Green Biosynthesis of Nanoparticles

Mechanisms and Applications

Edited by
Mahendra Rai and Clemens Posten

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Preface

There are physical and chemical methods for the synthesis of nanomaterials. But, due to the damage these methods cause to the environment, there is a pressing need for a green nanotechnology that is clean and eco-friendly for the development of nanomaterials. More precisely, green nanotechnology can be developed to minimize the potential environmental and human health risks associated with the fabrication and use of nano-based materials and products.

Recently, biological synthesis has attracted the focus of scientists. The importance of biological synthesis is being emphasized globally, because chemical methods are capital-intensive, use toxic chemicals and have low productivity. Thus, the need for clean, eco-friendly, cost-effective and biocompatible synthesis of metal nanoparticles has encouraged researchers to exploit biological sources as nanofactories. Biological synthesis of nanoparticles is quite novel, leading to a truly green approach that provides advancement over chemical and physical methods, as it is cheaper, environment friendly and easily scaled up for large-scale synthesis. In these methods there is no need to use high pressure, energy, temperature and toxic chemicals.

Different biological systems are exploited for the rapid synthesis of nanoparticles, including bacteria, fungi and plant extracts. Microbes are the 'nanofactories' for the synthesis of nanoparticles.

This book includes the green synthesis of nanoparticles by algae, diatoms, bacteria and plants. Moreover, the mechanisms behind the synthesis of nanoparticles have been discussed.

The book should be immensely useful for students, researchers and teachers of biology, chemistry, chemical technology, nanotechnology, microbial technology and those who are interested in green nanotechnology.

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1 Green Technology for Nanoparticles in Biomedical Applications

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Introduction

A growing number of scientists and engineers are exploring and tweaking material properties at the atomic scale to create designer materials that ultimately might increase the efficiency of current energy sources or make new energy sources practical on a commercial scale. At the nanoscale, fundamental mechanical, electrical, optical and other properties can differ significantly from their bulk material counterparts, and materials can self-assemble spontaneously into ordered structures. Nanostructured materials also have enormous surface areas per unit weight or volume, so that vastly more surface area is available for interactions with the other materials around them. That is useful, because many important chemical and electrical reactions occur only at surfaces and are sensitive to the shape and texture of a surface as well as its chemical composition (Van Hove, 2006; Ashby *et al*., 2009).

Green technologies have been around since the first public health projects were set up in cities to provide people with clean drinking water. Since then, many other green techniques such as scrubbers for smokestacks, catalytic converters for cars, recycling plants, solar panels and energy-efficient appliances have been introduced. To date, a new generation of green technologies is imminent, as pressures on resources grow and investors see a healthy profit in a wide range of innovative products.

With the development of science and technology, a growing number of researchers are merging green chemistry and green engineering with nanotechnology, and these researchers see a bright future for a new field known as 'green nano'. Some want to help green up industries that use emerging nanotechnologies. Others who are working on green technologies such as solar cells, remediation techniques and water filters are turning to nanotechnology in order to achieve their goals of creating better devices to help the environment. These researchers assert that a strong marriage between nanotechnology and green chemistry/engineering holds the key to building an environmentally sustainable society in the 21st century.

Nanoparticles

Unlike bulk materials, nanoparticles have characteristic physical, chemical, electronic,

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electrical, mechanical, magnetic, thermal, dielectric, optical and biological properties (Chuang and Chen, 2011). Decreasing the dimension of nanoparticles has a pronounced effect on the physical properties, which differ significantly from the bulk materials. These physical properties are caused by their large surface atom, large surface energy, spatial confinement and reduced imperfections. Nanoparticles have advantages over bulk materials due to their surface plasmon resonance (SPR), enhanced Rayleigh scattering and surface-enhanced Raman scattering (SERS) in metal nanoparticles and their quantum-size effect in semiconductors and supermagnetism in magnetic materials. Therefore, nanoparticles are considered as building blocks of the next generation of optoelectronics, electronics and various chemical and biochemical sensors, etc. (Hahn *et al*., 2011; Kameya and Hanamura, 2011).

By now, an astonishing multitude of materials ranging from inorganic to polymeric nanoparticles, biological building blocks and nanostructured thin films with many different electronic, magnetic, optical and bio properties have been synthesized and characterized in great detail. The pivotal point is the directed assembly or self-assembly of these systems into hierarchically ordered and/or arbitrarily defined structures. The production and use of nanostructured and nanoscaled materials has become a key technology in many more fields, for example pharmacy (Kathiravan *et al*., 2011; Tran *et al*., 2011), regenerative medicine (Harrison and Sirivisoot, 2011), diagnostics (Zhang and Kataoka, 2009), cosmetics (Kokura *et al*., 2010) and food technology (Dudo *et al*., 2011).

Progress in nanotechnology is aiming not only at miniaturization but also at systems with increased complexity. This is not only just a matter of geometrical structurization but also a matter of specific functionalities that are positioned at discrete locations and in defined distances. Nature and its highly precise mechanisms of life, mainly based on two classes of biomacromolecules, proteins or polypeptides and polynucleic acids, set the benchmark for functional structures down to atomic scales. Thus, the use of biomolecules is considered as an obvious step in the synthesis and construction of next-generation nanomaterials and devices. A whole new branch termed 'bionanotechnology' seeks for scientific as well as economic breakthroughs in the development of bioinorganic nanomaterials with novel properties for computation and nanotechnology, new methods in diagnosis and analytics or new drugs and drug delivery systems (Mahmoud *et al*., 2011).

In medicine, nanoparticles can be used in bioanalysis and as biosensors. Bioanalysis can have a variety of applications. For example, nanoparticles can be used to induce signal transduction, as quantitation identifiers, in bioassays, and finally they can be used for specific functions in biological systems (Penn *et al*., 2003). Maxwell *et al*. (2002) showed that colloidal gold could be used to create biosensors to identify specific DNA sequences and base mutations. It has also been shown that copper–gold bimetallic nanoparticles can be used as oligonucleotide labels for the electrochemical stripping detection of DNA hybridization (Cai *et al*., 2003).

Related to health and environmental issues, it has been shown that nanoparticles can be used in the remediation of organic pollutants in the environment (Obare and Meyer, 2004). Iron nanoparticles have been proven to be effective in the dechlorination of polychlorinated biphenyls. It has also been shown in the literature that bimetallic nanoparticles can be used for groundwater treatment (Elliott and Zhang, 2001). Results show the destruction of trichlorethylene (TCE) and other chlorinated hydrocarbons using bimetallic nanoparticles. The results of this study showed that 96% of the TCE was eliminated within 4 weeks of injecting the nanoparticles.

Over the past few decades, nanoscale particles have elicited much interest due to their distinct chemical, physical and biological properties. A variety of nanoparticles (NPs) with various shapes such as spheres, nanotubes, nanohorns and nanocages, made of different materials, from organic dendrimers, liposomes, gold, carbon, semiconductors, silicon to iron oxide, have already been fabricated and explored in many scientific fields, including chemistry, materials sciences, physics, medicine and electronics.

The novel properties of NPs, attributed primarily to the quantum size effect, are confronted by their conventional ecologically hazardous synthesis protocols (Jackson and Halas, 2001). Endeavours are under way to develop greener avenues in the domain of nanotechnology. It is pertinent to mention that carbohydrate-templated silver NPs (Babu *et al*., 2010) have carved a unique niche in the domain of nanobiotechnology with an immense spectrum of applications, particularly as antimicrobial biopolymer nanocomposite. Macromolecules such as starch, when used for encapsulation or entrapment of inorganic particles, can impart novel properties to the latter (Ziolo *et al*., 1992). Enhanced compatibility, reduced leaching and protection of surfaces from damage, with concomitant improvement in dispersibility and stability of the NPs, are a few of the desired facets of polymer-templated nanomaterial over uncoated counterparts (Bourgeat-Lami and Lang, 1998).

Green Nanoparticles

Silver nanoparticles

Nanotechnology is emerging as a cutting-edge technology interdisciplinary with biology, chemistry and material science. Silver nanoparticles (Ag-NPs) are important materials that have been studied extensively. Such nanoscale materials possess unique electrical, optical, as well as biological properties and are thus applied in catalysis, biosensing, imaging, drug delivery, nanodevice fabrication and medicine (Smith *et al*., 2010). Due to strong antimicrobial activity, Ag-NPs are also used in clothing, the food industry, sunscreens and cosmetics (Kokura *et al*., 2010). Additionally, Ag-NPs have been shown to undergo size-dependent interactions with HIV-1 and inhibit binding to the host cell *in vitro* (du Toit *et al*., 2010; Shegokar *et al*., 2011).

Although different techniques such as ultraviolet irradiation, aerosol technologies, lithography, laser ablation, ultrasonic fields and photochemical reduction have been used successfully to produce metal NPs, they remain expensive and sometimes involve the use of hazardous chemicals (Butkus *et al*., 2003; Ashby *et al*., 2009). Consequently, green synthesis of NPs has received increasing attention due to the growing need to develop an environmentally benign technology in nanoparticle synthesis. Several biological systems including bacteria, fungi, yeast and plants have been used in this regard (Nabikhan *et al*., 2010; Shivaji *et al*., 2011; Zaki *et al*., 2011). Although the green synthesis of Ag-NPs by various plants has been reported, the potential of plants as biological materials for the synthesis of NPs is yet to be explored fully. In addition, information on the biological response of human cells to green synthesized Ag-NPs is also very limited.

Furthermore, it should be noted that lack of access to potable water is a leading cause of death worldwide. Dehydration, diarrhoeal diseases, contaminated water sources, waterborne pathogens, water needed for food production (starvation) and water for sanitation are just some of the factors that impact health. The water–health nexus is crucial for the survival of humanity. Meanwhile, people all over the world face profound threats to the availability of sufficient safe and clean water, affecting their health and economic well-being. The problems with providing clean water economically are growing so quickly that incremental improvements in the current methods of water purification could leave much of the world with inadequate supplies of clean water in mere decades. Recent advances strongly suggest that many of the current problems involving water quality can be addressed and potentially resolved using nanosorbents, nanocatalysts, bioactive nanoparticles, nanostructured catalytic membranes and nanoparticle-enhanced filtration, among other products and processes resulting from the development of nanotechnology (Zäch *et al*., 2006; Ashby *et al*., 2009; Van Hove, 2009). Moreover, nanotechnology solutions are essential because the abiotic and biotic impurities most difficult to separate in water are in the nanoscale range. At the same time, nanotechnology has enabled the development of a new class of atomic-scale materials capable of fighting waterborne disease-causing microbes. The explosive growth in nanotechnology research has opened the doors to new strategies using nanometallic particles for oligodynamic disinfection (Anshup, 2009; Diallo *et al*., 2009). The excellent microbicidal properties of the oligodynamic NPs qualify their use as viable alternatives for water disinfection. Oligodynamic metallic NPs such as silver, copper, zinc, titanium, nickel and cobalt are among the most promising nanomaterials with bactericidal and viricidal properties owing to their charge capacity, high surface-to-volume ratios, crystallographic structure and adaptability to various substrates for increased contact efficiency. This new class of nanometallic particles produces antimicrobial action referred to as oligodynamic disinfection for their ability to inactivate microorganisms at low concentrations. When oligodynamic metals with microbicidal, bactericidal and viricidal properties are reduced to nanosize scale, they show tremendous advantages in disinfection capacity due to the greater surface area, contact efficiency and often better elution properties. These qualities enable materials such as silver (Ag), copper (Cu), zinc (Zn), titanium (Ti) and cobalt (Co) to be considered as viable alternative disinfectants. New combinatorial oligodynamic materials consisting of these nanometallic particles have been deployed among a number of substrates for their use in water disinfection (Kim *et al*., 2006). Materials such as Ag deposited on titanium oxide and Ag-coated iron oxide have displayed faster kinetics and greater efficiency in eliminating bacteria.

To date, Ag is the most widely studied oligodynamic material due to its wide range in microbicidal effectiveness, low toxicity and ease of incorporation on various substrates in a host of dynamic disinfection applications. Furthermore, the systems supported with nanometallic Ag particles are effective in reducing the presence of target microorganisms in a wide variety of water disinfection applications. The main known negative health effect from Ag is argyria, which is an irreversible darkening of the skin and mucous membrane resulting from overexposure to ionic silver (Ag(I), Ag+) (Butkus *et al*., 2005).

Typically, Ag-NPs are derived from silver salts (silver nitrate ($AgNO_3$), silver chloride (AgCl), silver bromide (AgBr) and silver iodide (AgI)), and a variety of the substrates that Ag is deployed on, such as activated carbon, activated carbon fibres (ACFs), polyurethane, zeolites and ceramics in point of entry (POE) and point of use (POU) applications, display the effective inactivation of pathogens in water (Byeon and Kim, 2010).

Wang *et al*. (1998) prepared viscose-based activated carbon fibre supporting silver (ACF(Ag)) by pretreatment, carbonization, activation, vacuum impregnation and decomposition processes. The ACFs were then subjected successively to a vacuum impregnation treatment in unsaturated silver nitrate (analytical grade) aqueous ($AgNO_3$) solutions ($NH_4H_2PO_4$ 3.3 gl^{-1}, $(NH_4)_2SO_4$ 6.7 gl^{-1}) with varying concentrations for different times and were finally heated to different temperatures for decomposition, thus producing ACF(Ag). Moreover, ACF(Ag) containing as little as 0.065 wt% of Ag exhibits strong antibacterial property against *Escherichia coli* and *Staphylococcus aureus*.

Garlic (*Allium sativum*) has long been considered a herbal remedy to prevent and treat various metabolic diseases such as thrombosis, hypertension, diabetes, dementia and atherosclerosis. Garlic is a very good source of vitamin C and vitamin B6, along with beta-carotene, thiamine, riboflavin, niacin and folate, which function as antioxidants. Recently, Ahamed *et al*. (2011) studied a simple, cost-effective and environmentally benign synthesis of Ag-NPs at ambient conditions using garlic clove extract as a reducing and stabilizing agent in order to apply the biological response of Ag-NPs in human lung epithelial (A549) cells.

Furthermore, Guidelli *et al*. (2011) investigated a totally green synthesis of colloidal Ag-NPs using the natural rubber latex (NRL) extracted from *Hevea brasiliensis*. The synthesis was fast and occurred at a relatively low temperature (water boiling temperature). Moreover, it was very simple, inexpensive and environmentally benign, devoid of photochemical, electrochemical or irradiation processes. The colloidal particles could be used and stored in their liquid form, or even as a film obtained by drying the starting solution. Combining the angiogenic properties of the NRL and Ag-NPs, the nanostructured material obtained could be used in a wide range of applications such as a hybrid biopolymer, and was aimed at the fabrication of a wound dressing with potential healing action. Also, the Ag-NPs could protect the wound against microorganism contamination.

The results showed that the formation of Ag-NPs was increased on raising the NRL and $AgNO_3$ content. The particle size seemed to be related to the $AgNO_3$ concentration, in such a way that larger Ag particles were produced when more $AgNO_3$ was added to the reaction medium. The dynamic light scattering technique and the transmission electron microscope (TEM) micrographs suggested the formation of aggregates of Ag-NPs by increasing the $AgNO_3$ concentration.

Gold nanoparticles

Today, a cadre of research scientists and engineers is working to develop cutting-edge methods for the green manufacturing of nanoelectronics and other nanoproducts that are more people/planet friendly, such as gold (Au) NPs, which are promising materials for use in new kinds of electronics and medical imaging. It is well known that Au-NPs have been considered an important area of research due to their unique and tunable surface plasmon resonance (SPR) and their applications in biomedical science, including drug delivery, tissue/tumour imaging, photothermal therapy and immunochromatographic identification of pathogens in clinical specimens (Chen *et al.*, 2010; Kim *et al.*, 2010; Cao *et al.*, 2011). The use of Au compounds and Au-NPs, with respect to their potential therapeutic applications such as anti-angiogenesis, as an antimalarial agent, an anti-arthritic agent, and as an agent in biohydrogen production, has driven various breakthroughs in the field of nanotechnology. The standard method to synthesize Au-NPs uses large amounts of toxic solvents that can be flammable and explosive.

An innovative synthesis method investigated by J.E. Hutchison uses non-toxic solvents, a new catalyst and purification by nanoporous filtration. This technique not only has proved to be greener, safer and faster than the old method but also is much cheaper, showing that the green synthesis of nanomaterials can boost efficiency and save money (Hutchison, 2008).

As one of the world's healthiest foods, the major constituents of honey are fructose and glucose, and it also contains amino acids that help build up calcium (Ca) in the body. All over the world, honey has been subjected to extensive study of its ingredients, physicochemical properties, vitamins, mineral content and quality control. It is reported to benefit human longevity due to its high energy and presence of chemical elements, vitamins and enzymes. Honey is rich in vitamin C and the important minerals present are potassium (K) and magnesium (Mg). Also, it contains ingredients that can function as antioxidants, which play a vital role in the prevention of cancer. Philip (2009) investigated a greener synthesis method for the preparation of Au-NPs in water using natural honey, which acted as both a reducing and a protecting agent. In addition, the synthesis was carried out at room temperature.

The typical TEM images obtained for colloids (g_1) and (g_4) are shown in Fig. 1.1. The decrease in anisotropy and particle size with the increase in the quantity of honey is evident from the images. Colloid (g_1) consists of a larger propensity of triangular NPs (Fig. 1.1a) when compared with those in the TEM image of colloid (g_4) shown in Fig. 1.1b. Colloid (g_4) consists of almost spherical NPs with an average size ~15 nm. Sintering of Au-NPs and their adherence to the nanotriangle in colloid (g_1) is evident from Fig. 1.2. The blunt-angled nanotriangles in Fig. 1.1a are a result of the shrinking process arising from the minimization of surface energy.

Recently, Narayanan and Sakthivel (2011) took the facile environmentally friendly greener synthesis of anisotrophic nanostructures and isotrophic spherical Au-NPs using the cell-free filtrate of the fungus *Sclerotium rolfsii*. The results show that modulation of size and shape can be achieved by varying the ratio of Au salt and the cell-free filtrate of the fungus (*S. rolfsii*). The production of anisotrophic and isotrophic Au-NPs is quite stable in aqueous solution for 2 months. This simple, efficient, eco-friendly process is very rapid

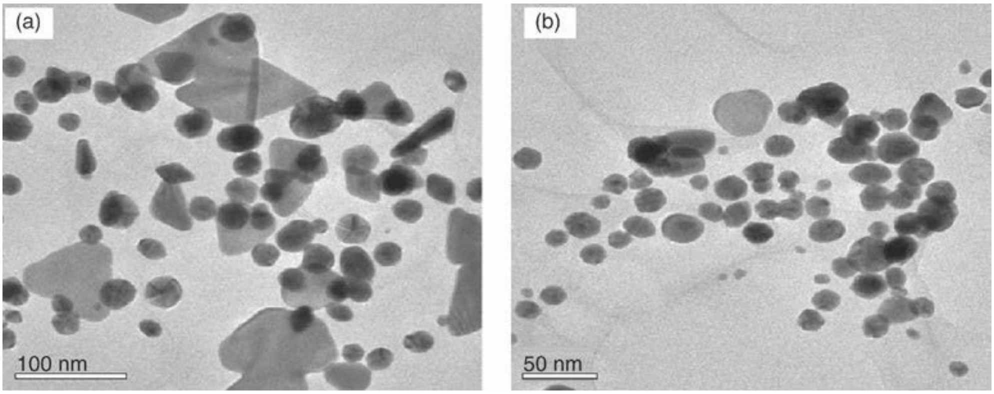

Fig. 1.1. TEM images of colloids: (a) g_1; (b) g_4 (Philip, 2009).

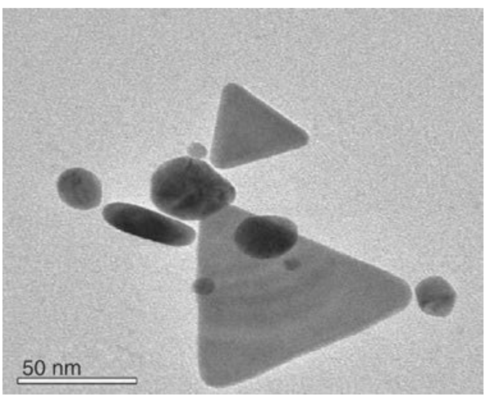

Fig. 1.2. Gold nanotriangle in colloid g_1 showing adherence of smaller particles (Philip, 2009).

and completes in 10–15 min. In addition, Kalishwaralall *et al*. (2010) employed the response surface methodology (RSM) and central composite rotary design (CCRD) to optimize a fermentation medium for the production of α-amylase by *Bacillus licheniformis* at pH 8 to evaluate the relationship between a set of controllable experimental factors and observed that a limited number of experiments resulted in the rapid and enhanced synthesis of Au-NPs.

Greener Nanoparticles

Researchers at Monash University (Australia) have produced metallic nanostructures at room temperature by the spontaneous reduction of Ag^+ and Au^{3+} in a 'green' ionic liquid (Bhatt *et al*., 2007). Room-temperature ionic liquids (RTILs) are an increasingly important area for chemistry research as possible replacements for conventional solvents as they are more environmentally friendly and can be used at lower temperatures. Unfortunately, the advantageous properties of RTILs become disadvantages when removal of solvents from synthesized products is required.

However, a special class of 'distillable' ionic liquids, dialcarbs, exists. Unlike conventional RTILs, these can be easily purified, recovered and separated to their constituent parts by low-temperature distillation. Using Ag+ in the dialcarb, DIMCARB, the Monash researchers observed spontaneous chemical reduction of Ag+ to Ag nanostructures. This alternative synthesis route using an ionic liquid negates the need for the high temperatures and large quantities of toxic and volatile organic solvents normally associated with nanostructure formation. In addition, the distillable nature of the solvent allows facile removal of the solvent at relatively low temperatures. Although the work has been expanded to include Au nanostructure synthesis from Au^{3+}, a number of areas still require research, including looking at other metals of interest and the use of solvents other than DIMCARB. The eventual aim is to find optimal conditions for nanoparticle and/or nanowire synthesis.

Greener Nanostructures

The fabrication of relatively large quantities of organic nanostructures is now possible using a new method that combines tools from microelectronics manufacturing and organic chemistry invented by Joseph DeSimone (Gratton *et al.*, 2007; DeSimone *et al.*, 2011). His general-purpose 'moulding' technique, called particle replication in non-wetting templates (PRINT), as a low-waste, green method that can be used to manufacture a broad range of organic NPs, enables the rapid, error-free reproduction of NPs of any shape. Moreover, functional groups can be added to tailor nanomaterials for biomedical applications. His team has successfully fabricated nano- and microparticles containing bioactive compounds.

Whereas monofunctional NPs provide a single function – a quantum dot can exhibit high fluorescence but it cannot be removed from a matrix using a magnetic field – multifunctional nanoparticles (MF-NPs) are able to achieve a mixed effect using one system. In these systems, variable strategies are used to attain a combination of targeting specificity, optimized optical, electrical and/or magnetic properties and analysis capability.

MF-NPs are not a new nanotechnological innovation. Perusal of the literature demonstrates that the unique properties of MF-NPs, along with the size effect of NPs, have already opened exciting avenues for developing new and advanced nanoparticle probes for biomedical imaging and drug delivery, which have great potential for therapy in areas such as cancer, diagnostics and neuropathologies. Great effort is also devoted to the characterization, understanding and improvement of the structural properties of such multifunctional nanostructures. However, the unique features of these MF-NPs remain practically unexplored in analytical chemistry and applications to the development of new analytical methodologies and/or devices with the aim of determining species in solution are really scarce (Han *et al.*, 2007; de Diosa and Díaz-García, 2010).

The number of different types of NPs is increasing rapidly. However, from the analytical standpoint, they can mostly be classified into two major types: particles that contain inorganic elements, usually metals and metal oxides, as a core (Fe_3O_4, semiconductors, Ag, Au, TiO_2, SiO_2) and those that are based on organic molecules (carbon nanotubes, dendrimers, liposomes) as major building materials.

The Drawbacks of Nanoparticles

Several particle types and structures have been discovered. Noteworthy structures include polymeric micelles, dendrimers, quantum dots (QDs) and solid NPs. Although these structures may promise endless opportunities, their safety should not be ignored. The reactivity of these tiny particles may be due to their large surface area in comparison to their overall mass. Semiconductor metals such as colloidal gold and iron oxide crystals are commonly used and have demonstrated toxicity. Additionally, these tiny particles permeate the skin and blood–brain barrier easily, leading to several potential toxicities. Research should be carried out to investigate fully any toxicity issues associated with these structures.

Quantum dots

Quantum dots (QDs), approximately 2–100 nm in diameter, are luminescent semiconductor nanocrystals. QDs have advanced optical properties compared with traditional organic fluorophores: (i) a high brightness due to the extinction coefficient and quantum yield; (ii) broad absorption characteristics and a narrow line width in emission spectra; (iii) continuous and tunable emission maxima due to quantum size effects; and (iv) a longer fluorescence lifetime ranging from 10 to 40 ns. Their controllable tiny size (in nanoscale) gives QDs good biocompatibility; some QDs can pass biological barriers such as cell membranes easily (Jaiswal *et al.*, 2003), for which it is impossible for bulk particles to pass. The surface coating is a key factor in the biological utilization of QDs, as the modifications form a functionalized surface for the particle, which is important for delivering QDs to