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NEWS AND OPINIONS

Green nanomaterials: On track for a sustainable future☆

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Summary Nanotechnology is one of the most significant scientific and industrial breakthroughs of the twenty-first century. With applications that cross scientific boundaries—from electronics to medicine, to advanced manufacturing, to cosmetics—nanotechnology has the potential to dramatically change lifestyles, jobs, and whole economies [1]. However, many of the materials and processes currently used not only are dependent on nonrenewable resources but also create hazardous wastes. The combination of green chemistry techniques with nanotechnology applications has thus become a key component of the nanotechnology future. The use of natural ingredients to synthesize nanomaterials and design environmentally benign synthetic processes has been extensively explored. While many of these so-called ''green nanotechnologies'' are now finding their way from the laboratory to commercial application, green nanotechnology still faces significant challenges. This article presents the recent advances and challenges in green nanotechnology, and suggests ways to improve the commercial readiness of these technologies.

In the past few decades, nanomaterials have demonstrated superior performance in numerous applications, including medicine, energy, and advanced manufacturing. However, many of the materials and processes currently used are not only dependent on nonrenewable resources but also create hazardous wastes. Green nanotechnology, the combination of nanotechnology and the principles and practices of green chemistry, may hold the key to building an environmentally sustainable society in the twenty-first century [1]. Green chemistry is a set of principles or rather a chemical philosophy that encourages the design of products and processes that reduce or eliminate the use and generation

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of hazardous substances [2—5]. Current green nanotechnology practices often involve the use of natural sources, nonhazardous solvents, and energy-efficient processes in the preparation of nanomaterials.

Natural, renewable sources of reducing agents

Nature provides us with numerous chemical substances that serve as suitable reducing agents for the synthesis of nanoparticles, including plant extracts, biopolymers, vitamins, proteins, peptides (e.g., glutathione), and sugars (e.g., glucose, fructose) [1,6]. Plant extracts are the most studied category to date. Given their abundance, plant extracts are regarded as one of the most promising natural reducing agents [7]. One area of particular success is the synthesis of metal nanoparticles, useful in electronics and medical applications, using plant extracts as reducing agents [3]. Biomedical applications such as drug and gene delivery using gold and silver nanoparticles have recently become a very active research area. To improve the biocompatibility, nontoxic green reduction agents, plants, algae, bacteria and fungi are used. Elia et al. synthesized gold nanoparticles by using four different types of plant extracts, *Salvia officinalis*, *Lippia citriodora*, *Pelargonium graveolens*, *Punica granatum*, as a reducing and stabilization agent [8].

Biopolymers are another family of natural sources used as reducing and stabilizing agents for metal nanoparticle synthesis. These polymeric carbohydrate molecules have already been used in various industries and thus are readily available for the large-scale production of nanoparticles. Examples of biopolymers for nanoparticle synthesis are cellulose, chitosan, and dextran, which are isolated from plants, the exoskeleton of crustaceans, and sugar cane, respectively [9—11].

Vitamin C is a well-known natural reducing agent or antioxidant. Similar to other natural reducing agents, vitamin C can reduce metal ions in an aqueous solution to produce metal nanoparticles [12]. Interestingly, it can also be used to synthesize Fe_3O_4 nanoparticles by reducing colloidal iron hydroxide under hydrothermal conditions [13]. Other vitamins used for metal nanoparticle synthesis include vitamins B and E [14]. Despite the widespread commercial availability of vitamins, their relatively cost effectiveness may be a hurdle for commercial application. Other natural sources, such as proteins and peptides, also suffer from cost-related challenges and thus are ill-suited for the large-scale production of nanomaterials [15—17].

Natural sources as precursors for carbon nanomaterials

One emerging area of green nanotechnology research is the use of natural sources as precursors for carbon nanomaterials, useful in a host of applications due to their unique properties. For example, vegetable oil has proven itself to be a viable precursor for high-quality carbon nanotubes using a spray pyrolysis approach. Using different catalysts, both single-walled and multi-walled carbon nanotubes can be produced by this method [18]. In another example, sugars and biopolymers have been used as precursors for carbon quantum dots via a microwave approach. Given the abundance of carbon-rich natural sources, it is expected that their use as precursors for carbon nanomaterials will increase rapidly in the next few years [18].

Figure 1 Natural, renewable, sources for green nanotechnology.

Nanocellulose—a green nanomaterial

As shown in the previous sections, a significant portion of green nanotechnology is the development of green chemistry to synthesize nanomaterials. However, recently much attention has been devoted to the use of natural nanomaterials as alternatives to synthetic products. One example is nanocellulose materials, which are nanosized cellulose fibers or crystals produced by bacteria or derived from plants. These materials exhibit exceptional strength characteristics, light weight, transparency, and excellent biocompatibility. Compared to some other nanomaterials, nanocellulose is renewable and less expensive to produce. Because of this, nanocellulose has shown great promise as an alternative to synthetic nanoparticles in areas such as polymer nanocomposites and drug delivery [19—22]. Nanocellulose aerogel has also been used as a sacrificial templating material for metal oxide nanotubes [23]. Interest in green nanomaterials is increasing, as evidenced by the growing number of publications in this area and the recent initiative of the government and private sectors on its commercialization (Fig. 1).

Green processesing

In addition to using natural starting and processing materials for nanoparticle synthesis, the other half of green nanotechnology is developing environmentally friendly, sustainable processes. In this regard, water and supercritical carbon