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REVIEW ARTICLE

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Synthesis and applications of multifunctional composite nanomaterials

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Abstract

Nanocomposites have attracted a huge amount of interest due to their improved mechanical properties, dimensional stability, thermal/chemical stability, and electrical conductivity. Nanostructures are found to be of great significance because of their inherent properties such as large surface area to volume ratio and the engineered properties such as porosity, stability, and permeability. Composite material can achieve multifunctionality by combining the relevant, desirable features of different materials to form a new material having a broad spectrum of desired properties. These properties include liquid/gas sensing, self-repair nano/microstructure, catalysis initiator/inhibitor, as well as biomedical engineering. In this article, the nano/microcomposites are critically analyzed against the combination of functionalities i.e. mechanical, optical, chemical, electrical, and thermal properties. This review specifically presents a narrative summary on the use of multifunctional nanomaterials for energy as well as environmental applications, along with a discussion on some critical challenges existing in the fields.

Keywords: Nanomaterials; Biocomposites; Sensors; Energy; Biomedical applications

Introduction

Nanocomposites are a new generation of novel materials, which are formed by mixing one or more dissimilar materials at the nanoscale in order to control and develop new and improved structures as well as properties (Figure 1). The term nanocomposite encompasses a wide range of materials right from three-dimensional metal matrix composites, two-dimensional lamellar composites, and nanowires of single dimension to zero-dimensional core shells representing many variations of nanomixed and layered materials (Figure 2). The properties of nanocomposites depend not only upon the individual components used, but also upon the morphology and the interface characteristics. Enhanced properties such as improved friction and abrasion resistance, fouling resistance, super hydrophobicity, super hydrophilicity, thermal energy transport, electronic and ionic transport, and liquid transport displayed by nanocomposites compared to individual materials make them attractive for a wide range of engineering applications.

As per (Freedonia 2008), the demand for nanocomposites in 2011 reached 150,000 TPA in USA. Growth in this area will be fuelled by declining prices of nanomaterial, increase in production levels, and by resolving the technical issues concerning their mass-scale production. It is expected that nanocomposites by 2025 will be the US $9 billion market, with volumes nearing 5 million tons. The forecasted nanocomposites based on commodity plastics, such as polypropylene, polyethylene, and PVC, will dominate the market. By optimizing the fabrication process and limiting the size of the second-phase dispersion to nanometer length scales, mechanical properties of the composites such as adhesion resistance, flexural strength, toughness, and hardness can be enhanced. It is argued that packaging and motor vehicles have accounted for nearly 50% of total demand in 2011 and also estimated that it will account for 40% of demand in 2020. However, by 2025, electrical and electronics applications will gain in prominence, as nanofiber-based composites will penetrate a sizable portion of the market as a substitute for other conductive materials.

Multifunctional nanocomposites combining the merits of two or more base materials have received a great deal of attention due to their synergy or enhanced properties compared to their base counterparts (Akbulut et al. 2009; Gobin et al. 2004; Yang and Ko 2008). In the realm of

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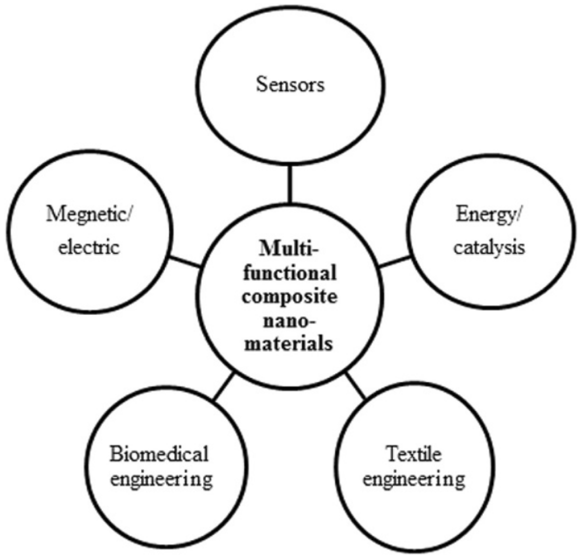

Figure 1 Characterization of nanocomposites based on their applications.

multifunctional nanomaterials, considerable effort has been centered on the noble metal-based systems by immobilizing noble metal onto diverse inorganic/organic supports to obtain the desired functional nanomaterials. In addition, effort has been made in loading noble metals on semiconductor metal oxides such as TiO_2 and highly conductive nanomaterial such as CNTs using any surfactant or linkers (Jose et al. 2009, Peining et al. 2011). It is well known that at nanoscale, the physical, chemical, and biological properties of materials differ fundamentally and often, unexpectedly, from their corresponding bulk counterpart because of the quantum confinement. For instance, gold and silver nanoparticles are characterized by their strong ability to absorb visible light at certain wavelengths, which depend on the size and shape of the nanomaterials. Solids with nanoparticle size cannot be prepared by traditional methods simply because the reactants are not mixed on the atomic scale. All the alternative methods, e.g., hydrothermal, sol–gel, Pechini, CVD, electrospinning, and microwave, described in the rest of this section address this problem by achieving atomic-scale mixing of reactants, in gas, liquid, or even solid phases. Although these are low-temperature methods, nevertheless, high-temperature processing may be required, especially for ceramic-based nanomaterials. These methods enable the final product to be homogenous nanosized materials with narrow particle size distribution. The appropriate methodologies for the preparation of these multifunctional nanomaterials are depicted in Table 1.

Synthesis of nanocomposites

Hydrothermal synthesis

Hydrothermal synthesis is one of the prominent methods employed to precipitate single/multiphase

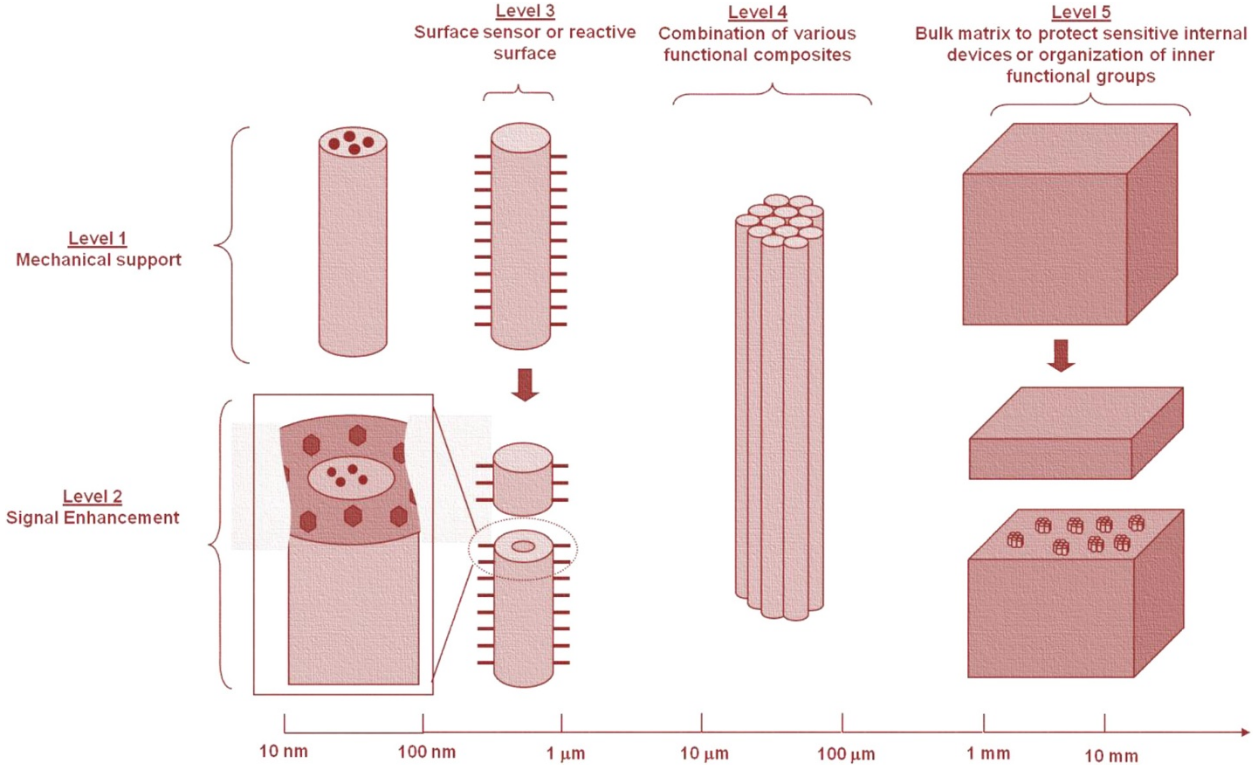

Figure 2 Hierarchical organization of multifunctional composites (Teo and Ramakrishna 2009).

Table 1 Methodologies for the preparation of multifunctional nanomaterials

Phase system	Applications mode	Inherited properties	Applications
Single-phase NF	A composite system with the relevant metal oxides NF/NP	Large surface to weight ratio	High effective energy storage at reduced material cost and improved cycling performance, and
			Improved ion-transporting membranes for fuel cells, tailoring of the nanoarchitecture for thickness, density, porosity, surface area, and conductivity for the breakthrough of the technology
	Combined with polymer matrix to form composite system	High strength and stiffness	High flux and low-energy filtration media for water and air
			Interleave material for improved damage tolerance structural composites
Single-phase NP	A composite system with the relevant metal oxides NF/NP	Large surface area per unit volume	Stronger, corrosion/wear-resistant tunable platform for controlling surface wetting
	Combined with polymer matrix to form composite system	Thermally stable	Aerospace components, housings for electronics
Two-phase NF (composite NF)	A composite system with the relevant metal oxides NF/NP	Multifunctionality	Anti-counterfeiting of drugs, thermal interfaces
	Combined with polymer matrix to form composite system	Thermally and electrically stable, light weight	Smart textiles, coatings
			Thermal interface materials, clothes
Two-phase NP (composite NP)	A composite system with the relevant metal oxides NF/NP	Multifunctionality	Sensors having the ability to detect lower concentrations of biologically important species/detectable analytes
			The coatings having both electric/magnetic properties to effectively shield electromagnetic waves generated from an electric as well as the magnetic source, especially at low frequencies
	Combined with polymer matrix to form composite system	Highly resistant	Smart textiles

metal/semiconductor metal oxides directly from their corresponding homogeneous/heterogeneous solution. Hydrothermal synthesis is a single-step process preferred for preparing several single/multiphase oxides and phosphates (Dai et al. 2009; Fang et al. 2006; Ye et al. 2010; Ji et al. 2009). Due to its simplicity and versatility, hydrothermal synthesis is also being used to grow single crystals ranging from emeralds, rubies, quartz, to alexandrite. The technique is also being employed to obtain nanomaterial for energy as well as environmental applications ranging from dye-sensitized solar cells to catalysis (Hsu et al. 2008; Zhou et al. 2010).

Sol–gel synthesis

In sol–gel synthesis, a colloidal solution (sol) is being used to prepare a compound consisting of a metal or metalloid element surrounded by appropriate ligands (gel). This process results in the fabrication of variety of nanocrystalline elemental, alloy, and composite metal/semiconductor metal oxides. The sol–gel synthesis provides greater control in the process parameters, resulting in the synthesis of a variety of metal/semiconductor metal oxides (Leventis et al. 2009).

Polymerized complex method (Pechini process)

A wet chemical method using polymeric precursor based on the Pechini process has been employed to prepare a wide variety of ceramic oxides. The process offers several advantages for processing ceramic powders such as direct and precise control of stoichiometry, uniform mixing of multicomponents on a molecular scale, and homogeneity. The method is being widely used for the synthesis of dielectric, fluorescent, magnetic materials, high-temperature superconductors, and catalysts. The method is also preferred for the deposition of oxide films as coatings, for instance, nanostructured electrode in dye-synthesized solar cells and lithium ion battery (Sahay et al. 2012a; Sahay et al. 2012b; Suresh Kumar et al. 2012).

Chemical vapor deposition

Chemical vapor deposition (CVD) can deposit a film of solid material on a heated surface from a chemical reaction in the vapor phase. The versatile process can result in nano/microstructured coatings, powders, fibers, as well as multiphase compounds from metals, metal oxides, as well as nonmetallic elements such as carbon and silicon (Hitchman and Tian 2002; Iguchi et al. 2009; Mills et al. 2002). The advantage of CVD includes high throughput due to high deposition rate, as well as fabrication of single/multiphase nanomaterials. CVD process has been given enormous attention, owing to the possibility of mass production of nanomaterials; nevertheless, the mechanism of powder synthesis kinetics is still not completely known for this technique.

Microwave synthesis

The applicability of microwave processing spans over a number of fields, ranging from food processing to medical and chemical applications. A major area of research in microwave processing includes microwave material interaction, microwave equipment design, new material development, sintering, joining, and modeling. As microwave processing offers uniform heating at a lower temperature, it is being successively utilized in the fabrication of ceramics as well as carbon fibers at low temperature and time (Reddy et al. 2009; Chae et al. 2010).

Classification of multifunctional nanomaterials

Polymer nanocomposites

Polymer nanocomposites have attracted considerable interest because of their enhanced properties, i.e., fire retardation, mechanical, electrical, and thermal properties, etc. Several methods of preparing nanocomposites have been investigated, such as organic and inorganic multifunctionalization, self-organization, *in situ* polymerization, etc. A variety of characterization techniques have been adopted for polymer nanocomposites such as X-ray diffraction and spectrometry, light and electron microscopy, thermogravimetric analysis, nuclear magnetic resonance, and mass spectroscopy with relevant specific measuring instruments for achieved/intended property.

The addition of nanoparticles to the polymer matrix has been the most commonly adopted method for producing polymer nanocomposites. Titanium dioxide (TiO_2) has been investigated during the last decade as one of the candidates as nanoparticle for composites because of its scientific and technological importance (Song et al. 2006; Sun et al. 2007). For instance, Wang et al. (2009a) reported a double *in situ* approach for the preparation of PET/titanium dioxide (TiO_2) nanocomposites having flame retardant properties with improved mechanical strength. The appreciable flame retardation ability of the composite was shown by improved values for limiting oxygen index (LOI) and vertical burning test compared to bare PET. Krishna et al. (2010) showed that surface hydroxyl groups of nanocrystals could be further tailored with various functional molecules, making them potential multifunctional platforms for detection, sensing, and energy harvesting in biological as well as inorganic systems. Krishna et al. (2010) achieved nanosecond pulsed laser-induced self-organization via spontaneous pattern formation in immiscible Ag and Co bilayer liquid films. The obtained bilayer arrangements can change the signs of intermolecular interactions, which in turn change the mode of coupled deformations and the patterning characteristics resulting in adjustable properties.

Zhou et al. (2011) presented a general strategy to synthesize multifunctional aqueous nanocrystals using high molecular weight (>20 kDa) multihydroxy hyperbranched polyglycerol (HPG) as a stabilizer with a variety of nanocrystals, depicted in Figure 3. The stability of HPG-stabilized nanocrystals was verified with UV/Vis spectroscopy. The resulting HPG-stabilized nanocrystals showed good solubility in water and polar organic solvents, favorable biocompatibility, and excellent stability. The obtained functionalized nanocrystals could serve as a building block for next-generation multifunctional polymer nanocomposites.

Novel metal-based nanomaterials

The novel metal nanomaterial finds application in a variety of advanced applications ranging from energy to thermal therapy. The fabricated nanomaterials are usually characterized using X-ray photoelectron spectroscopy, transmission electron microscopy, circular dichroism spectroscopy, nuclear magnetic resonance spectroscopy, and UV-visible spectroscopy. These nanomaterials include silver and gold, which have the unique capability to convert light to heat and have recently found to be extremely applicable for tumor treatment. The tumors can be treated by either heat-triggered drug release, where drugs are stored inside the nanoparticle or via photothermal therapy, which involves heat damage to cells and tissues containing the nanoparticles. Lee et al. (2011) fabricated core-shell magnetic nanoparticles for photothermal therapy. These magnetic nanomaterials in the presence of an alternating current or magnetic field undergo fluctuations in their magnetic properties, resulting in variation in heat energy. Measurement of heat energy was conducted using a high-radiofrequency heating machine. Radio frequencies are usually employed to produce the fluctuations in the magnetic nanoparticles, due to appreciable depth of penetration as compared to the magnetic fields. The magnetic nanoparticles serve a dual purpose as they can be detected through magnetic resonance imaging (MRI), allowing researchers to monitor their movement inside the human body during treatment. Lee et al. (2011) further improved the magnetic properties of nanomaterials by creating core-shell nanoparticles, having a core of one type of magnetic material surrounded by a shell of another type of materials. These core-shell nanoparticles were found to be up to 34 times more efficient in producing heat from incident radiofrequency waves than the single base material, for instance, iron-oxide magnetic nanoparticles used in MRI studies. Their other functionality includes superior cancer-fighting properties against tumors in mice to the common anticancer drug doxorubicin.

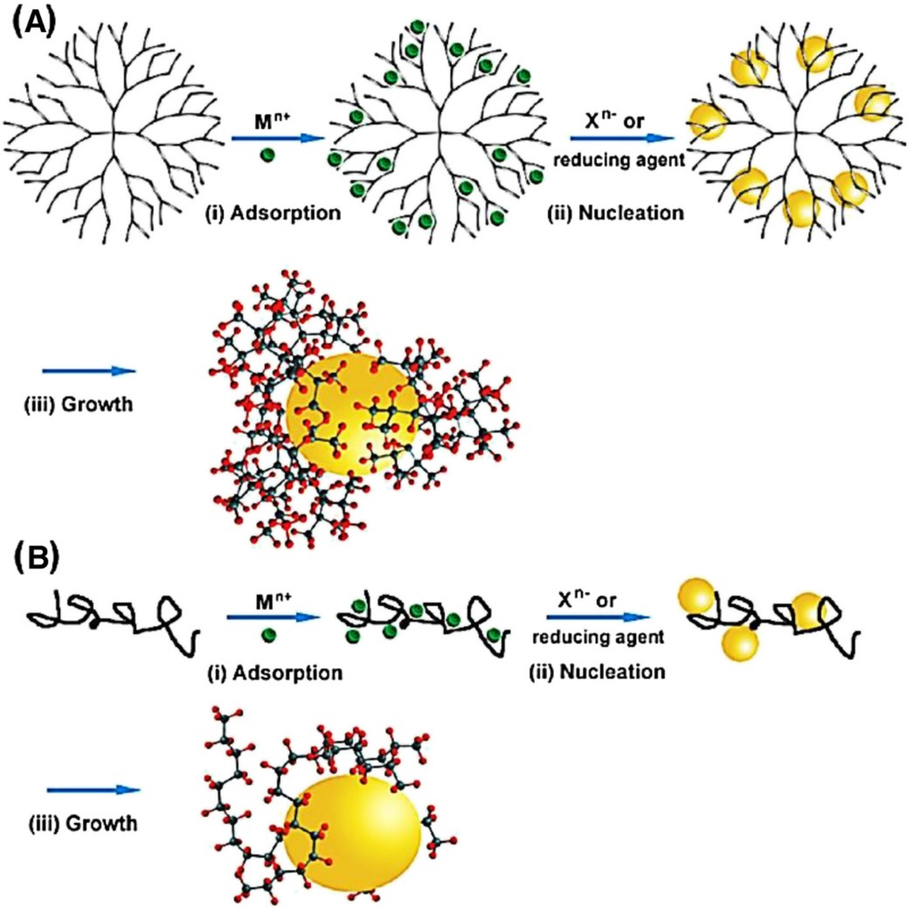

Figure 3 Synthesis of aqueous nanocrystals using stabilizers (A) dendritic and (B) linear polymer (Zhou et al. 2011).

Catalysts

The multifunctional nanomaterials can serve the purpose by providing functionalities such as specific crystal structure, controlled porosity, large surface area, enhanced electronic structures and interfaces (i.e. crucial for optimal light absorption and charge separation), improved mechanical stability, as well as specific magnetic properties essential for catalysis. Khlebtsov et al. (2011) fabricated composite nanoparticles (Figure 4) consisting of a gold-silver nanocage core and a mesoporous silica shell functionalized with the photodynamic sensitizer Yb-2,4-dimethoxyhematoporphyrin (Yb-HP). In addition to the long-wavelength plasmon resonance near 750–800 nm, the composite particles exhibited a 400-nm absorbance peak and two fluorescence peaks, near 580 and 630 nm, corresponding to the bond Yb-HP. The fabricated nanocomposites generated singlet oxygen under 630-nm excitations and produced heat under laser irradiation at the plasmon resonance wavelength (750–800 nm). Enhanced killing of HeLa cells was observed when incubated with nanocomposites and irradiated by 630-nm light. Additionally, an advantage of fabricated conjugates was an IR-luminescence band ranging from 90 to 1060 nm courtesy Yb^{3+} ions of bound Yb-HP. This modality was used to control the accumulation and biodistribution of composite particles in mice bearing Ehrlich carcinoma tumors in a comparative study with intravenously injected free Yb-HP molecules. The multifunctional nanocomposite seems to be an attractive theranostic platform for simultaneous IR-luminescence diagnostic and photodynamic therapy owing to Yb-HP and for plasmonic photothermal therapy owing to Au-Ag nanocages (Khlebtsov et al. 2011).

Chen et al. (2011) synthesized multifunctional nanoparticles composed of Fe_3O_4-Au nanocomposite core and a porous silica shell ($pSiO_2$), aimed at achieving magnetic and optical properties of magnetic-gold nanocomposite, shown in Figure 5. The catalytic activity of the porous silica shell-encapsulated Fe_3O_4-Au nanoparticles was investigated by the reduction of o-nitroaniline to benzenediamine by $NaBH_4$. The high catalytic activity of core (Fe_3O_4-Au)/shell ($pSiO_2$) nanocomposite in comparison to bare Fe_3O_4-Au was attributed to the porous silica shell. The porous silica

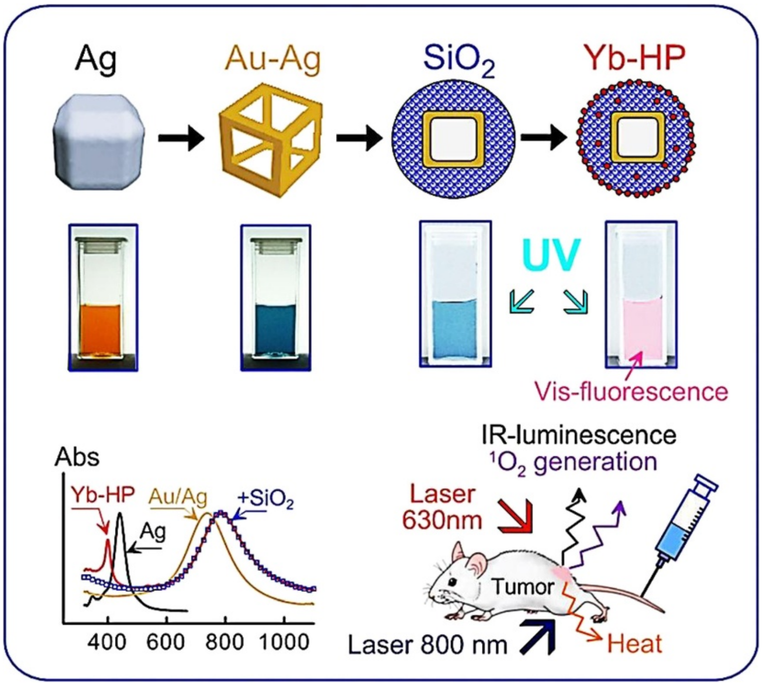

Figure 4 The fabrication and analysis of fluorescent composite nanoparticles. (Row 1) formation of Yb-HP functionalized core (Au-Ag) - shell (SiO_2) nanocomposites from silver nanocubes, (Row 2) The absorbance spectra of silver (black), Au-Ag (yellow gold), core (Au-Ag) - shell (SiO_2) (blue), and Au-Ag/SiO_2/Yb-HP nanocomposites (red), and (Row 3) Photothermal therapy using the heat generated by plasmonic Au-Ag/SiO_2, Photodynamic therapy using IR-luminescence and singlet oxygen ($^1O_2$) generated by Yb-HP and (Khlebtsov et al. 2011 and SPIE Newsroom, 22 September 2011, DOI: 10.1117/2.1201109.003832; https://www.spie.org/x57239.xml?highlight=x2400&ArticleID=x57239).

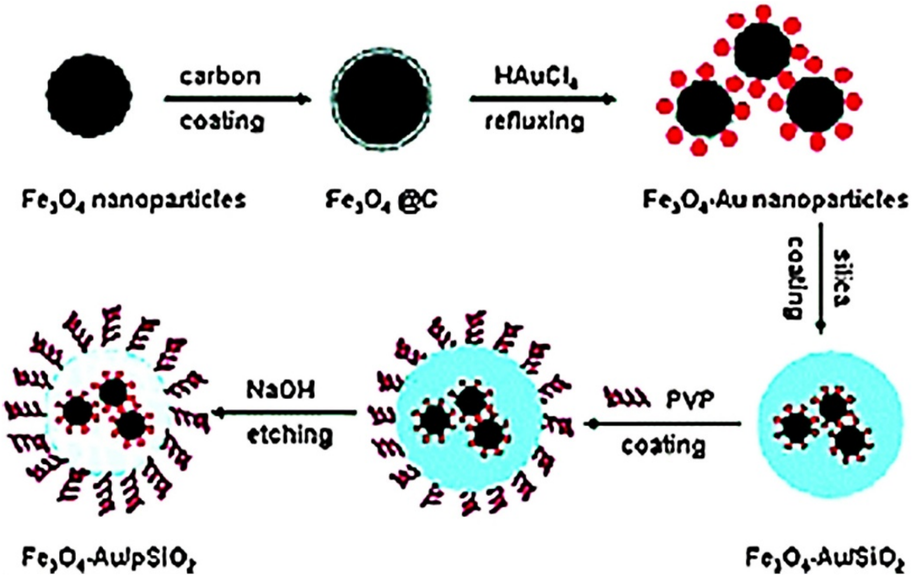

Figure 5 Multifunctional nanoparticles composed of Fe_3O_4-Au nanocomposite cores and a porous silica shell (pSiO_2) (Chen et al. 2011).

shell prevented the aggregation of neighboring nanoparticles and offered a large surface area, resulting in high catalytic activity. Klabunde et al. (2010) fabricated solid decontamination to serve as destructive adsorbents, photooxidation catalysts under visible and UV light, and decoagents for CWAs and BWAs. The authors designed nontoxic metal oxide nanomaterials with chemically active Lewis acid/base sites having chromophores to absorb visible light and composed mainly of a semiconductor material for rapid energy transfer of electrons and holes to reactive sites, resulting in a multifunctional decoagent of high surface area and low toxicity to humans and animals.

Sensors

These multifunctional nanomaterials also serve the purpose of efficient sensors having multi-functionality. Wang and Irudayaraj (2010) performed the site-selective assembly of magnetic nanoparticles onto the ends and sides of gold nanorods to create multifunctional Fe_3O_4/Au rod, Fe_3O_4 nanodumbbells, and Fe_3O_4/Au rod necklace-like constructs with tunable optical and magnetic properties (Figure 6), applicable for multiple constituent detection and separation. More specifically, nanomaterials are applied for simultaneous optical detection based on their plasmon absorbance, magnetic separation, and thermal ablation of multiple pathogens from a single sample. Similarly, Titos-Padilla et al. (2011) fabricated SiO_2 nanocomposite with a spin-crossover polymer core and a luminescent shell. These nanomaterials exhibit a thermally induced transition from low spin to high spin convoyed by a drastic colour change. This optical bistability tunes the luminescence of the fluorophores grafted on the surface of the materials. The thermal dependence of the molar magnetic

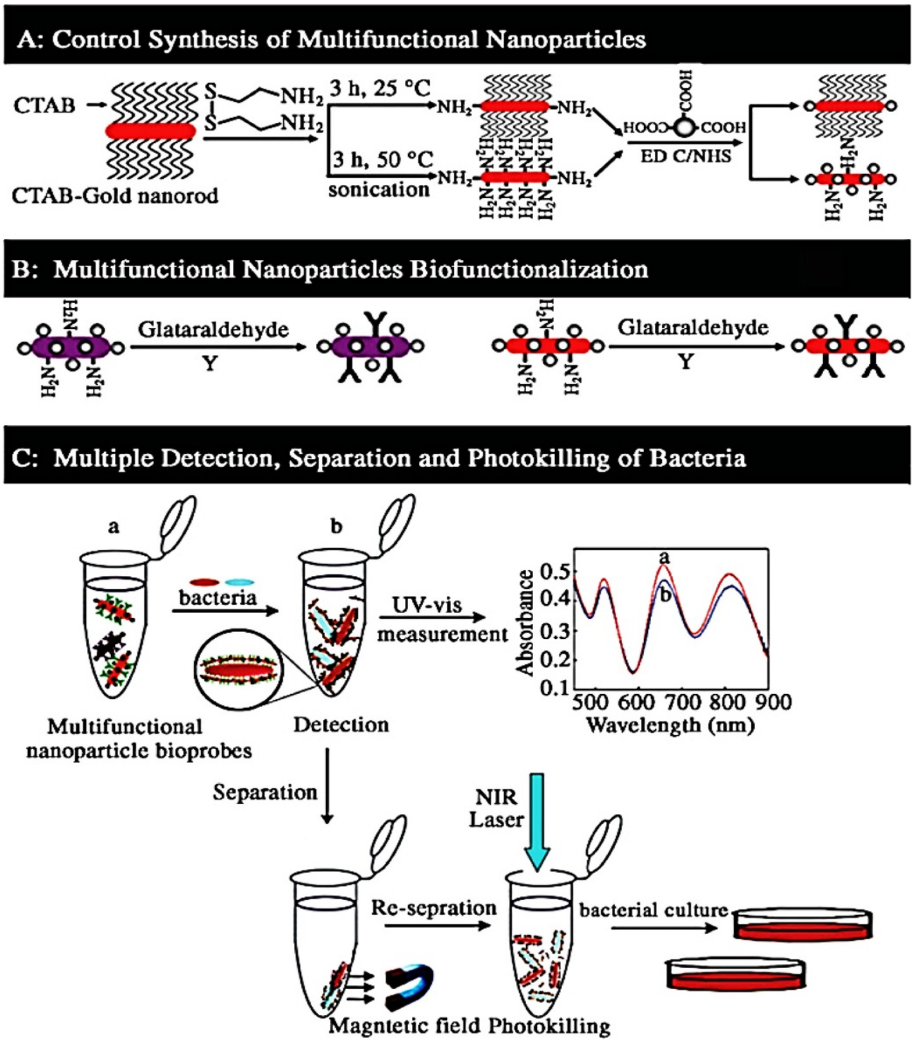

Figure 6 Schematic depicting (A) assembly, (B) biofunctionalization of Fe3O4, (C) photokilling of bacterial targets (Wang and Irudayaraj 2010).

susceptibility was measured with a heating and cooling sweep rate of 10 K/min, whereas, fluorescence spectrophotometer was used to correlate fluorescence intensity with the thermally induced spin transition. Zhang et al. (2011) fabricated Au(Pt)-functionalized α-Fe_2O_3 multifunctional nanospindles for gas sensing and CO oxidation. Gas sensing measurement system performed the gas-sensing test, whereas catalytic activity was measured in a fixed-bed stainless-steel tubular reactor. The results demonstrated that functionalization with Au nanoparticles resulted in higher activity in both applications compared to pristine α-Fe_2O_3. The improved performance should be associated to the active AuNPs, which act as catalysts for surface sensing reactions and show high active for low-temperature CO oxidation. Similarly, Mullen et al. (2011) produced rare earth-based nanostructures, having combined structure and optical properties. A nanosphere lithography strategy combined with surface chemistry enables the production of arrays of β-$NaYF_4$: Yb,Er nanorings inlaid in an octadecyltrichlorosilane matrix.

Wang et al. (2011) fabricated multifunctional magnetic and luminescent Fe_3O_4@C@CdTe core/shell microspheres (Figure 7) that act as a new type of synthetic fluorogenic chemosensor for probing Cu^{2+} ions in aqueous solutions. The resulting nanosensor exhibits a high sensitivity to Cu^{2+} ions over the other competing metal ions tested in water. In addition, the strong magnetic property of the core/shell Fe_3O_4 microspheres helps in the separation and collection of Cu^{2+} ions using a commercial magnet. Lim et al. (2010) grew uniformly, radially oriented and densely packed zinc oxide nanorods on fiber to form a conductive fabric having robustness against stress and washing cycles. The nontoxic conductive fabric showed excellent multiple sensing (gas and optical) performances at room temperature applicable for healthcare, military, and environmental applications.

Bioengineering

Nanomaterials that interact with light offer a unique opportunity for the applications in biphotonic nanomedicine. Image-guided therapies could be designed based on multifunctional nanocomposites having tunable surface plasmon resonance absorption in the near-infrared region, detectable by multiple imaging modalities such as magnetic resonance imaging, nuclear imaging, and photoacoustic imaging, etc. These novel nanostructures, once introduced, are expected to home in on solid tumors either via a passive targeting mechanism (i.e., the enhanced permeability and retention effect) or via an active targeting mechanism facilitated by ligands bound to their surfaces. Once the nanoparticles (NPs) reach their target tissue, their activity can then be turned on using an external stimulus. For example, photothermal-conducting NPs primarily act by converting light energy into heat. As a result, the temperature in the treatment volume is elevated above the thermal damage threshold, which kills the cells. In addition, photothermal-conducting NPs can also efficiently trigger the release of drugs and activate RNA interference. A multimodal approach,

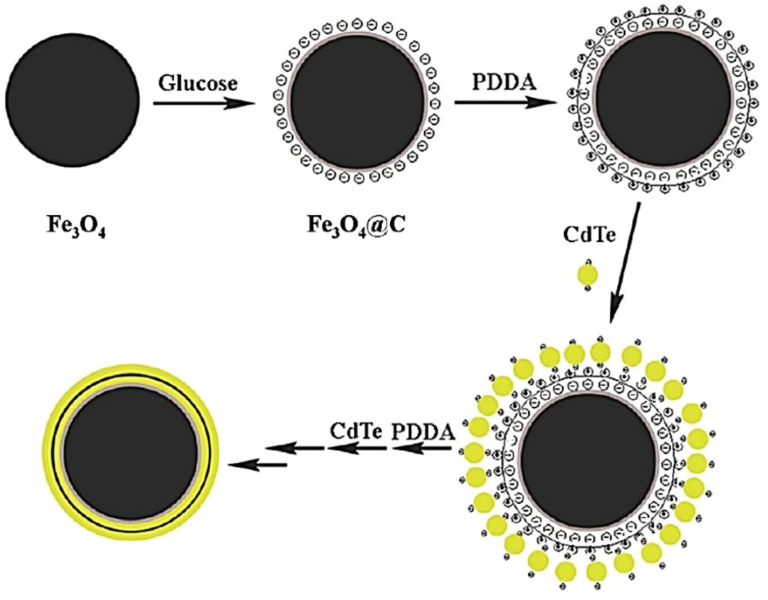

Figure 7 Schematic illustration for preparation of Fe_3O_4@C@CdTe core/shell microspheres (Wang et al. 2011).

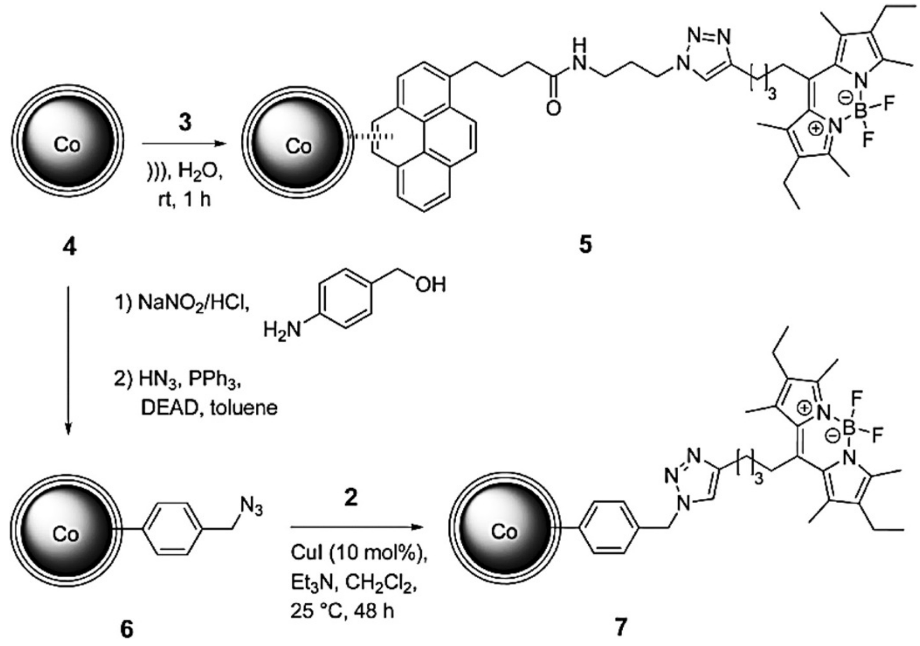

Figure 8 **Noncovalent (top) and covalent (bottom) functionalization of magnetic Co/C nanoparticles (Kainz et al. 2011).**

which permits simultaneous photothermal therapy, chemotherapy, and therapeutic RNA interference, has the potential to completely eradicate residual diseased cells.

Gold nanocages represent a novel class of nanostructures, well suited for biomedical applications. They can be readily prepared via the galvanic replacement reaction between silver nanocubes and chloroauric acid. Their optical resonance peaks can be easily tuned in the near-infrared region from 650–900 nm, the transparent window for blood and soft tissues. Furthermore, their surface can

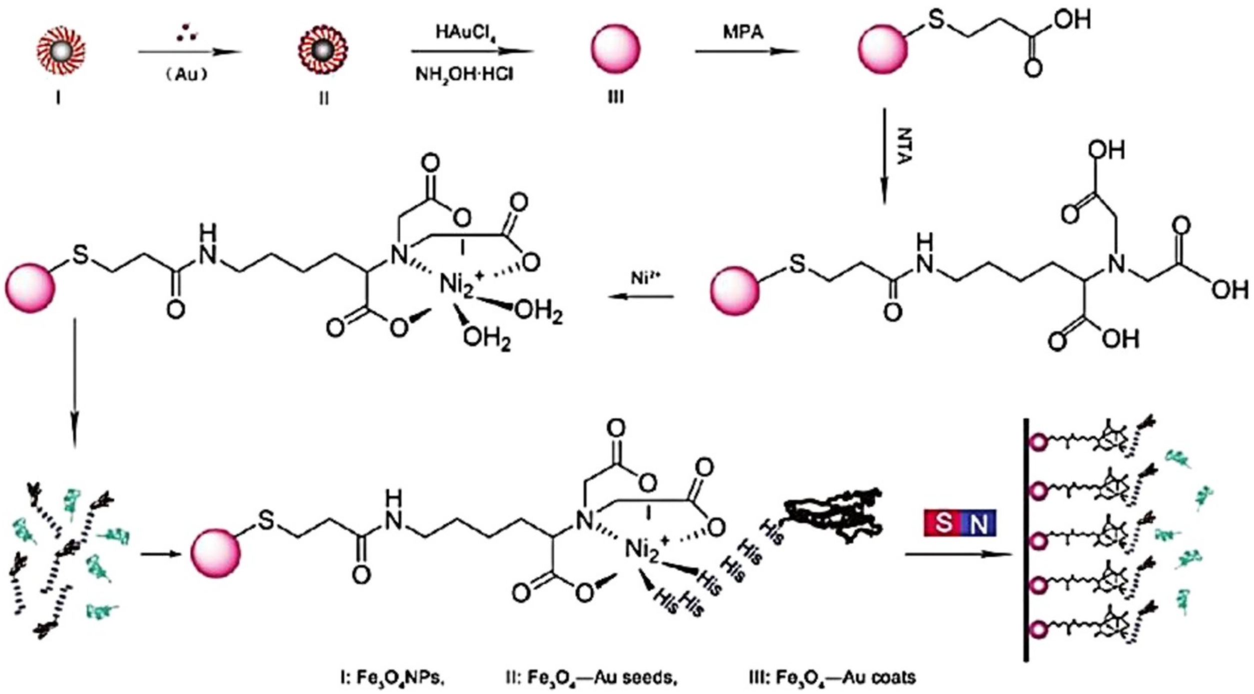

Figure 9 **Preparation procedure of biofunctionalized magnetic Fe_3O_4/Au-NTA-Ni^{2+} NPs and their enrichment and separation of the proteins (Xie et. al., 2010).**

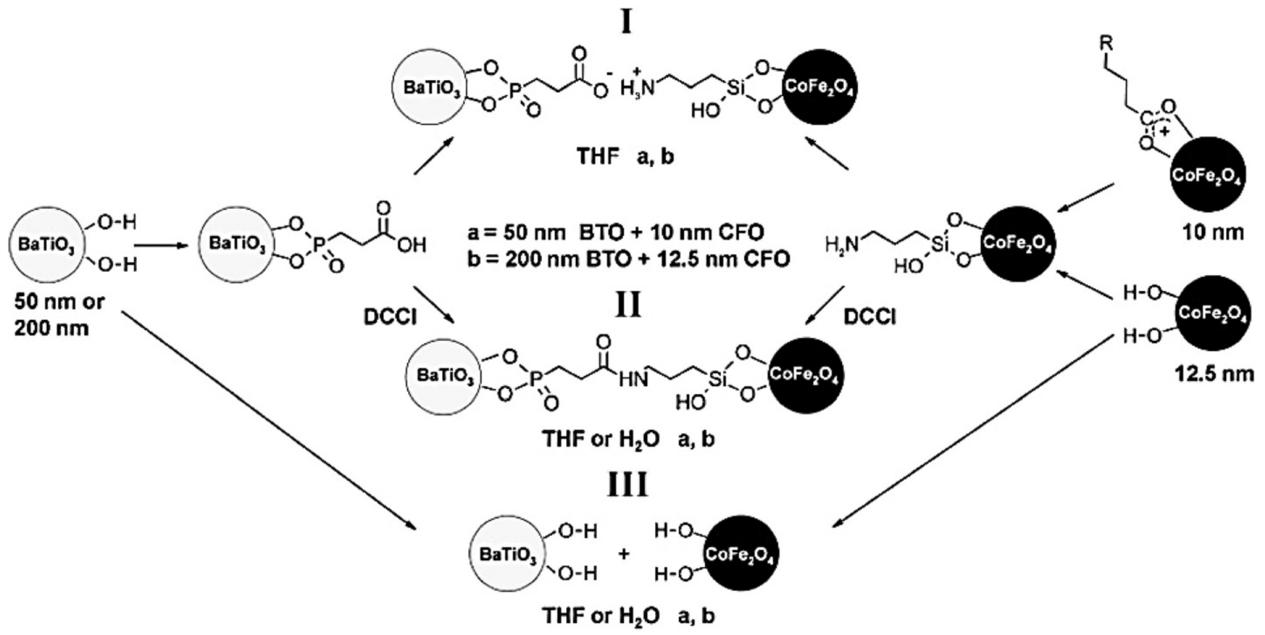

Figure 10 Functionalization and assembly of magnetoelectric nanostructures.(I) assembly of $BaTiO_3$ and $CoFe_2O_4$ in THF, (II) DCCI-coupled assembly of $BaTiO_3$ and $CoFe_2O_4$ in THF, and (III) control reaction performed with unfunctionalized particles in THF, where (a) 50 nm $BaTiO_3$ and 10 nm $CoFe_2O_4$; and (b) 200 nm $BaTiO_3$ and 12.5 nm $CoFe_2O_4$. (Evans et al. 2010).

be conveniently conjugated with various ligands for targeting cancers (Chen et al. 2010).

Kainz et al. (2011) covalently as well as noncovalently functionalized graphene surfaces with functional molecules such as BODIPY, shown in Figure 8. It was noted that both functionalization pathways render the particles highly fluorescent. The researchers also noncovalently bonded a dye to the nanoparticles with a prevalent covalent coating. This system resulted in a multifunctional nanomaterial making use of the possibility to attach drugs or targeting molecules at the periphery of the dendrimers and simultaneously label the particles noncovalently with the BODIPY dye. Whereas, Huang and Juang (2011) fabricated multifunctional magnetic nanoparticles, combining nanomaterials and iron oxides having special optical and magnetic properties shown in Figure 9. The next-generation molecular probes fusing multiple fluorescent dyes, drugs, and multiple NPs into a single nanoprobe should provide superior fluorescence, appreciable sense capabilities, enhanced MRI contrast, and targeted drug-delivery capabilities.

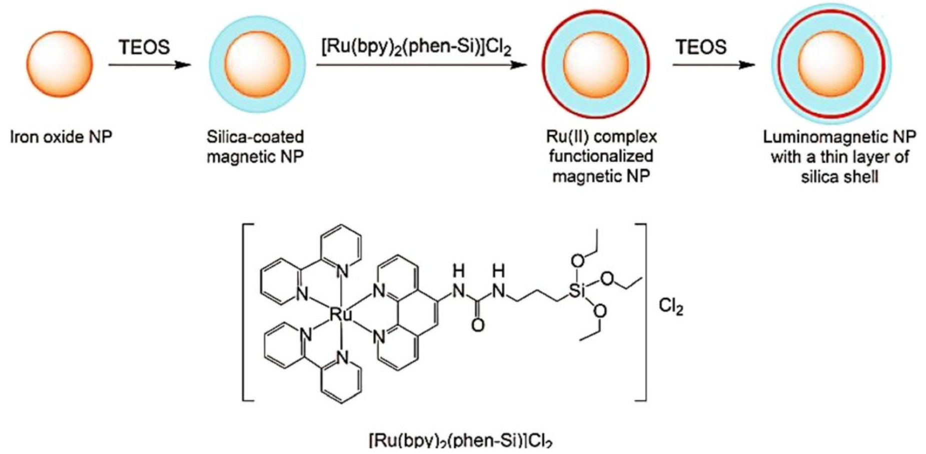

Figure 11 Synthetic scheme for the multifunctional magnetic nanoparticles and the chemical structure of $[Ru(bpy)_2(phen\text{-}Si)]Cl_2$ (Li et al. 2008).

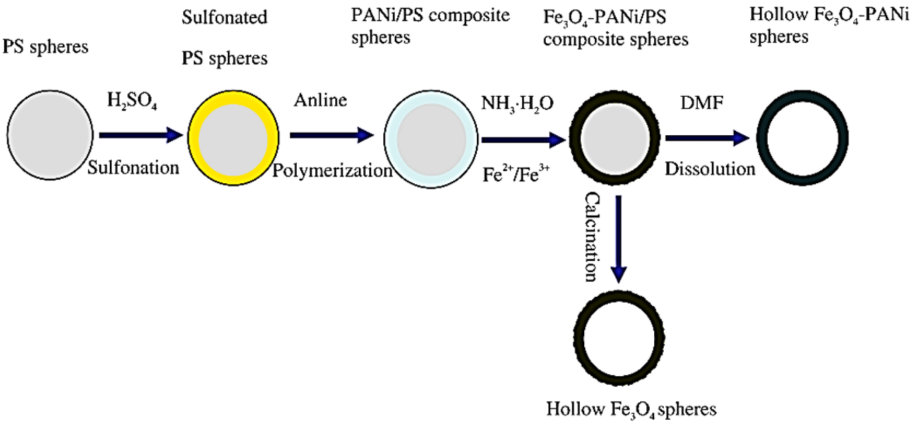

Figure 12 The preparation processes of the composite spheres and their corresponding hollow spheres (Wang et al. 2009b).

Multifunctional magnetic nanomaterials

Evans et al. (2010) functionalized and assembled $BaTiO_3$ and $CoFe_2O_4$, having magnetoelectric properties shown in Figure 10 applicable for magnetic-electric transducers sensors, actuators, and memory devices. This group of nanoparticles ($BaTiO_3$ and $CoFe_2O_4$) was chosen for their distinct sizes and shapes, i.e. near-cubic for $BaTiO_3$ and spherical for $CoFe_2O_4$, and facilitated their identification in the composite by TEM. Li et al. (2008) fabricated multifunctional nanoparticles (Figure 11) consisting of silica-coated magnetic cores and luminescent ruthenium (II) polypyridine complexes. These multifunctional nanocomposites exhibited super-paramagnetic behavior, higher emission intensity, and electrochemiluminescence. Wang et al. (2009b) fabricated multifunctional composite spheres consisting of Fe_3O_4-polyaniline (PANi) shell and polystyrene (PS) cores were fabricated using core shell-structured sulfonated PS spheres as templates shown in Figure 12. Both the Fe_3O_4-PANi/PS composite spheres and the hollow Fe_3O_4 spheres exhibited super-paramagnetic

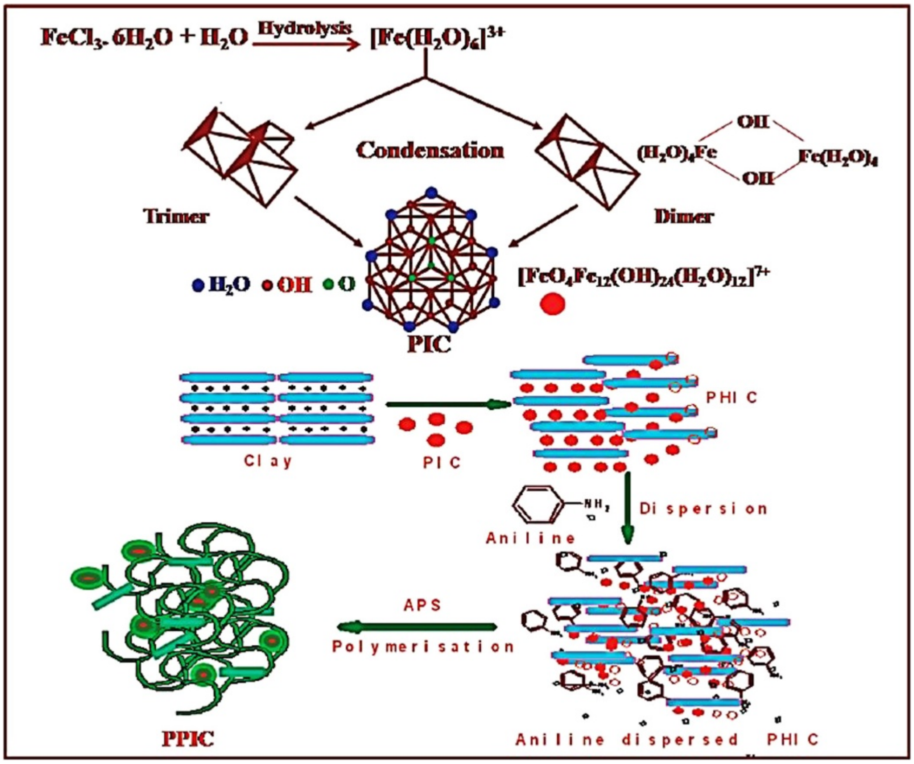

Figure 13 Preparation of multifunctionalized nanostructured electromagnetic materials (Reena et al. 2010).

behavior. It was realized that super-paramagnetic behavior could be altered by changing the content of Fe_3O_4 and conductivity by PANi in the nanocomposites.

Nunes et al. (2010) demonstrated the fabrication of highly tailored nanoscale and microscale magneto-polymer composite particles using a template-based approach, suitable for biomedical and material-based applications. Region-specific surface functionalization of the nanoparticles was performed by chemical grafting and evaporative Pt deposition. The energy-dispersive spectroscopy (EDS) elemental line scan was employed to detect the relative locations of the platinum and iron in the Pt-end-capped, magneto-polymer nanoparticle. Manipulation of the particles by an applied magnetic field was also demonstrated in mediums such as water and hydrogen peroxide. Reena et al. (2010) fabricated electromagnetic polyaniline-polyhydroxy iron-clay composite (PPIC) (Figure 13) by oxidative radical emulsion polymerization of aniline in the presence of polyhydroxy iron cation (PIC) intercalated clays. Magnetic property measurements showed an increase in the magnetization with the PHIC content. The materials exhibited appreciable electrical conductivity, magnetic susceptibility, and good thermal stability, making them suitable for application such as EMI shielding materials and chemical sensors.

Conclusions

The unique and interesting properties of nanostructured materials due to the quantum confinement of charge carriers in small dimensions have given rise to significant desirable properties. These desirable properties include improved electrical, chemical, as well as mechanical properties as compared to their bulk counterpart. These desirable properties have resulted in a variety of applications ranging from bioengineering to catalysis as well as from sensors to renewable energy. A variety of nanomaterial from organic dendrimers, liposomes, gold, carbon, semiconductors, and silicon to metal oxide have already been fabricated and explored in many scientific fields, including chemistry, material sciences, physics, medicine, and electronics. In this article, the nanomaterial synthesis processes as well as their applications is being systematically analyzed to give a thorough analysis of the underlying phenomenon. Despite the success of these nanomaterials, their synthetic process may suffer from drawbacks such as multistep synthesis, use of toxic multifunctional agent, high fabrication cost, high-temperature synthesis, and long synthesis time. Therefore, it is still a challenge to develop a facile, green, and cost-effective method to fabricate multifunctional nanomaterials. Nevertheless, research need to be identified to fabricate these multifunctional nanomaterials with tailored functionalities by linking nanoscale structures to macroscopic functional properties to withstand the extreme operating conditions. The article characterized the relevant development made in the field of nanomaterials. Although multifunctional nanomaterial can be fabricated on the laboratory scale, work is needed to be done to fabricate these nanomaterials at high throughput for energy as well as environmental applications.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

All authors contributed equally. All authors read and approved the final manuscript.

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