1

What Are Bionanocomposites?

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1.1 Introduction

Almost all natural materials, which are formed through metabolic processes of an organism, are nanocomposite materials, that is, materials associating at least two distinct phases, one of which being of nanometer scale dimension. The term “natural” is most often synonymously used with the term “biological.” Natural nanocomposite can be therefore characterized as bionanocomposites. Basically two kinds of solid composite materials are generated in natural systems: soft matter and hard matter (Figure 1.1). Natural soft matter composites are composed of at least two types of organic biomacromolecules. The most prominent example here is wood, which is a hierarchically structured bionanocomposite consisting of polysaccharides (mainly cellulose) and lignin (Figure 1.1a). Biological hard matter is generally composed of an inorganic phase and an organic phase. Biominerals (sea shells) and hard tissue (bone) are two typical forms of appearance of biological hard matter (Figure 1.1b). Natural bionanocomposites combine a high resilience and tolerance toward failure, adaptation, modularity, and multifunctionality [1, 2]. They are originally designed and optimized for the needs of life and to meet the surrounding environmental conditions in order to guarantee the survival of the respective species they are associated with.

Nature provide a rich pool of raw materials for mankind with easily accessible constituents for habitation, clothes, weapons, and arts, among many
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Further, the development of chemistry allowed for the transformation of this raw matter into synthetic materials. At the end of the last century, the conjunction of economic and environmental issues, combined with the growing development of multidisciplinary scientific research, has led to reconsider natural processes in general and natural materials in particular as an enormous pool of inspiration with an incredible structural and functional variability. Such bioinspired materials, achieved by using Nature guidelines to tailor and design a novel class of bionanocomposites or nanostructured biohybrid materials, have the potential to conquer complex multivariant environments [3–7].

However, it is interesting to note that under the constraints of living environments and required metabolic conversion processes, only a small number of organic compounds (based on the light elements carbon, hydrogen, oxygen, nitrogen, sulfur, and phosphorus) and a few inorganic phases (i.e., calcium phosphates and carbonates, silica, and iron oxides) are used for the formation of bionanocomposites [8]. This strongly contrasts with engineering materials that are prepared from almost all the elements of the periodic table. In parallel, structures and properties of biological polymers have been, and still are, studied by biologists mainly to understand their essential roles in biological systems. However, the potential applications of biological molecules in the design of bionanocomposites require to consider them as synthetic “building blocks” that may eventually be used in a context distant from their natural environment or function.

Figure 1.1 Examples for biological soft and hard matter: (a) trunk disc of an oak tree and (b) lower jawbone of a cow (mandible).
1.2 A Molecular Perspective: Why Biological Macromolecules?

This is a relatively new view as biomolecules have long been considered, outside the biological or biomedical field, as highly complex systems, difficult to modify, and too fragile to be of any practical utility. Indeed, proteins or nucleic acids have characteristic features that are not common in the synthetic chemical world. Their natural functionality in living cells and their potential applications outside biology precisely result from these properties:

- First, proteins and nucleic acids are very long copolymers in which the different monomers are linked with a defined order. In other words, these polymers have a defined “sequence,” a property that usually does not exist in polymers made by chemical synthesis.
- Second, the specific sequence of any nucleic acid or the coding sequence of a protein gene can be viewed and is actually used, by living cells as well as by biologists, not only as a substance but also as information: biological sequences can be duplicated, transmitted, eventually modified, and executed. Information processing occurs naturally between generations of cells and organisms that select, amplify, replicate genes, and control their expression. Information processing similarly occurs when a sequence is designed in a laboratory, transmitted by e-mail, synthetized as a synthetic gene, amplified by PCR, and translated in protein in a recombinant microorganism.
- Third, biological polymers are self-assembling materials. The information content embedded within each sequence is often sufficient to allow each nucleic acid or protein to reach its highly organized structure, and the functional properties of biological molecules directly result from their three-dimensional structure.
- Fourth, nucleic acids or proteins can evolve. Each natural protein or nucleic acid sequence is not simply a molecule: its informational content is the product of a historical process. In the current structure and function of any natural protein, there is the memory of all past successful trials that occurred during its evolution. It is this historical information accumulated over billions of years that explains the amazing diversity and extreme sophistication of natural protein structures and functions.

1.3 Challenges for Bionanocomposites

Going back 50 years ago, the design of specific peptide or nucleic acid sequence to control the organization of gold nanoparticles into perfectly controlled crystals was probably as unexpected as the application of the same particles for cell imaging. Thus, the progresses made in the field of bionanocomposites over the
last decades largely result from the evolution of both chemistry and biology fields (but also of physics, engineering, and computer science) that, in some specific areas, has led to conceptual and experimental convergences. The processing of natural macromolecules in artificial conditions has been as fruitful as the confrontation of chemical and biological to define how the two worlds can cohabitate. This has led to an impressive list of “hybrid” objects that will be described in the following chapters.

However, there are several characteristics present in biology that have not been translated in engineering materials so far. The extraordinary structures and functions of biological materials strongly relate to their organization over several length scales. In particular, the importance of hierarchical structuring has long been identified and was widely investigated in the recent years [3, 9]. A variety of functional materials solutions relying on structural hierarchy were described in natural materials [10–14] (Figure 1.2). However, whereas such organizations could be obtained for organic or inorganic structures [15–17], they are still challenging to achieve in bionanocomposite systems.

Figure 1.2 Structural hierarchy of soft tissue (oak wood) and hard tissue (bone): (a1) tissue, (a2) cells, (a3) cell walls, (a4) elementary fibrils, and (a5) biomolecules (cellulose and lignin); (b1) compact and spongy bone, (b2) osteons, (b3) collagen fibril, (b4) mineralized collagen triple helices, and (b5) collagen molecule and calcium phosphate nanocrystal.
Another key feature of biological aspects yet to implement in materials science involves dynamic processes such as evolution, growth, and continuous structure formation (self-organization, remodeling). This means that according to the local and temporal needs, the organism supplies the required material “on demand” with an extremely high spatiotemporal precision [18]. As a consequence, building blocks for the bionanocomposite formation (inorganic and organic phases) are continuously supplied and assembled from finely tuned cooperative interactions by regulatory processes as an answer to external and internal stimuli (Figure 1.3). This ultimately means that natural materials are dynamic in terms of structure and composition. These basic principles are related to two fundamental biological processes termed (i) ontogenesis and (ii) morphogenesis. Both processes are not known for engineering materials but

![Collagen fibril](image)

**Figure 1.3** Fundamental biological and dynamic processes that are absent in engineering materials. The development of the material during the lifetime of an organism is termed ontogenesis: (a) juvenile bone (woven bone) with unoriented collagen fibrils and (b) adult bone (lamellar bone) with highly oriented collagen fibrils. Morphogenesis is the development of form: (c) juvenile skull and (d) adult skull.
might lead to advanced materials with unforeseen properties and open new horizons for high-level applications.

To conclude, bionanocomposites are attracting more and more interest not only from the natural sciences but also from materials chemists and engineers. Although synthetic materials might never be as sophisticated as natural systems, integration of key processes involved in the building-up of biological materials in the fabrication of bionanocomposites would pave the grounds for the development of a new generation of advanced materials that can cope with spatiotemporal multivariant environments and combine multiple properties.

References


