

# Green Nanotechnology: The Latest Innovations, Knowledge Gaps, and Future Perspectives

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## 1. Introduction

Nanotechnology is a key enabling technology bringing together chemists, biologists, physicists, and materials science engineers, among others [1–6]. It has been proposed for addressing societal challenges due to its vast range of applications, such as on nanomedicine, food, nanoelectronics, energy, packaging, composite materials, coatings, construction, agriculture, water treatment and environmental remediation [5,7,8]. Not surprisingly, the use of nanostructured materials has been raising health and environmental safety concerns [5,9,10], favoring the expansion of a sub-field dedicated to green and safe-by-design solutions [1,2,6]. Novel solutions should minimize environmental and human health risks of nanomaterials during their lifetime, e.g., through the replacement of toxic products or current processes by suitable eco-friendly alternatives [2,11]. Green nanotechnology relies on the principles of green chemistry towards a sustainable design, manufacture, use, and end-of-life of nanomaterials [11,12].

## 2. Latest Innovations and Insight on the Domain of Green Nanotechnology

This Special Issue, spread through five original research articles [2–6], aggregates innovative applications, products, technologies and processes beyond the state-of-the-art in several scientific green nanotechnology-related fields (e.g., drug delivery systems, antifouling nanoadditives and coatings for optical applications) as well as identifying some knowledge gaps on this domain. Research on sustainable production of nanomaterials based on safe-by-design approaches and (eco)toxicological assessment of novel nanomaterials was also provided (Figure 1).

Gemini surfactants are being proposed as promising eco-friendly replacements of state-of-the-art surfactants, for instance, to synthesize greener nanomaterials. In this domain, Brycki et al. [3] proposed an ecofriendly synthesis of AgNPs stabilized by gemini surfactants produced with a solvent-free method. The smallest AgNPs were obtained using the surfactant 16-6-16 as a stabilizing agent, molar ratio nAg:nGemini = 5 and with an excess of reductant [3]. In the same rationale, Kaczerewska and co-authors suggested that it is possible to use novel gemini surfactants to synthesize greener silica mesoporous nanocapsules (SiNC) [2]. SiNC is a widely used nanomaterial that has been raising some environmental concerns due to the use of the cationic surfactant N-hexadecyl-N,N,N-trimethylammonium bromide (CTAB) that remains inside the nanostructure before being released over time when dispersed in seawater [5,9,10,13–16]. Thus, Kaczerewska et al. [2], used 1,4-bis-[N-(1-dodecyl)-N,N-dimethylammoniummethyl]benzene dibromide (QSB2-12) as a low toxicity template agent to replace CTAB [11]. Newly developed silica nanocapsules were quite



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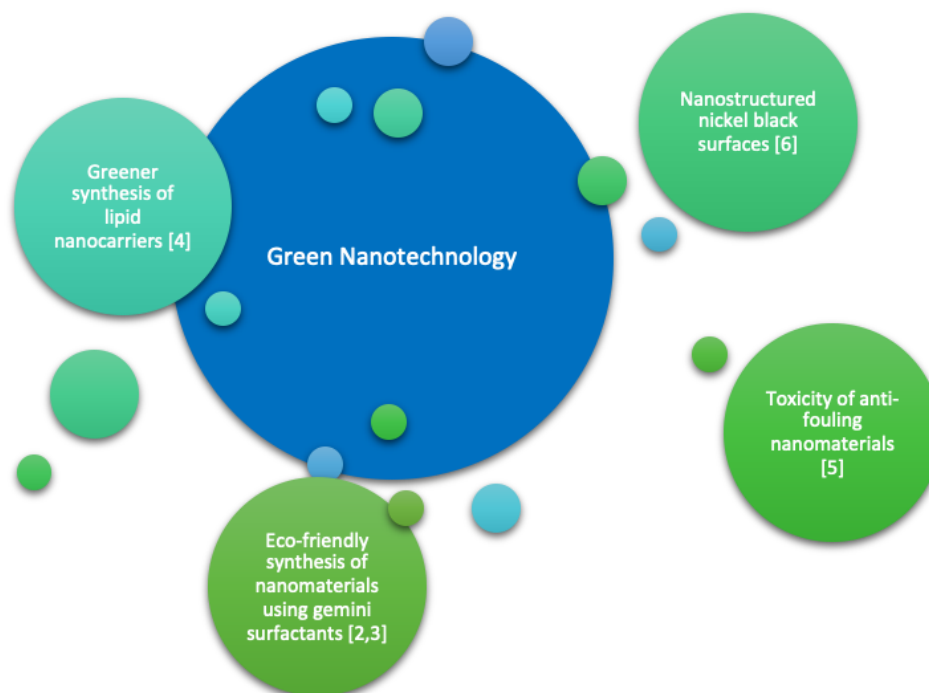
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similar to the conventional ones and exhibited significant reduction in the toxicity of such nanomaterials in marine microalgae and microcrustaceans [2].



**Figure 1.** Main contributions of the present Special Issue to the field of green nanotechnology.

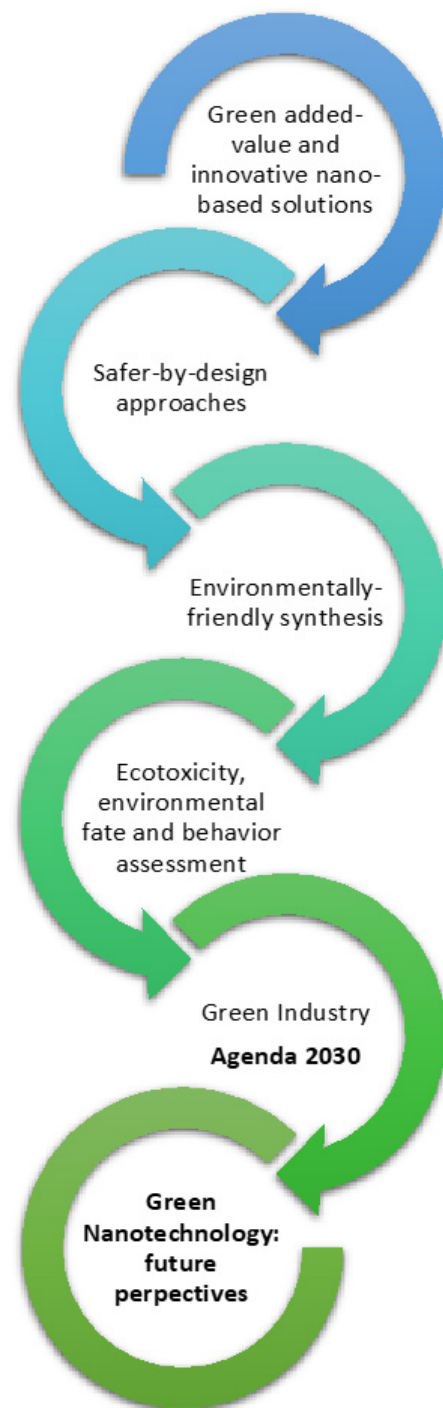
Another interesting topic is the development of safe and multi-purpose nanostructured lipid carriers, which have been widely proposed for pharmaceutical applications. The use of natural lipids is desirable for drug-delivery systems. Galvão et al. [4] assessed the influence of carvacrol in the crystallinity of solid natural lipids (stearic acid, beeswax and carnauba wax) to synthesize greener nanostructured lipid carriers. The authors showed that the higher the carvacrol content, the lower the crystallinity of the solid bulks of targeted lipids, demonstrating the promising properties of this monoterpene phenol towards the development of green drug delivery systems based on lipid nanoparticles [4].

Green nanotechnology has also been applied to the coatings industry through the replacement of toxic compounds [6], or their immobilization and controlled release over time [5,9,13]. Mennucci et al. [6] demonstrated that nanostructured nickel black surfaces can have good corrosion resistance and can be a great replacement for chromium finish, which is widely used in optical and solar applications, but also for decorative purposes. On the other hand, recent advances demonstrated that the nanoencapsulation of anti-fouling biocides (e.g., DCOIT, Zn and Cu pyrithiones within in SiNC or other engineered nanomaterials), widely used in maritime coatings, can significantly decrease their toxicity and hazard on marine species [9,10,13–16]. Santos et al. [5] demonstrated for the first time that the SiNC-DCOIT has high anti-fouling efficacy towards target early life stages of the tropical mussel *Perna perna*, while it is less toxic than free DCOIT during the larval development stage. This novel insight reinforces the benefits of the encapsulating toxic chemicals in nanocarriers.

### 3. Future Perspectives

Nowadays, science and technology are moving at a rapid pace and crossing scientific frontiers. Articles published in this Special Issue showed different directions for further progress in green nanotechnology. Future perspectives are dictated not only by new scientific ideas but largely by today's societal challenges, such as environmental regulations, and the need to increase innovation and sustainability in the industrial processes and decrease the loss of ecological biodiversity due to the combination of pollution and climate

changes, among others, in the framework of the sustainable development goals (Agenda 2030) defined by the United Nations. As an example (Figure 2), and to avoid the repetition of past mistakes, the upcoming generation of nanomaterials must be truly environmentally friendly. For that purpose, synthesis should prioritize no/low toxic products, obtained from sustainable sources, and new nanomaterial must be carefully assessed in terms of environmental behavior, fate, effects, and hazard in the aquatic and terrestrial ecosystems, whenever possible. Efforts must be made to bridge the gap between industry and academia towards the development of green added-value and innovative nano-based solutions for real problems (e.g., corrosion, biofouling, water remediation, agrochemicals).



**Figure 2.** Future perspectives on the field of green nanotechnology.

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