Nano remediation i.e. the use of nanomaterials for environmental remediation is being explored to treat wastewater, ground water, soil, sediment and other environmental contaminants. Nanotechnology offers the potential of using nanomaterials for the treatment of aquatic bodies and other landscapes contaminated by xenobiotics.

Nanotechnology can exploit the solar energy as well as the recent advances in nano-engineered titania photo catalysts and membranes for the destruction of potentially harmful compounds and novel emerging pollutants like pharmaceuticals, toxins and hormones which can have long lasting environmental and health impact[75]. This can ensure availability of clean water at low cost. Nanotechnology can help to combat climate change by bringing new energy sources (developing low-carbon forms of energy) to the market and reducing greenhouse gas emissions. Five areas where nanotechnology can make a significant difference with respect to environmental remediation are:
(a) Development of fuel additives that will increase the efficiency of diesel engines,
(b) Development of photovoltaic technology for solar cells,
(c) Hydrogen economy and fuel cells,
(d) Batteries and super capacitors for energy storage, and
(e) Improved insulation for houses and offices.

Facilitating Green Nanotechnology

Emerging governance strategies and mechanisms should aim to ensure that effective oversight mechanisms are in place to foster the responsible development of nanotechnology[46]. Stakeholders should consider undertaking the following steps to foster the development of green nanotechnology[46]:
(i) Develop a life-cycle assessment appropriate for green nanoproducts.
(ii) Establishing specific standards for green nanotechnology so that such products can be branded as 'green nano'.
(iii) Provide tax and business incentives to innovators to take care of the cost of commercializing a product and the shortage of investment capital which is likely to encourage application of green nanotechnology
(iv) Extended patent term protection for green nanoproducts.
(v) Provide more resources for green nano research in the form of funding and improvement in public-private partnership opportunities.
(vi) Establish a Design for the Environment (DfE) award for 'Green Nano' category.
(vii) Convening a forum to discuss, develop and implement green nano principles in a more systematic way.

Conclusion

The need of today is to foster development but not at the cost of mankind. Thus, there is an urgent need to promote green nanotechnology for human and environmental sustainability. The development and commercialization of viable green nanotechnologies is difficult and require concerted effort from the researchers, government and other stakeholders. The development of this environmentally friendly technology can go a long way in accelerating human welfare.

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