

Synthesis and Characterization of Polymer Nanocomposites for Biomedical Applications - Current Perspectives and Challenges

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ABSTRACT: Polymer nanocomposites are hybrid organic–inorganic materials with at least one dimension of the filler phase less than 100nm. Bio-nanocomposites have established themselves as a potential class of hybrid materials resulting from natural and synthetic biodegradable polymers and organic/inorganic fillers. Different compositions of Polymer Bio-nanocomposites can lead to applications from tissue engineering to load-bearing composites for bone reconstruction. A critical factor underlying biomedical polymer nanocomposite properties is interaction between the chosen matrix and the filler. This article discusses current efforts and key research challenges in the development of these materials for use in potential biomedical applications. Polymeric nanoparticles have been extensively studied as particulate carriers in the pharmaceutical and medical fields, because they show promise as drug delivery systems as a result of their controlled and sustained release properties, sub cellular size, biocompatibility with tissue and cells. Several methods to prepare polymeric nanoparticles have been developed and these techniques are classified according to whether the particle formation involves a polymerization reaction or nanoparticles form directly from a macromolecule or preformed polymer. In this review the different techniques for preparation and characterization of polymeric nanoparticles are described.

Keywords - Polymer Nano-composites, Bio-Compatibility, Bio-Nanocomposites, Tissue Engineering

I. INTRODUCTION

Bionanocomposites form a fascinating interdisciplinary area that brings together biology, materials science, and nanotechnology. Generally, polymer nanocomposites are the result of the combination of polymers and inorganic/organic fillers at the nanometer scale. The extraordinary versatility of these new materials springs from the large selection of biopolymers and fillers available to researchers. Existing biopolymers include, but are not limited to, polysaccharides, aliphatic polyesters, polypeptides and proteins, and polynucleic acids, whereas fillers include clays, hydroxyapatite, and metal nanoparticles¹. Development of new nanocomposites by using various materials is highly demanding area by advance techniques. Apart from any discipline, chemistry has played a major role in developing new materials with novel and technologically important properties².

Polymer metal nanocomposites can be prepared by both physical and chemical methods. The polymer is a cross-linked structure to forming a network via chemical or physical interactions³. Current opportunities for polymer nanocomposites in the biomedical arena arise from the multitude of applications and the vastly different functional requirements for each of these applications. For example, the screws and rods that are used for internal bone fixation bring the bone surfaces in close proximity to promote healing. This stabilization must persist for weeks to months without loosening or breaking⁴. The modulus of the implant must be close to that of the bone for efficient load transfer^{5, 6}. The screws and rods must be noncorrosive, nontoxic, and easy to remove if necessary. Thus, a polymer nanocomposite implant must meet certain design and functional criteria, including biocompatibility, biodegradability, mechanical properties, and, in some cases, aesthetic demands. The underlying solution to the use of polymer nanocomposites in vastly differing applications is the correct choice of matrix polymer chemistry, filler type, and matrix–filler interaction.

This rapidly expanding field “Nanotechnology” is generating many exciting new polymer nanocomposites with novel properties. The later can be derived by combining properties from the parent constituents into a single material. There is also the possibility of new properties which are unknown in the parent constituent Materials⁷. Nanocomposites combine favorable features of the constituents on the nanoscale to obtain new functionalities. This article discusses current efforts and focuses on key research challenges in the emerging usage of polymer nanocomposites for potential biomedical applications.

II. NANOCOMPOSITES PREPARATION

A nanocomposite is a composite filled with a reinforcing material having dimensions at the nanometric scale and a high surface area. Despite the existence of different nano-reinforcements, layered silicate clay materials have attracted great attention due to their wide availability, low cost, and also low environmental impact. Clay is a type of commonly used fillers in composite manufacturing with nanoscale dimensions thereby providing an increased surface area⁸.

To enhance the affinity between the clay minerals and the polymer matrix, modification of their surface chemistry through ion-exchange reactions with organic and inorganic cations have been considered⁹. The natural clay is hydrophilic, thus, makes the intercalation of hydrophobic polymer chains into the gallery difficult and prevents clay delamination¹⁰. Therefore, clay modification with a surfactant is required to make it organophilic and compatible with common hydrophobic polymers. To achieve such hydrophobic surface characteristic, a cationic surfactant like alkylammonium or alkylphosphonium should be substituted for the hydrated cations of the interlayer⁹ the most commonly used layer silicates are montmorillonite, hectorite, and saponite, having two types of structure including tetrahedral-substituted and octahedral-substituted. Contrary to the octahedral-substituted structure, the negative charges are located on the silicate layer surface in the tetrahedral-substituted structure, leading to enhanced polymer-clay interaction in comparison with the octahedral-substituted one. Clays are usually characterized by a moderate negative surface charge called cation exchange capacity, CEC. Since, this charge is not locally constant and varies from layer to layer, an average value over the whole crystal must rather be considered.

2.1 Melt Intercalation Process

Melt intercalation is the typical standard approach for synthesizing thermoplastic polymer nanocomposites. It involves annealing the polymer matrix at high temperatures, adding the filler, and finally kneading the composite to achieve uniform distribution, as illustrated in Figure 2. It has the advantage of being environmental friendly because of the lack of solvent usage. In addition, it is considered compatible with industrial processes such as injection molding and extrusion, which makes it more convenient to utilize and, thus, more economical. However, the high temperatures used in the process can damage the surface modification of the filler. For example, organoclays modified with alkyl ammonium usually decomposes at temperatures higher than 140 °C; however, the processing temperature of melt intercalation is in the range of 190–220 °C¹¹. Therefore, optimization of the processing conditions is a very important factor that plays a big role in achieving good dispersion and exfoliation. For instance, operating at lower temperatures or using more thermally stable modifications can avoid degradation¹². Weak electrostatic forces among the filler interlayers and compatibility with the polymer matrix allow the polymer to crawl into the interlayers forming intercalated or exfoliated nanocomposites⁹.

Exfoliation adsorption, also called polymer or prepolymer intercalation from solution, is based on a solvent in which the polymer or prepolymer is soluble. The layered silicate, for instance, is first swollen and dispersed in solvent before mixing it with the polymer solution. The polymer chains then intercalate and displace the solvent within the silicate interlayers. Eventually, on removal of the solvent, a multilayer structure is formed as the sheets reassemble trapping the polymer chains, as shown in Figure3^{9, 12, 13}.

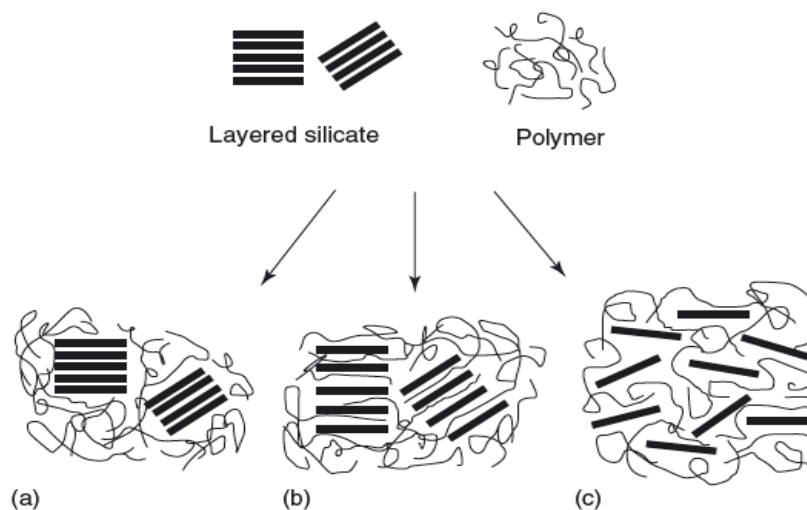


Fig.1 Types of composite microstructures: (a) Unintercalated (Phase separated (microcomposite)), (b) intercalated (Intercalated (nanocomposite)), and (c) exfoliated (nanocomposite).

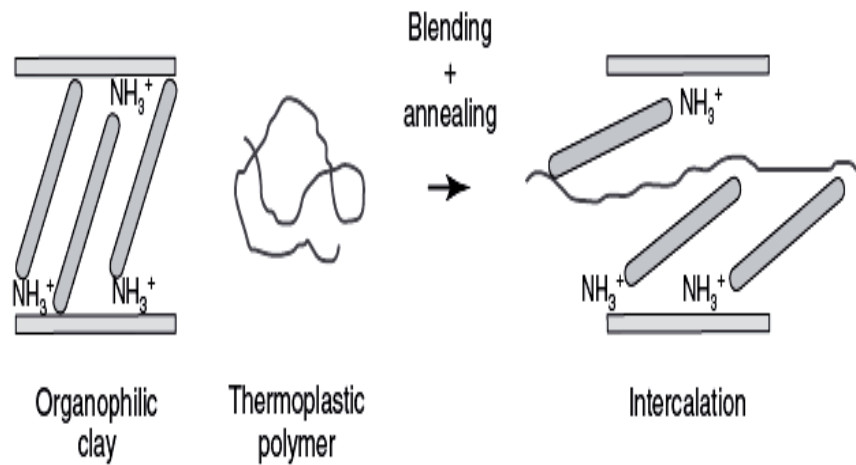


Fig. 2 Melt intercalation process.

This approach is widely used for water-soluble polymers to produce intercalated nanocomposites based on polymers with low or no polarity such as poly (vinyl alcohol), poly (ethylene oxide), poly (vinylpyrrolidone), or poly (acrylic acid)^[14,9]. However, unlike melt intercalation, this method is environmentally unfriendly because of the usage of large amounts of solvents. Emulsion polymerization is considered to be under this method as monomers; usually methyl methacrylate and styrene are dispersed in water along with an emulsifier and different silicate concentrations. The monomer is polymerized with a part of silicate embedded inside the polymer particle and a part adsorbed on the particle surface, forming a nanocomposite.

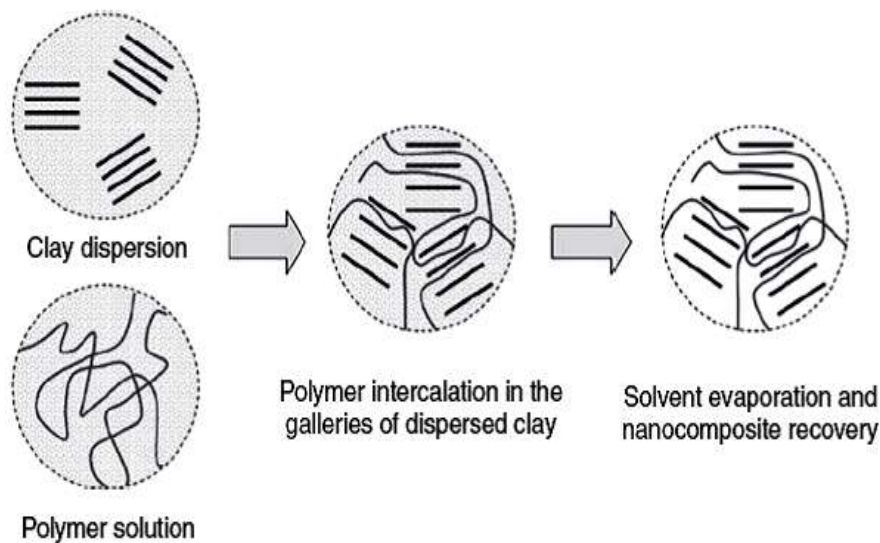


Fig.3 The exfoliation adsorption process.

2.2 Liquid-Liquid Interfacial polymerization

Graphene was used in preparing many nanocomposites via *in situ* polymerization such as nylon-6 (PA-6)¹⁵ and poly (butylene terephthalate) (PBT)¹⁶ – graphene composites. Moreover, ring opening polymerization was used to prepare those nanocomposites. In both cases, good dispersion of graphene was achieved because of the enhanced interfacial interactions^[15, 16]. 1wt%, d-spacing decreased and this was attributed to the strong $\pi - \pi$ interactions between graphene sheets that did not permit polymer intercalation.

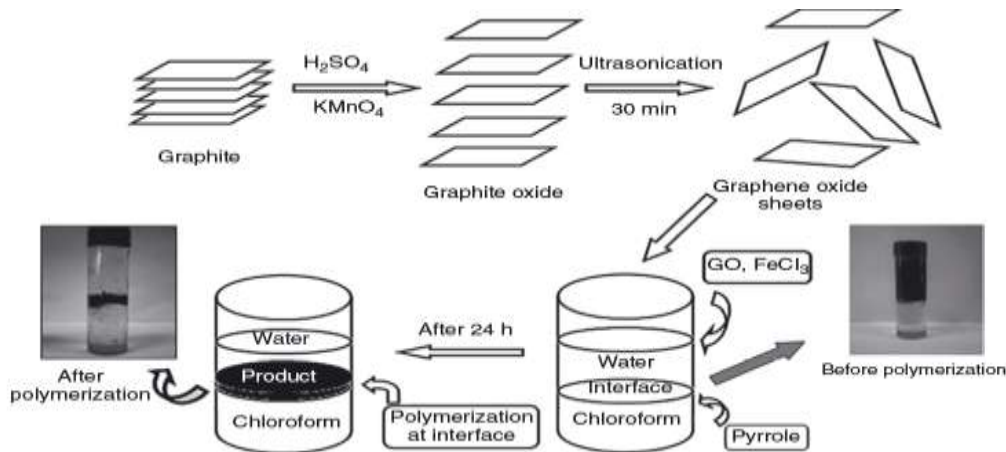


Fig. 4 Schematic of liquid-liquid interfacial polymerization of PPy/GO Nanocomposites

2.3 Hydroxyapatite–Polymer Nanocomposites

Producing bionanocomposites based on biomimetic approaches has been a recent focus of researchers. Among these materials, hydroxyapatite (HAP)–polymer nanocomposites have been used as a biocompatible and osteoconductive substitute for bone repair and implantation^{17, 18}. As the main inorganic component of hard tissue, HAP [Ca₁₀(PO₄)₆(OH)₂] has long been used in orthopedic surgery. However, HAP is difficult to shape because of its brittleness and lack of flexibility. HAP powders can migrate from implanted sites, thus making them inappropriate for use. Moreover, these powders do not disperse well and agglomerate easily¹⁹. Therefore, the incorporation of HAP in polymeric nanocomposites to overcome processing and dispersion challenges is of great interest to the biomedical community. Consequently, a desirable material for use in clinical orthopedics would be a biodegradable structure that induces and promotes new bone formation at the required site. Nanocomposites formed from gelatin and HAP nanocrystals are conducive to the attachment, growth, and proliferation of human osteoblast cells. Collagen-based, polypeptidic gelatin has a high number of functional groups and is currently being used in wound dressings and pharmaceutical adhesives in clinics. The flexibility and cost-effectiveness of gelatin can be combined with the bioactivity and osteoconductivity of HAP to generate potential engineering biomaterials. The traditional problem of HAP aggregation was overcome by precipitation of the apatite crystals within a polymer solution^{20,21}. The porous scaffold generated by this method exhibited well-developed structural features and pore configuration to induce blood circulation and cell ingrowth. Such nanocomposites have high potential for use as hard-tissue scaffolds.

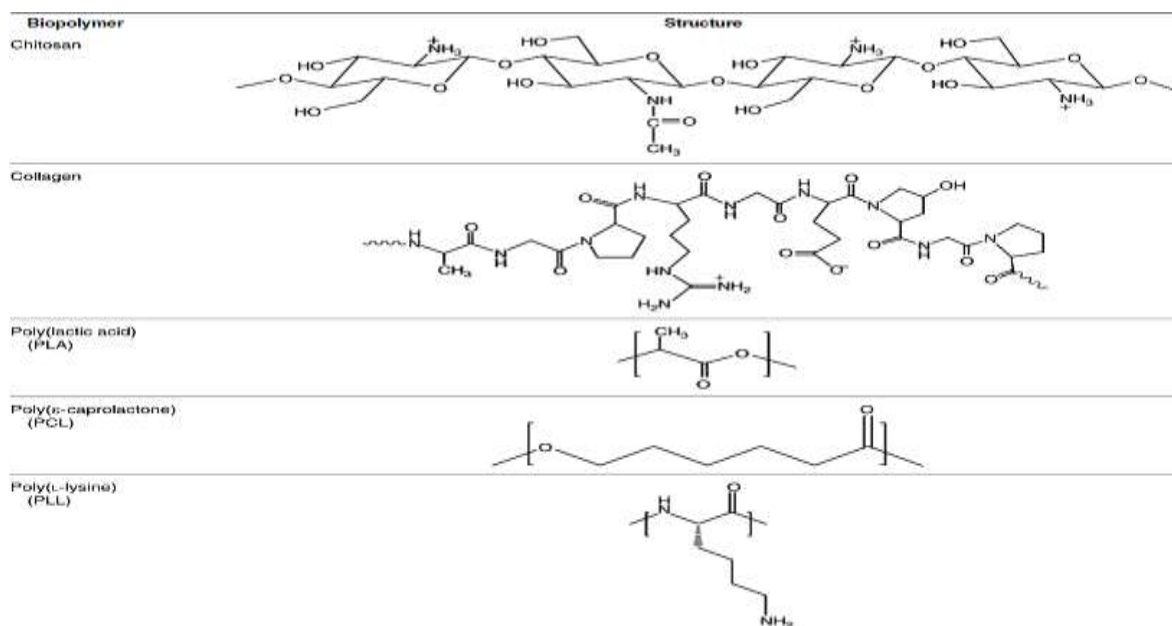


Fig.5 Biopolymers commonly used in biomedical applications

2.4 Bimetallic Nanoparticle Hydrogels

Bimetallic nanoparticles, composed of two different metal elements are of superior interest than monometallic nanoparticles, from both the scientific and technological point of view, for the improvement of the catalytic properties of metal particles^[22-24]. This is because bimetalization can improve the catalytic properties of the original single-metal catalysts and create a new property, which may not be achieved by monometallic catalysts. These effects of the added metal component can frequently be explained in terms of an ensemble and/or a ligand effect in catalyses. Sinfelt and coworkers have vigorously studied inorganic oxide-supported bimetallic nanoparticles for catalysis and analyzed their micro-structures by an EXAFS (Extended X-Ray Absorption Fine Structure) technique^[25-27]. These supported bimetallic nanoparticles have already been used as effective catalysts for the hydrogenation of olefins and carbon-skeleton rearrangement of hydrocarbons^[28]. The alloy structure can be carefully examined to understand their catalytic properties. In contrast, colloidal dispersions of bimetallic nanoparticles have not been well examined^[29].

III. CHARACTERIZATION METHODS OF POLYMER NANOCOMPOSITES

The Characterization methods of polymer nano-composites provide the information on sizes, shapes and physicochemical properties of the nanoparticles.

3.1 UV visible spectroscopy

Colour is the most immediate observable property for certain metal nanoparticles dispersions. This colour effects based upon the surface plasmon resonance or particle plasmon resonance. Noble metal nanoparticles such as Au, Ag and Cu have characteristic colours that are related to their particle size, shape, and particle distance and on the matrix material. For these metals, observation of UV-visible spectra will be a useful complement to other methods in characterizing the nanomaterials^[30].

3.2 Infrared spectroscopy (IR spectroscopy)

IR spectroscopy is one of the methods most extensively used for the investigation of polymer structure as IR band characteristics of the polymers are readily observed^[31]. It is very helpful in the characterization of nanocomposites prepared by the polymerization of the monomers as the formation of the polymer in the nanocomposite is confirmed by this method. To prevent agglomeration of nanoparticles during polymerization and to achieve their compatibility with the polymer, the surfaces of some nanoparticles had been coated with oleic acid. IR spectroscopy gives evidence of the surface coating and is used to investigate the surface chemistry of the nanoparticles as polymer-stabilized nanoparticles give IR bands characteristics of the polymer.

3.3 X-Ray diffraction (XRD)

X-ray diffraction (XRD) is a method of choice to investigate the solid structure of metal nanoparticles and morphology of polymer in polymer-metal nanocomposites. The phase changes with increasing diameter of nanoparticles and the crystal structure can be determined with XRD. The polymer and the metal nanoparticles can be identified by their characteristics peaks in XRD patterns. This technique can investigate the formation of bimetallic nanoparticles as opposed to a mixture of monometallic nanoparticles, since the diffraction pattern of the physical mixtures which may consist of overlapping lines of the two individual monometallic nanoparticles and is distinct from that of the bimetallic nanoparticles. Information on the morphology of the polymer constituent of the composite could be derived also from XRD. The technique can reveal the degree of crystallinity in the polymer component of the nanocomposites as sharper peaks with increased relative peak intensity implies a more ordered arrangement shown by the XRD spectrum of metal nanocomposite.

3.4 Thermo gravimetric Analysis (TGA)

Thermo gravimetric analysis finds application in the characterization of polymer-metal nanocomposites as it provides information on the thermal stability of the nanocomposite relative to the polymers. During composite formation, stabilizers (polymers/surfactants) make organic coating on the nanoparticles surface and TGA can be used to evaluate the amount of stabilizer chemisorbed on the surface of the nanoparticles^[31].

3.5 Transmission electron microscopy (TEM)

Transmission electron microscopy (TEM) was used to find out the size of nanoparticles inside the hydrogel nanocomposites. Size analysis of metal nanoparticles was carried out using electron microscope. Solid samples were studied in dilute aqueous suspensions while in the case of sols; droplets of the undiluted material were placed on Formwar-coated copper mesh grids (diameter 2 mm). The average particle diameter and size distribution of the samples were determined by using TEM images. The nanoparticles formed inside the gel networks are spherical in shape could be found.

IV. CONCLUSION

In this review article, we have discussed an emerging group of hybrid materials based on various polymers and nanofillers that are either used extensively or show promise in the area of biomedical materials. These novel materials vary from inorganic/ceramic-reinforced nanocomposites for mechanical enhancement to peptide-based nanomaterials in which peptides are both the filler and the matrix, with the chemistry designed to render the entire material biocompatible. Requisite functional criteria include mechanical strength, biocompatibility, biodegradability, morphology, and a host of other parameters, depending on end use. However, at the basis of the performance of these nanocomposites are interactions between the biopolymer or synthetic polymer and the filler, which can be tuned and perfected to suit specific needs. The advances in nanotechnology have proved to find excellent approaches for the stabilization and production of controlled nanostructures using various polymeric systems. We hope that further research into these interactions will prove valuable in contemplating the design of novel bionanocomposites for biomedical applications.

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