

Chapter 7

Nanocomposites: Preparation, Characterization, and Applications

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Increasing dependence on traditional materials has enforced the need for replacing them with more capable alternatives, promising stronger resilience, and strength to be fitted in dynamic and robust applications. These requirements have necessitated the controlled mixing of more than one kind of materials, which can provide the proportionate improvements in performance attributes. Thereby, composites have rightly emerged as the amicable substitutes wherein faster response, greater stress-bearing capability, and

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longer lasting times could be attained. The best instances include development of stronger materials for sophisticated areas like those of defense and corrosion, where either there is a prompt requirement, or we are already spending too much to counter. The advent of nanomaterials has further strengthened the performance attributes of these materials, leading to improved mechanical strength, load bearing, and tolerance of environmental stresses. The shear stress of carbon nanotubes (CNTs) is no more a fascination to discuss or illustrate as also the flexibility of fullerenes and nanometallic solid structures. Nanocomposites basically involve the reinforcements of nanomaterials (may be one or more) to a bulk material, which is presumed to play the role equivalent to that of an adsorbent matrix. These entities have been extensively evaluated for their mechanical strength, buckling capability, corrosion tolerance, extreme order conductivity variations, thermal stress tolerance, and light-reflecting characteristics. The research is in swift progress for still finer development of stronger materials. With these insights, this article discusses the development of nanocomposites alongside their performance ascertaining characterizations and breakthrough applications of recent origin.

7.1 Introduction

Development of better and more resilient materials has been a persistent requirement of humankind, more so with the present-day dynamic lifestyle and mounting needs of automation and faster communication. Since the sustainable natural resources supporting the life on earth are finite, it has emerged as a liability to conserve them and ensure their judicious use, preventing any unchecked exploitation and wastage. Owing to this, a persistent thought of global economy has rallied behind generation of clean energy with reduced waste creation and recycling of nutrients, wherever possible. Composites are intentionally created entities in this regard, made with the intent to co-propagate the performance-optimizing aspects of two or more individual objects [1–3]. For instance, one material has good electrical conduction ability but gets corroded easily. Thereby, commercial use of such a material creates economic

pressure for its regular generation. However, if this material is combined with another substance capable of resisting corrosion, it could provide a better product having enhanced electrical conductance as well as the ability of reasonably sufficient usage. Similarly, several electronics industries require materials with high dielectric constant, flexibility, simplicity in development, and mechanical as well as textural strength. A single entity with all such attributes is significantly tough to be located and unearthed. Thereby, ceramic materials (having high dielectric constant and exhibiting brittle texture even at high temperature) impart a better suitability, particularly with their ability to withstand high temperature. On the contrary, the polymeric materials have easier processing attributes but have low dielectric constants. Composites comprising micron-level ferroelectric ceramics as liquid crystal (LC) filler or as thermoplastic polymer matrices do not have suitable processing attributes. Hence, it is difficult to modify them into thin uniform films, required in multipurpose microelectronics utilities. Under these circumstances, nanocomposites (NCs) provide amiable remedies wherein, a much greater useful combination of material properties could be exercised through nanometer-scale mixing. Thus, composites address such natural limitations of individual material entities.

Nanocomposites are a further specific class of composites having a nanomaterial as fillers dispersed in a bulk matrix. Typical composition resembles a coexistence of matrix and filler, where the fillers could be particles, fibers, or fragments that are generally surrounded and bound together as distinct entities using the matrix [4, 5]. The nomenclature “nanocomposites” spans significant diversity of materials, including three-dimensional (3D) metal matrix materials to two-dimensional (2D) lamellar composites, unidimensional nanowires (NWs) to non-dimensional (0D) core-shell configurations, collectively substantiating diversified mixed and layered materials [6, 7]. The obvious curiosity after knowing what NCs are remains the need to know about the fundamental essence of NCs with their intent. It is not surprising, perhaps, that nanomaterials have been the subject of intense interest not only in academic research but also from the point of view of

(scale-up driven) industrial applications. The reason behind this is that nanomaterials simply have tremendously high surface areas for exploring and improving their interaction properties, which consequently results in significant distinctions of physical, chemical, optical, and magnetic properties [8, 9]. As a consequence, the properties of NCs depend not only on the behavior/stimulus specific response of their individual constituents but also on their respective inclusion extent, the interaction-driven morphology, and interfacial characteristics. Studies have even yielded NCs that are thousand times tougher and stronger than their bulk component. With reference to their applications of a better material behavior, NCs constitute a combination of organic and inorganic materials, wherein the inorganic phase could be 3D framework systems (such as zeolites), 2D layered substances (such as clays, metal oxides, metal phosphates), and even 1D rod-like structures. Thereby, the essence of making NCs revolves around accomplishing the nonexistent qualitative attributes, similar to light weight reinforced mechanical adhesives, noncorrosive and long-lasting battery cathodes, better shock- and stress-bearing capabilities, higher mechanical strength, buckling capability, and several others.

It might be yet another surprise wherein the terminologies organic and inorganic phases have been used when so many other criteria of defining materials are known and established. This is because of the fact that inorganic layered materials prevail in several distinct configurations, bearing significantly accessible well-defined, symmetric intra-lamellar space [10, 11]. This particular property rightly describes the utility of layered materials as matrices for polymers, laying the foundation of hybrid NCs. Lamellar NCs signify a rare possibility wherein interfacial interactions among the constituent phases are maximized. As a result, concurrent variations in the matrix and fuller compositions and their mutual interactions could provide NCs with a broad range of properties. This is best illustrated by the distinct constitutional makeup of intercalated and exfoliated lamellar NCs, with the former comprising alternate assembly of polymer chains having inorganic layers being in a fixed compositional stoichiometry, together contributing to a systematically even count polymer layers in the intra-lamellar space.

Contrary to this, in exfoliated NCs, the relative extent of polymer chains intervening matrix layers varies with interlayer separation being in the order of 100 angstroms. While intercalated NCs find their usage driven by their electronic and charge transport characteristics, their exfoliated counterparts are preferred for superior mechanical properties. Thus, the most generalized definition of NC could be a several-phase-constituted solid material, with at least one nanoscale dimension. It is perhaps under the control of our will to control the number of nanoscale dimensions, usually optimized with reference to specific applications or requirements in consideration. Typical nanomaterials used in making NCs include nanoparticles (NPs), nanofibers, and nanoclays. In one line, the essence of making NCs is their inherent ability to provide varied material properties (chiefly being mechanical and physical) without changing the wholesome chemical compositions [12, 13].

7.2 Formation Rationale and Variations of Nanocomposites

Based on the fundamental nature of the material of the basal matrix, three main variations of NCs are recognized: ceramic, polymer, and metal matrices. It is pertinent to know here that generation of NCs is strictly with respect to better application fulfilment, and there are some localized aspects only, where NCs fare better than their bulk counterparts. Some of the notable challenges in NC fabrication include the difficulty in homogeneous distribution of the filler material, wherein the structure–property relationship needs to be understood better. Thereby, there is an urgent need to develop simpler mechanisms of filler (exclusively NPs) material exfoliation and dispersion. Besides this, the expenditure incurred in making NCs is also significantly high compared to those of normal composites.

Thus, though NCs promise better wear-and-tear resistance alongside higher load-bearing capability, the specific formation mechanisms necessitate the requirement of sophisticated processing, thereby increasing the incurred expenditure. The stage is optimum for a discussion of different types of NCs, being distinguished into metal, ceramic, and polymer, on the basis of specific matrix regime (Fig. 7.1).

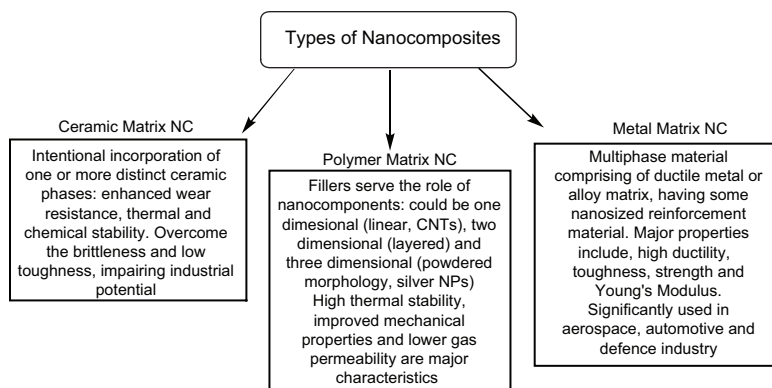


Figure 7.1 Different classes of nanocomposites with their characteristic features. Requirement of bulk matrix and filler ingredient as the nanomaterial contributor is common to all.

7.2.1 Ceramic Matrix Nanocomposites

The ceramic matrix nanocomposites (CMNCs) are materials made after the intentional inclusion of one or more different ceramic phases, especially with reference to hydrophilic resistance, thermal and chemical stability enhancement. The rationale of making CMNCs is attributed to their brittleness and low toughness of ceramic materials, limiting their industrial applications. Examples of CMNCs include matrix wherein energy-distributing agents (fiber, platelets, or particles) are selected for moderating the brittleness and enhancing fracture durability [14, 15].

7.2.1.1 Processing methods

Several methods have been optimized for CMNC synthesis, and latest among which are single-source precursor methodologies, decided through hybrid precursor melt spinning, subsequently being subjected to curing and pyrolysis.

Some previously known methods of this regime are conventional powder, polymer precursor route, spray pyrolysis, and vapor deposition methodologies (chemical and pulse vapor depositions) [16–19]. A brief glance of some of the NCs using these methods can be found in Table 7.1 along with the salient advantages and performance sensitive cautions.

Table 7.1 Different CMNC processing methods with their advantages and limitations

Method	System	Advantages	Limitations
Powder procedure	Al ₂ O ₃ /SiC	Easier in approach	Low formation pace and phase dispersion, agglomeration
Polymer precursor method	Al ₂ O ₃ /SiC, SiN/SiC	Possibility of finer particle preparation, better reinforcement dispersion	Agglomeration and ultrafine particle dispersion (causing phase segregation)
Sol-gel procedure	SiO ₂ /Ni, ZnO/Co, TiO ₂ /Fe ₂ O ₃ , La ₂ O ₃ /TiO ₂ , Al ₂ O ₃ /SiO ₂ , NdAlO ₃ /Al ₂ O ₃	Simple, versatile, chemical homogeneity	Compact, low void formation compared to mixing method

7.2.1.2 Structural overview

A typical CMNC comprises a matrix containing nanosized reinforced components, which could be particles, whiskers, fibers, or even nanotubes. High brittleness and easy fracturing of ceramic material necessitate the incorporation of ductile metal phase within matrix, thereby improving durability as well as mechanical properties (hardness and fracture toughness). These improvements are the outcomes of more controlled interaction between different phases, matrices, and reinforcements. Understanding the structure-property relationship of CMNCs requires a thorough knowledge of the inter-relationship between the surface area and the volume of reinforcement materials. The variation of matrix and filler inclusion extents of CMNCs is a decisive factor to confer several improved properties, of which fracture strength toughness and high-temperature resistance are major. Table 7.2 presents a few examples of CMNCs, with the characteristically improved material properties, corresponding to the specified matrix and reinforcement combination.

Table 7.2 Some characteristically improved properties corresponding to different CMNC matrix and reinforcement constituents

Matrix/Reinforcement	Improved properties
$\text{Si}_3\text{N}_4/\text{SiC}$	Strength and durability
$\text{Al}_2\text{O}_3/\text{SiC}$	Strength and durability
$\text{B}_4\text{C}/\text{TiB}_2$	Strength and durability
$\text{Al}_2\text{O}_3/\text{NdAlO}_3$	Photoluminescence

CMNCs are highly durable industrial materials, owing to their high-temperature resistance, significant mechanical strength, and chemical inertness. Bioceramic materials have no undesirable effect on humans and are, therefore, highly preferred for designing prosthetics. On being freely left, CMNCs remain unaltered for a reasonably long time. The recyclability of these materials is a positive sign for their usage, promising a long-lasting life along with reduced carbon emission and cost effectiveness [20].

7.2.2 Metal Matrix Nanocomposite

Metal matrix nanocomposites (MMNCs) represent multiphased materials comprising a ductile metal or alloy matrix, having the provision of implanting nanoscale reinforcement. Salient MMNCs traits include high ductility, toughness, strength, and Young's modulus, making them useful in aerospace and automotive industries.

7.2.2.1 Processing and preparation

Metal matrices for the preparation of MMNCs include Al, Mg, Pb, Sn, W, and Fe, while the reinforcing entities (the nanomaterial constituents) vary from metal powders such as silica, clays (as crystalline grade). More common reinforcements include low-particle size and well-versed interaction-chemistry-bearing layered silicates and clays.

Among the preparation methods, there exist chemical and physical methods, making use of bottom-up and top-down principles. The physical methods include spray pyrolysis, liquid metal infiltration, rapid solidification, plasma and chemical vapor depositions, and electrodeposition.

Table 7.3 Select compositions of MMNCs with their fabrication method

Method	System
Spray pyrolysis	W/Cu, Fe/MgO
Liquid filtration	Pb/Cu, W/Cu-Nb/Cu, Pb/Fe-Nb/Fe, Al-C60
Sol-gel	Fe/SiO ₂ , Ag/Au, Au/Fe/Au
Rapid solidification	Al/X/Zr (X= Si, Cu, Ni), AL/Pb, Fe alloy
Ultrasonication	Al/SiC

Contrary to this, chemical methods include colloidal assembly and sol-gel processing. Some of the relatively less used methods for making MMNCs are melt falling drop quenching and one-step preparation of carbon dot and Au nanoparticle consisting NCs [21–24]. Table 7.3 summarizes the different methods to make MMNCs, along with the potential advantages and cautions.

7.2.3 Polymer Matrix Nanocomposites

Polymer matrix nanocomposites (PMNCs) consist of a polymer material as matrix, whereas the fillers can be different nanomaterials such as 1D (carbon nanotubes, CNTs), 2D (layered materials, montmorillonite), and 3D powdered textures (e.g., AgNPs) [25]. Interactions between the polymer matrix and the nanoscale reinforcement on a molecular scale are accountable to the attractive forces operating between the two. Consequently, the inclusion of a small extent of nanofiller (having dimensions below 100 nm from that of the matrix) brings about a change in the material properties. Typical methods for making PMNCs are same as that for composites, vis-à-vis in situ intercalative polymerization, solvent approach, and mixing melted polymer matrix. The major characteristics of PMNCs include significant inertness toward varying temperatures, better mechanical characteristics (high abrasion resistance), and meagre gas porosity (higher barrier capacity) [26].

7.2.3.1 Processing approaches

Several mechanisms are known for the preparation of PMNCs, more popular of which include solution-driven intercalation, in situ intercalative polymerization, melt intercalation, and template

synthesis (sol–gel methodology) [27]. The first major method, the intercalative polymerization approach, involves the formation of polymer in the midst of two intercalated sheets. The working relies on layered silicate swelling within liquid monomer, thereby initiating the polymerization (through the availability of heat/radiation or by the diffusion of a suitable initiator) [28]. Initially, this method was applied for producing nylon-montmorillonite nanocomposite, but after some time, it became a common mechanism for making several thermoplastics. This method promises a convenient method to make thermoset-clay NCs [29]. A few demerits of this method include slow reaction rate, dependence of clay exfoliation through clay swelling, diffusion rate of monomers in the layered segments, and incomplete polymerization-driven oligomer formation [20].

In the melt-intercalation approach, there is no requirement of solvent and polymer matrix, and the typical makeup comprises a molten layered silicate. Conventional methods such as injection molding or extrusion make use of high-temperature thermoplastic polymer mechanical mixing with organophillic clay [30]. In this stage, polymer chains get exfoliated to generate NCs. The method is easily the best choice for making thermoplastic NCs and can be a significant remedy in the event of unsuccessful in situ polymerization or due to the inappropriate polymer selection. Crucial hurdles of this method include its restrictive suitability to polyolefins, accounting for a majority of used polymers [20].

In the sol–gel method, the formation of clay minerals occurs within the polymer matrix through the application of an aqueous or semi-solid solution comprising polymer and silicate as constituent units. Processing begins by nucleation, subsequent to which, the polymer inclusion facilitates the development of inorganic host crystals, while being enclosed in between the layers. This method is generally preferred for making double-layered hydroxide-based NCs and is much less suited for layered silicates [28]. Two major concerns of the process are high temperature requirement for clay mineral synthesis (that often decomposes the polymers) and the aggregation tendency during the silicate growth. Table 7.4 provides different methods for making PMNCs along with their advantages and cautions.

Table 7.4 An overview of PMNC preparation methods along with potential merits and demerits

Method	Major use	Advantages	Disadvantages
In situ interactive polymerization	Manufacture of nylon-montmorillonite NCs and thermoplastics	Tethering effect enabling the linkage	Slow reaction rate, dependence of clay exfoliation
Melt interaction	In making thermoplastic NCs	Replacement method for in situ polymerization	Limited application to polyolefins
Template preparation (sol-gel technology)	In making double-layered hydroxide-based NCs	Aids in the dispersion of silicate layers in a single-step process	High temperature for making clay minerals, often involves polymer decomposition and aggregation during silicate growth

7.2.3.2 Properties of PMNCs

The native characteristics of PMNCs project their usefulness in being widely used across cutting-edge applications. Compared with traditional materials, these composites possess greater specific strength and specific modulus, damage tolerance, flame retardant and damping properties. Glass fiber presents a befitting example of a high specific strength and Young's modulus material, having high density with lower specific modulus of glass fiber resin matrix [31]. In terms of stress tolerance, NCs exhibit matrix cracking (in place of fracture causing crack propagation), fiber pull-out, interfacial structure breaking, and fiber breaking. An unfortunate event of minute fiber fracturing results in load transfer through the matrix on intact fibers, a generalized frequent observation. On being substituted by an NC in a shorter time limit, there is seldom any loss of bearing capacity despite the observations of defects and cracks [31]. In terms of flame retardation, the search in earlier

studies revealed that addition of even 5% nanosized clay particles could induce a 63% lowering of nylon-6 flammability. Herein, recent studies have shown a boost in this flame-reading ability through enabling molecular-level clay dispersion. This phenomenon is manifested through enhancement of barrier properties by the clay generated “tortuous path,” delaying gas movement through the matrix (Fig. 7.2) [32]. Similar to the above attributes, NCs impart the ability of vibration absorption through the incorporation of a damping material, enabling a cessation of vibrations in a shorter time [31].

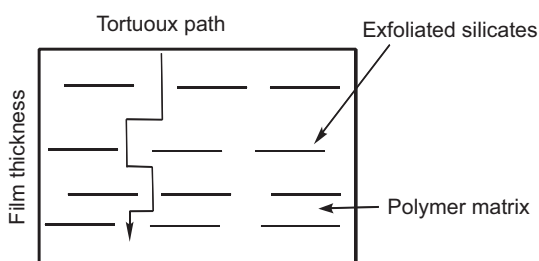


Figure 7.2 Neison's path model for NCs conferred barrier enhancement [32].

The stage is now perfectly augmented to switch over to the characterization techniques relevant for analyzing NCs, since these are specially designed materials after keeping the intended applications in consideration. Based on the exclusive results of characterization, different NCs are used for their specified applications. Three different levels of NCs prevail: optical, crystallographic, and spectroscopic. Each mode of characterization provides implicit information about the fabricated NCs, although analysis from crystal structure study is the first and basic level of study. This is because the implicit confirmation of a material nature (from its chemical composition point of view) is inferred from the database of its particular geometry.

7.3 Characterizations of Nanocomposites

The characterizations of NCs have increased the interest of researchers with theoretical and experimental techniques due to

their versatile applicability. Here a wide range of methodologies are practiced as inspecting techniques for NCs by influencing their physical and chemical behaviors, biological interactions, optical characteristics, and generation cost. Hence, a thorough and in-depth characterization of NCs is required to achieve an efficient accommodation in their nanoscale features to realize their manifested benefits. Characterization methods for NCs practiced significantly for NC characterization over the last decade include scanning electron microscopy (SEM), transmission electron microscopy (TEM), optical microscopy (OM), and atomic force microscopy (AFM). These techniques have emerged significantly crucial to investigate and correlate the structure, size, and morphology of NCs with their intended applications [33–36]. Most extensively, SEM has been used for NC structural characterization despite having a lower resolution compared to AFM or TEM [37–41]. It is difficult to obtain accurate and detailed knowledge regarding the constitutional distribution within the matrix of a PMNC. Though advancements for better resolution prevail, in the form of SEM and field emission gun SEM (FESEM), all of these operate at precisely low potential differences, rendering it infeasible to screen organic entities without conductive coating. Apart from SEM, AFM and TEM are also used for the structural prediction of NCs, particularly cellulose- or chitin-like nanomaterials distribution and dispersion [37–39, 42, 43]. The structure of PMNCs is conventionally illustrated through combined TEM and wide-angle X-ray diffraction (WAXD) [38]. The text ahead chronologically describes the microscopic, crystallographic, and spectroscopic techniques practiced for NC characterization.

7.3.1 Optical Characterization

Optical microscopy is significant in characterizing the macroscopic structures when the matrix is transparent and the sample is extremely thin. However, it is not suitable for characterization of CNTs within NCs. For instance, polarized optical microscopy (OM) is used for assessing the crystallization behavior of CNT-modified and unmodified carbon nanocomposites (CNCs) along with silylated CNCs, where CNC without surface modification gets aggregated [44–46].

7.3.1.1 Scanning electron microscopy

SEM is easily the most rigorous microscopic methods for surface characterization, having 1–5 nm ranged resolution, so that the analyzed materials have a large field depth, helpful in producing 3D images. The working principle comprises an electron gun through which electrons are accelerated across the lenses that focus the beam over a very little size. These electrons penetrate the sample being analyzed to about 1 μm depth, generating image-forming signals. Among all the generated signals, three most important are backscattered electrons (BEs), secondary electrons (SEs), and X-rays. The BEs comprise elastically scattered electrons conferring the specimen atomic-number-dependent compositional contrast. These electrons have high energy and come from 1 μm or more specimen depth. SEs comprise low-energy electrons, emerging from the specimen surface, and are mostly used for topography imaging [47]. The PMNCs where both matrices and reinforcing fillers are nonconductive mostly constitute low-atomic-number elements, used for topography visualization.

7.3.1.2 Transmission electron microscopy

This microscopic characterization tool is characterized by the transmission of high-energy electrons through an ultrathin specimen domain. The image is generated on account of electron emission after the incident electron beam hits the specimen [48]. The electrons are emitted from an electron filament, having two or more condenser lenses beneath it, for de-magnifying the electrons emitted by the gun as well as controlling its diameter, while they hit the specimen (held inside the objective positioned below the condenser lens). After the objective lens, there are two lenses, namely, intermediate and projector, producing a real and magnified image on the fluorescent imaging screen or film. The contrast of TEM image is due to electron scattering, where the imaging mode is described by the bright field (BF), having an objective opening inserted to form the images by direct unscattered electrons. Thicker or high-density regions in the specimen generally scatter strongly and appear darker because of the obstructed flow by the objective aperture. The image region with no specimen is bright in BF. The diffraction, mass thickness,

and phase contrast are three basic mechanisms contributing toward image formation [45, 48]. The NCs having low-atomic-number element only induce a weak electron scattering, resulting in below par image contrast. For these materials, the mass thickness contrast mechanism can be applied using thin sample staining involving heavy metal enabled scanning of interesting features. For instance, uranyl acetate is an appropriate staining agent for CNTs to induce better contrast [44]. Thereby, extensive characteristics of nanoparticle-reinforced polymer composites are affected by inter-matrix nanoparticle phase distribution. The corresponding capability to ascertain the nanoparticle surface distribution or being rooted in a polymer matrix is crucial, in the course of relating the resulting composite attributes to characteristic enhancement mechanism. TEM is, therefore, a universally acclaimed technique for determining NCs thought thickness, making it arguably the most suitable microscopy subject to homogeneous CNT distribution and dispersion [38].

7.3.1.3 Atomic force microscopy

AFM is a scanning probe module that inspects an NC sample using nanometer resolution probe, having 10 nm as typical radius of curvature. The monitoring of probe and sample surface interaction response is responsible for producing the sample topography [49–51]. Two operating modes, namely, contact and noncontact, are used where the measurements could be made under vacuum, vapor, and liquid environments. The contact mode provisions the AFM cantilever tip scan the specimen surface, maintaining a constant force between the tip and sample. While ascertaining the impacts and counter-impacts of this probe–specimen interaction, the typical probe vibration frequency aids in maintaining a constant force over the sample in noncontact/tapping mode. Advantages of this mode are lower lateral forces contrary to contact mechanism, making it feasible to acquire phase image like additional contrast channels. The sub-nanometer height and nanometer-scale lateral resolutions are permitted for reference inspection of cellulose NCs, propelling in the concomitant surface roughness [52, 53]. In the noncontact mode, the phase imaging regulates the amplitude of probe vibration and

nanoparticles distribution within the polymer matrix. It also implies recording cantilever oscillation phase lag, relative to cantilever's piezo driver's transmitted signal. The phase lag is much sensitive to adhesion variations, viscoelasticity and thus manifests contrast among the different material components of NCs. Additionally, phase imaging highlights edges, typically remaining unaffected by significant amplitude differences, inferring clear observation of fine features, like those of grain edges. Such phase imaging characteristics make AFM a useful technique for ascertaining typical nanoparticle distribution within polymer composites [42, 43, 54]. It is essential to scan multiple sample sections through varied NC thickness as conventionally AFM is used to screen the nanoparticles scattering through the composite thickness. The imaging for topography and phase provides information about the typical CNC alignment within NCs where the degree of CNC alignment is qualitatively described via a variety of image analysis methods [55–57]. Typically, raw AFM image depicts the post-processing long CNC axis, where the angle of the CNC long axis with respect to geometry or CNC alignment is measured. Such working explains the 2D CNC alignment, supposing that all CNCs recline along the AFM imaging plane. For additional degrees of freedom along the CNC orientation, a method for 3D alignment of short fiber composites involving elliptical cross section on a polished surface could be appropriate [58–60].

7.3.2 Crystal Structure Inspection

The WAXD is used to ascertain the CNC alignment within the composites where distinctions in diffracted X-ray strength are measured corresponding to each specified diffraction plane as a function of orientation along with composite geometry [56, 61–63]. The diffracting X-rays with reference to primary X-ray beam direction, like monochromatic X-ray, $\gamma = 0.1541$ nm from $\text{CuK}\alpha$ radiation, generated at a fixed accelerating potential difference and current, are measured by WAXD. Diffracting X-rays appear merely in specific circumstances, depending on the internal solid crystalline morphology. For instance, the 2θ diffraction peaks at $\sim 14.5^\circ$, 16.6° , 20.4° , 22.7° , and 34.4° are obtained for cellulose, corresponding to

plane miller indices [58, 64]. The extent of CNC arrangement can be estimated using 2D WAXD diffraction patterns, providing diffraction intensities for $(5-50)^\circ 2\theta$ and Azimuthal angle ϕ (360°) rotation about one NC axis. The resulting 2D diffraction patterns depict the Debye–Scherrer rings, inferring Azimuthal intensity dispersal for each 2θ diffraction peak [59]. On linking the diffraction patterns with the axis of the to-be-scanned composite sample, one can retrieve further details pertaining to the inter-composite CNC alignment [65]. For CNC, diffraction patterns are obtained corresponding to accommodate a composite specimen so that the alignment remains along the axis [59, 65].

7.3.3 Spectroscopic Characterization

Owing to the mounting interest in the structural chemistry of NCs, their molecular characterization has become necessary for understanding their characteristics as well as new material development. Spectroscopic techniques provide significant details about polymers, fillers, and composites, wherein variations in fluorescent intensity, nuclear magnetic spin frequency matching, infrared and Raman frequencies elucidate the filler dispersion extent across the host matrix, the extent of polymer and filler particle interaction along with the polymer chain dynamics at the polymer–filler interface.

7.3.3.1 Fluorescence spectroscopy

Analysis by fluorescence spectroscopy requires amalgamation in the presence of a fluorescent probe, employed at an extremely dilute concentration such that the sample bulk is not unduly attenuated. The probe is selected for its sensitivity to ascertain variations in the immediate surroundings, through varied emission features. Typical investigation of the luminescence attributes of a small probe embedded within a polymer matrix deciphers key polymer science prospects, like counting dynamics of polymer chains via excimer fluorescence, phase separation and polymer mixing ability, transport phenomenon or polymer deterioration [66, 67]. Application of fluorescence attributes of polymer composites extensively

intercepts a characteristic photophysical process such as energy transfer or fluorescence suppression. The interface properties and dispersion in PMNCs are investigated by the Förster resonance energy transfer (FRET) mechanism [68]. This mechanism explains energy transfer from a donor fluorophore (having excited electronic state) to an acceptor via non-radiative dipole–dipole coupling. It needs an overlap between donor’s fluorescence and acceptor’s absorption spectra. Furthermore, typical FRET competence depends on the intermolecular separation, should be ideally within 1–10 nm. FRET is applied to reveal nanoscale features happening at the polymer–filler system interface, depicting the labelled phases with appropriate donor–acceptor chromophores [68]. An attractive application of fluorescence spectroscopy remains the stress-softening process investigation in filled elastomers (Mullins effect), inferred by moderate decrement in the load subsequent to a material’s stretching after the first load release [69].

7.3.3.2 Solid-state NMR spectroscopy

The solid-state nuclear magnetic resonance (NMR) allows the screening of polymer–filler interfaces on account of mutual NMR spectral sensitivity with the relaxation parameters to native as well as segmental molecular activities (of polymer chains) [70]. The interactions of polymer–filler typically contribute to an adsorption layer formation, wherein the chain motilities are far too limited than the bulk structure, distinguishing the workable polymer nature in the interfacial region. In solid-state H^+ NMR using spin-echo technique, the transverse magnetization relaxation function is also studied (for instance in poly(dimethylsiloxane)) [70].

7.3.3.3 Infrared and Raman spectroscopy

Infrared ray (IR) absorption and Raman scattering are the spectroscopic protocols extensively employed to collect vibrational-features-determined information about the polymeric systems [71, 72]. The IR radiation originates from the direct interaction between the frequencies of the IR incident ray with a specified vibrational mode. On the other hand, the Raman effect is basically an inelastic light scattering, happening subsequent to a molecule’s irradiation with monochromatic/laser illumination. Raman scattering allows

scrutiny of thick polymeric samples but not very thin films that remain fit to be analyzed using IR spectroscopy, owing to a robust absorption of IR radiations by the polymer functional groups. The analysis of such spectra not only provides organic and inorganic phase interaction estimate but also respective intercalation and exfoliation polymer states. Such composites contain layered silicates, filler dispersion/functionalization, and varying-orientation-bearing polymer chains/anisometric particles. A combination of AFM and IR techniques to retrieve IR spectra with a nanoscale spatial resolution is also used to screen the NCs [73]. Such an analysis mode lowers the extent of normal IR spectroscopy, just like the diffraction-imposed spatial resolution limits. It is used for characterizing the nanoscale aspects of polymer NCs, within the cross and interdisciplinary domains of conventional and material sciences [74].

7.4 Material Significance of Nanocomposites in Inter- and Cross-Disciplinary Domains

7.4.1 Aerospace Sector

Numerous composite materials are involved in building the aerospace structures such as equipment inclusions, aircraft internal parts, coatings, cockpit, crew gear, heat-contracting tubing, space accommodating mirrors, housings, nozzles, and solar array substrates. Apart from their physicochemical inertness, light weight, low operating cost, and fire resistance, these materials also have a few disadvantages that restrict their use. First, their higher electrical resistance hinders an involvement in electromagnetic shielding, lightning strike defense, antennas, and circuits [75]. Then, a lower thermal conductivity enhances the pressure on discrete structures depending on electrical heaters. Last, they are less resistant to moisture absorption, easily influenced by environmental clues, and degraded with time [76, 77]. Therefore, to overcome such limitations, researchers have developed some NCs based on matrix and filler used. The PMNCs and CMNCs having thermal, chemical, electrical, and mechanical properties have fulfilled the aerospace requirements with nanofiller inclusions such as nanoclay, alumina,

CNTs, TiO₂, PZT (lead zirconate titanate), and others. For instance, polyamide/clay nanocomposite exhibited enhancement in heat resistance, Young's modulus, strength, biodegradability besides reduced flammability and gas permeability, making them suitable for aerospace applications [78, 79]. Moreover, higher reduction in gas permeability in case of polyamide/clay nanocomposite enhances their usefulness for floor patterning in the cargo part of airliners as well as manipulation of lightweight and strong cryogenic gas storage tanks [80]. Similarly, montmorillonite- and DOPO-based phosphorus tetraglycidyl NCs have reduced the manifold necessities in aircraft design [81, 82], whereas polyurethane-consisting CZT (cadmium zinc telluride) offers lightening-strike resistance, electromagnetic shielding, and radar-absorbing abilities to aircraft coating [75, 83]. Furthermore, CZT also imparts a stronger tensile strength with enhanced properties to the ceramic matrix than conventional carbon, which only provides toughness [84].

7.4.2 Automotive Industry

Till today, 80% of polymer/clay NCs are used in automotive applications. Owing to their extraordinary properties such as stiffness, thermo-mechanical resistance, and low power consumption, they are widely used in car part industry. In addition, they have the ability to be painted together with other car parts and undergo similar actions as metallic materials in vehicle manipulation. Such response of these materials makes them superior to the previously used polypropylene and glass fillers in car parts. For example, several entities within a car, such as timing belt, handles, rearview mirror, engine cover, bumper, gas tank, and others, are made using nylon (polyamide) as NCs by companies such as Bayer, Honeywell Polymer, Toyota Motors, RTP Company, UBE, and Unitika. Moreover, footboards of Safari and Astro cars are made up of polyolefin NCs such as polyethylene and polypropylene, produced by General Motors [85].

7.4.3 Food Packaging

NCs also play a vital role in the food packaging industry by extending the shelf life of products based on their restricting activities,

constitution, and relative interactions with food particles. Their antimicrobial activities are more effective than micro- or macroscale materials due to large aspect ratios and high surface reactivity [86]. Therefore, these properties can be helpful in preventing damage of the food product through one-to-one access between active NC ingredients and products, as well as via obstructing the O contact besides ethylene and water vapor that provide protective environment.

7.4.3.1 Direct contact of food with active components

Here the active components are nanofillers such as NPs, clay, and others, which possess antimicrobial activities and enhance the food's shelf life, quality, and safety through inhibiting microbial growth as well as manipulating the biotic and abiotic factors. The antimicrobial efficacy of NCs highly depends on various features such as size, agglomeration tendency, dispersion, and nanofiller-surface-matrix interactions. Several efforts have been made to enhance the food product's shelf life using NC packaging materials. For instance, packaging films consisting of ethylene vinyl acetate, functionalized nanoclay, and brewery waste extract exhibited antibacterial activities toward *Escherichia coli* and *Staphylococcus aureus*, extending the healthy existence durations of beef and meat products [87]. Nanocomposite films of polyethylene organically formed montmorillonite, having necessary oil mixtures of both carvacrol and thymol, have emerged effective in minimizing the effects of *Botrytis cinerea* on strawberry [88]. Likewise, incorporation of Ag-montmorillonite into packaging materials prolonged the shelf life of fresh fruit salad [89]. Another study exhibited significant extension in the shelf life of cold storage carrots using similar material in alginate-based films [90]. Similarly, nisin-loaded soy lecithin nanoliposomes, inserted into the HPMC-formed packaging films, showed inhibited growth of *Listeria monocytogenes*.

7.4.3.2 Gas barrier packaging materials

Nanocomposite packaging films bring about changes in the internal or external environment through oxygen impermeability attributes. Since oxygen within a food package decreases the duration of stable existence of food materials via involvement of several activities such

as microbial growth, enzyme activation, and oxidative reactions. Furthermore, this oxygen also generates ethylene, which further aggravates respiration in fruits and vegetables. Thereby, to prevent such a loss of food shelf life and concurrent food product quality, oxygen should be scavenged or removed from the package to a designated level needed to ensure healthy existence of a given food product. Apart from oxygen, other volatile compounds released from vegetables and fruits during storage should also be restricted to enhance the products' shelf life. However, improved gas barrier properties of NCs provided multilayered NCs, allowing firm packaging such as thermoformed containers. These containers provide a modified atmosphere for packaged fresh foods that rely on respiration rate, film permeability, gas transport, weight and surface area, free head space occupancy, and atmospheric structure within containers.

Many studies have reported the scavenging of residual oxygen within the package. For example, the synergistic effect of altered atmosphere in platters having Ag-cellulose absorbents together results in microbial growth inhibition and delayed senescence in processed melon [91]. Likewise, cellulose pads infused with Ag NCs retard the growth of bacteria, yeast, and molds in kiwi fruit [92]. Similar to oxygen scavenging, ethylene is also reported to be scavenged using TiO₂ NPs deposited on polypropylene films [93]. The addition of nanofiller within the polymer matrix improves several barrier features for NCs, thereby enclosing gases and water vapor. This inclusion of nanofillers confers an improved packaging quality compared to native polymer matrix. For example, gas barrier attributes of low-density polyethylene (LDPE) got enhanced even more than seven counts subsequent to montmorillonite incorporation [94]. Similarly, the inclusion of cellulose into a poly (ϵ -caprolactone) matrix reduced the water vapor permeability on increasing nanofiller concentration [95]. Likewise, in ethylene-co-vinyl alcohol (EVOH)/poly(lactic acid) (PLA), LDPE, polypropylene (PP), and high-density polyethylene constituted thin layers, the oxygen permeability lowered on nanocaly addition [93, 96–98]. A few commercial-grade NCs utilized for packaging are compiled in Table 7.5.

Table 7.5 Few commercial-grade NCs used for food packaging

Nanocomposites			
S. No.	(commercial name)	Uses	References
1.	Nylon-6 NCs	PET multilayer bottles for beverages and foods	[99]
2.	Imperm [®] , a nanoclay	Beer and carbonated drink bottles	[100]
3.	Durethan [®] KU2-2601,	Coating juice bottles	[101]
4.	AEGIS [™] OX	Beer bottles	[101]
5.	Biomaster [®] Ag based NCs	Sustained Ag ⁺ release assuring food packaging	[101, 102]
6.	Agion [®] Ag based NCs	Sustained Ag ⁺ release assuring food packaging	[101, 102]

7.4.4 Biomedical Applications

For the last 50 years, ceramic NCs have received great interest in the field of biomedicine for their unique structural and functional properties that allow withstanding soaring loading rates, thermal energy, physical stress, and chemical etching too unembellished for metal surface. Thereby, bone and dental implant applications are the most challenging for ceramics. But their brittleness restricts the potential applications to few, apart from defects induced during mechanical loading, which result in disastrous failure. Thus, to improve the activities of ceramic matrix in the biomedical domain, nanostructured ceramics are being explored to overcome extensive structural and biological complications. A nanophase ceramic composite can be produced using nanocrystalline materials or NCs having a large area-to-volume ratio, allowing significant modulation of physicochemical properties. The CNCs with improvements in strength, stability, stiffness, and creep resistance have enabled significant advances in medical science such as development of orthopedic, dental implants, tissue engineering, and drug-delivery systems for cancer treatment.

7.4.4.1 Orthopedic implants

Alumina and zirconia ceramics are crystalline in nature where atoms are bound together with strong ionic and covalent bonds. Owing to such chemical linkages, these materials have high strength, hardness, and elastic modulus, making them ideal for use in orthopedic implants. Moreover, their biocompatibility, chemically inertness, and resistance against corrosion are also fruitful in the case of lifetime implantation [103]. However, their intrinsic brittleness limits their usage as orthopedic implants. Therefore, this issue can be solved via potential improvements in the implant techniques and materials quality. Recently, numerous zirconia–alumina NCs have been reported with excellent control toward aging, resulting from their toughness and mechanical strength [104, 105]. In zirconia–alumina NCs, two types of composites can be synthesized: either zirconia-toughened alumina (ZTA) where zirconia particles are impregnated into the alumina matrix or alumina-toughened zirconia (ATZ) having alumina particles in the zirconia matrix. In the ATZ system, composites have high fracture toughness, whereas the ZTA system has composites with strong stiffness and low fracture toughness [106, 107]. Both these composites are commercialized under ZTA BioloX[®] Delta and ATZ BIO HIP[®] terminologies. In contrast to ATZ, the ZTA system is widely used in biomedical applications due the alumina matrix monodispersion of zirconia, subsequently getting transformed into a stable monoclinic phase under mechanical loading [104]. Another study developed Ce-TZP/Al₂O₃ NCs exhibiting high aging resistance, wear resistance, and biocompatibility [107–109]. Besides these NCs, Garmendia et al. established YTZP (yttria-stabilized zirconia)-CNT NCs via adding CNT into a zirconia matrix that showed an improvement in the mechanical, physical, and chemical properties.

7.4.4.2 Dental implants

CNCs find significant utility in the development of dental implants as they provide both strength and toughness that are necessary for a long-span fixed partial prostheses and implant supports. For dental implants, YTZP is an important ceramic having exceptional mechanical properties and biodegradability. But with zirconia ceramics, aging is still an issue as the implants are kept in humid,

acidic, or basic oral environment. There are some other features that require detailed investigation such as the influence of thermally aided manipulation on microstructure and strength, attachment as cover for porcelains, cement annealing, visible light transparency linked with aesthetic refurbishment, X-ray denseness, and experimental prevalence feasibilities. Many features of zirconia–alumina NCs present befitting opportunities for further optimization and betterment of these properties. For example, Philipp et al. investigated the veneered ceria stabilized zirconia–alumina NCs for making dental implants after its functioning for a year [110]. While Nevarez-Rascon et al. observed the properties of ATZ and ZTA NCs such as size, density, hardness, and fracture toughness, which were in good agreement with international standards thereof [105]. Therefore, ATZ and ZTA composites combination proved to be ideal than their pure oxides for dental purpose. Besides this, Kong et al. attempted the enhancement of zirconia–alumina matrix biocompatibility toward load-bearing applications via adding bioactive $\text{Ca}_3(\text{PO}_4)_2$ like HAP and TCP, which in turn improved the bone regeneration and osteointegration [111].

7.4.4.3 Tissue engineering

Tissue engineering has achieved a remarkable success in tissue repair and corrective surgeries aimed at regeneration. The fundamental science of tissue engineering makes use of a highly porous scaffold that acts as a supportive material for cells seeding in vitro where cells adhere, proliferate, and differentiate. This scaffold permits an invasion of blood vessels that provide strength as well as nutrients to the cells. Moreover, it should be biodegradable with controlled degradation rate and must vanish as soon as new cells regenerated. Several composites are being explored to fulfil these features and ensure self-sustainable functioning within the physiological boundaries. Recently, various ceramics such as hydroxyapatite and tri- and biphasic $\text{Ca}_3(\text{PO}_4)_2$ have been studied in bone tissue engineering [112]. But owing to their brittleness, their use is localized and far too restricted for load-bearing applications [113]. Thus, polymer–ceramic nanocomposites have been developed exhibiting similar inorganic–organic composition and mechanical properties of natural bone via adding $\text{Ca}_3(\text{PO}_4)_2$ [114]. Like ceramic, polymeric scaffolds of poly(lactic acid) (PLA), poly(glycolic acid)(PGA),

poly(lactic acid-co-glycolic acid) (PLGA), and poly(ϵ -caprolactone) (PCL) are being used for bone tissue engineering. However, their hydrophobic, biological inertness, and general weak texture have restricted their utilization in bone regeneration. With an intent to overcome these issues, Wei et al. prepared nanohydroxyapatite (nHAp)/PLLA composite on adding nanohydroxyapatite into PPLA scaffolds, which revealed increased protein absorption and thus ultimately improved cell adhesion [115]. Similarly, Wang et al. proposed nanohydroxyapatite/polycaprolactone (nHAp/PCL) scaffolds for improved bone marrow stromal cell growth compared to PCL scaffold [116]. Another investigation assessed the cellular proximity and compatibility of mesenchymal stem cells, with micro HAp and nano HAp/PCL composites. Their results indicated a higher cell proliferation for NCs having a large surface-area-to-volume ratio [117]. Apart from this, Hong et al. prepared a bioactive glass ceramic nanoparticle and PLLA NC gibbet. Such novel scaffold has high modulus (8.0 MPa), enabling paramount mineralization for imitation of physiological environment [118].

7.4.4.4 Drug-delivery system for cancer treatment

The development of targeted drug-delivery system has reduced the harmful effects related with the treatment of cancer, in particular resulting from lack of anticancer drug specificity. However, an extraordinary ability of NCs for targeting and controlling anticancer drug has attracted great attention among researchers toward the designing of nanoscale composites for cancer therapy. Therefore, such advancement in NCs has enhanced the versatility of drug-delivery systems via conjugating with drugs to treat specific tumor.

Many NCs have and are being used for delivery of anticancer drugs, having enabled their increased concentrations at a specific site and finally improving the efficiency. For instance, Rajan et al. established chitosan-based polyoxalate carriers for cisplatin delivery in MCF-7 cells that released the drug in a controlled manner [119]. These NCs having oxalic acid, succinic acid, tartaric acid, and citric acid were conjugated with ethylene glycol, subsequent to being examined as targeted and controlled drug-delivery vehicles for cancer treatment. Similarly, Dhanavel et al. prepared chitosan/palladium-5% nanocomposite for 5-fluorouracil and curcumin co-delivery to arrest acquired drug resistance by cancer cells. Such

NCs with dual drug binding exhibited better anticancer effect on HT-29 cells than single drug [120]. In another study, nanocomposite tagged with hyaluronidase favored drug diffusion from the carrier to cells as due to degradation activity of this enzyme. The chitosan-hyaluronidase-5-fluorouracil polyethylene glycol-gelatin (CS-HYL-5-Fu-PEG-G) combined association displayed an improved 5-Fu bioavailability as well as controlled release [121]. In another significant effort, Rasoulzadeh et al. encapsulated doxorubicin (DOX) in carboxymethyl cellulose containing graphene oxide (CMC/GO) hydrogel where CMC works in a pH-sensitive mode, mediating drug release at necessary pH. The prepared nanocomposite was used against human colon cancer cell line (SW480) and exhibited significant inhibition [122]. Similarly, gelatin-based magnetic hydrogel NCs were used as nanocarriers for DOX [123]. Moreover, curcumin-loaded PMMA-PEG/ZnO was examined toward gastric tumor by Dhivya et al. Their results indicated that such NCs are beneficial for loading hydrophobic drugs, which consequently resulted in improved bioavailability [124]. Quite often, for nucleus-specific delivery of anticancer drugs, functionalized reduced graphene oxide NCs are used. In one study, such NCs were conjugated with DOX that subsequently provided poly-L-lysine-functionalized graphene oxide that transferred the drugs precisely within the nucleus of HER2 breast cancer cells [125]. Apart from this, clay-based NCs also played a vital role in targeting cancer cell. Various types of clay are identified for constructing NCs. Halloysite (Hal) obtained from aluminum silicate is used to prepare nanocomposite hydrogel comprising Hal-sodium hyaluronate/polyhydroxyethyl methacrylate for colon cancer therapy using 5-Fu [126]. Likewise, palygorskite (Pal), a hydrated magnetic aluminum silicate used for nanocomposite synthesis was explored toward cancer treatment [127].

7.4.5 Electronic Applications

NCs are widely employed in chemical sensors, electroluminescent devices, batteries, memory-based gadgets, photovoltaic cells, supercapacitors, light-emitting diodes, and others [128]. PNCs conjugated with nanofillers have been explored for sensing purposes through multiple mechanisms. In this case, nanofillers include CNTs,

Au, Ni, Cu, Pt, metal oxide, and others [129]. Moreover, polymer-dependent solar cells are capable to prepare low-cost large flexible panels, for example CdS NPs embedded in a polymer matrix are used to make solar cells [130]. Nevertheless, graphene also takes part in electronic applications and increases the life span of electronic devices, which in turn reduces the cost [131]. In addition, graphene/polyaniline (PANI) NCs are used to detect ammonia, which is more sensitive for nanocomposite than PANI alone [132]. Similarly, such NCs are also used for H₂ gas detection with 16.57% higher detection efficacy than PANI (9.38%) and graphene alone (0.83%) [133].

Therefore, from the above-mentioned various applications of nanocomposites, we can conclude that mixing of two or more nanoformed fillers have tremendously enhanced the properties than particle alone. Table 7.6 summarizes the still remaining prominent utilities of different types of NCs.

Table 7.6 List of applications for different kinds of nanocomposites

S. No	Matrix	Nanofiller	Application	References
1.	Epoxy	Clay	Anticorrosion	[134]
2.	Pullulan	Clay	Oxygen barrier	[135]
3.	Polyvinyl alcohol	ZnO	Biosensor	[136]
4.	Ni-P	PTFE	Antibiofouling	[137]
5.	Polyvinylidene fluoride	Au	Dielectric	[138]
6.	PANI	Nanocellulose	Electrochromic	[139]

7.5 Future Directions and Inspirations

Composites have, thus, rightly emerged as the most suitable materials to meet the ever-increasing demand for faster and multifunctional materials. There is, no doubt, a compulsive need to improve the wear-and-tear attributes alongside prolonging the shelf life of available options. With nanocomposites, it has become possible to accomplish multiple needs via varying incorporation of nanomaterials. The

advances in the stress response and long-lasting functional abilities of NCs are substantially attributed to the existing richness of nanomaterials, which are responsible for conferring one-, two-, and three-dimensional attributes to the intact products. In developed countries, NCs have not only replaced most of the plastic gadgets but also iron and iron-comprising other materials constituted entities have been revolutionized through better anti-corrosive abilities. The inclusion of graphene, CNTs, carbon fibers, and the derivatives thereof has easily over-seeded their expected outcomes, and there is still plentiful to be enquired and investigated. While metal- and ceramics-based NCs are more suitable in daily use requirements, those of polymer NCs are exclusively befitting for strategic applications. A perfect example illustrating this is the use of Kevlar in the tires of US President's official vehicle, owing to its remarkable strength and toughness. Similarly, CNTs and fullerenes have been used to make the air bags of Toyota's automobiles, enabling quicker stimulus-driven expansion and contraction. Remarkable strength and mechanical properties of NCs have propelled them as rightful candidates toward making stronger ballistic support, missiles, roads, and several other automotive sector products. The clutches of two-wheelers, window-locking system of four-wheelers, and sensing-based devices (such as barcodes, nanoscalds, nanotweezers, and nanofibers) have witnessed the advances of nanomaterial wonders. These gadgets have not only reduced the expenditure on raw materials and care with respect to safeguarding from wear-and-tear damages but are also better in monitoring, quicker in response, and much easier to preserve. The crucial factor of mechanical strength is known to impair the working life of several materials; in this context, NCs have emerged as highly suitable replacements through improved stress response manifested by the included nanomaterials. Not limited to industrial and strategic domains, the versatility of NCs has blessed the biomedical diagnostics with a much-needed boost. Implants of nanomaterials combined with biomaterials (termed bionanocomposite) are being used in the corrective replacement of dislocated and damaged bones. NCs have been proposed in surface inactive forms, wherein the delivery of drugs has become much controlled and precise, ensuring the timing and quantity of

delivered drug in line with the requirement. The quest for bettering the existing or proven attributes still continues, although it is a big task to facilitate an efficient propagation of laboratory science and fundamentals to the normal lives of citizens. Only an integrated approach with the intent to understand the scientific rationale of various nanomaterial inclusions (with respect to their shape and size dependent activities) can revolutionize the science of NCs and improve the understanding of stronger and more resilient materials design.

7.6 Conclusion

We have presented the scientific rationale of composites as the modern-day improved materials with manifested abilities of improved performance through increased load-bearing capability along with reduced wear and tear. The formative strategies of different grades of composites propel them as robust materials having the potential of delivering as per the requirements and specific applications. The requirement arena comprises from household devices to industrial appliances and instruments along with stronger ballistic materials and more resilient gadgets. Incorporation of nanomaterials (having high aspect ratios and relatively finer constitutional distribution) confers a new realm to performance attributes of composites. One fine illustration of this strategy is the inclusion of multiwalled CNTs in the coal tar pitch matrices using a molding press. The nanomaterials as filler significantly strengthen the intermolecular forces across the entire structure alongside conferring stronger stress- and shock-withstanding abilities. Similarly, the inclusion of different nanoparticles confers stronger catalytic and adsorption performance to the bulk materials. Computational techniques can serve as incentives in this regard, through prediction of distribution and interaction behavior of nanomaterials using relative stability assessment before manufacturing. In short, nanocomposites are and have swiftly emerged as the most amicable solutions to progressively increasing requirements of better and stronger materials, enabling volumes to save energy, raw materials and reduce the intended labor needs.

References

1. McEvoy, M. A. and Correll, N. (2015). Materials that couple sensing, actuation, computation, and communication, *Science*, **347**, pp. 1261689 (1–8).
2. *History of Composite Materials*. Mar-Bal Incorporated. Accessed: Feb. 26, 2020. [Online]. Available: <https://www.mar-bal.com/language/en/applications/history-of-composites/>
3. Elhajjar, R. S., Valeria, L., and Muliana, A. (2017). *Smart Composites: Mechanics and Design (Composite Materials)*, 1st ed. (CRC Press).
4. Fakirov, S. (2015). Composite materials: Is the use of proper definitions important? *Materials Today*, **18**, pp. 528–529.
5. Kamigaito, O. (1991). What can be improved by nanometer composites? *Journal of Japan Society of Powder and Powder Metallurgy*, **38**, pp. 315–321 in Kelly, A. (1994). *Concise Encyclopedia of Composites Materials* (Elsevier Ltd.).
6. Madkour, L. H. (2019). Classification of nanostructured materials. In: *Nanoelectronic Materials (Advanced Structured Materials 116)* (Springer, Cham, Switzerland), pp. 269–307.
7. Visakh, P. M. and María, J. M. M. (2016). *Nanomaterials and Nanocomposites: Zero- to Three-Dimensional Materials and Their Composites* (Wiley VCH).
8. Tetiana, A., Dontsova, S. V. N., and Ihor, M. A. (2019). Metal oxide nanomaterials and nanocomposites of ecological purpose, *Journal of Nanomaterials*, **5942194**, pp. 1–31.
9. Njuguna, J., Ansari, F., Sachse, S., Zhu, H., and Rodriguez, V. M. (2014). Nanomaterials, nanofillers, and nanocomposites: Types and properties. In: *Health and Environmental Safety of Nanomaterials* (Woodhead Publishing Ltd.), pp. 3–27.
10. Kanatzidis, M. G., Wu, C. G., Marcy, H. O., and Kannewurf, C. R. (1989). Conductive-polymer bronzes. Intercalated polyaniline in vanadium oxide xerogels, *Journal of the American Chemical Society*, **111**, pp. 4139–4141.
11. Liu, Y. J., DeGroot, D. C., Schindler, J. L., Kannewurf, C. R., and Kanatzidis, M. G. (1991). Intercalation of poly(ethylene oxide) in vanadium pentoxide (V₂O₅) xerogel, *Chemistry of Materials*, **3**, pp. 992–994.
12. Paul, D. R. and Robeson, L. M. (2008). Polymer nanotechnology: Nanocomposites, *Polymer*, **49**, pp. 3187–3204.

13. Liu, Y. J., Schindler, J. L., DeGroot, D. C., Kannewurf, C. R., Hirpo, W., and Kanatzidis, M. G. (1996). Synthesis, structure and reactions of poly (ethylene-oxide)/V₂O₅ intercalative nanocomposites, *Chemistry of Materials*, **8**, pp. 525–534.
14. Lange, F. F. (1973). Effect of microstructure on strength of Si₃N₄-SiC composite system, *Journal of the American Ceramic Society*, **56**, pp. 445–450.
15. Becher, P. F. (1991). Microstructural design of toughened ceramics. *Journal of the American Ceramic Society*, **74**, pp. 255–269.
16. Ghasali, E., Yazdani-rad, R., Asadian, K., and Ebadzadeh, T. (2017). Production of Al-SiC-TiC hybrid composites using pure and 1056 aluminium powders prepared through microwave and conventional heating methods, *Journal of Alloys and Compounds*, **690**, pp. 512–518.
17. Yan, X., Sahimi, M., and Tsotsis, T. T. (2017). Fabrication of high-surface area nanoporous SiOC ceramics using pre-ceramic polymer precursors and a sacrificial template: Precursor effects, *Microporous and Mesoporous Materials*, **241**, pp. 338–345.
18. He, J., Gao, Y., Wang, Y., Fang, J., and An, L. (2017). Synthesis of ZrB₂-SiC nanocomposite powder via polymeric precursor route, *Ceramics International*, **43**, pp. 1602–1607.
19. Brooke, R., Cottis, P., Talemi, P., Fabretto, M., Murphy, P., and Evans, D. (2017). Recent advances in the synthesis of conducting polymers from the vapour phase, *Progress in Materials Science*, **86**, pp. 127–146.
20. Lee, H. S., Choi, M. Y., Anandhan, S., Baik, D. H., and Seo, S. W. (2004). Microphase structure and physical properties of polyurethane/organoclay nanocomposites, *ACS PMSE Preprints*, **91**, 638.
21. Kobayashi, T. (2016). Applied environmental materials science for sustainability. In: *Advances in Environmental Engineering and Green Technologies*, 1st ed. (IGI Global).
22. Kashinath, L., Namratha, K., and Byrappa, K. (2017). Sol-gel assisted hydrothermal synthesis and characterization of hybrid ZnS-RGO nanocomposite for efficient photodegradation of dyes, *Journal of Alloys and Compounds*, **695**, pp. 799–809.
23. Dermenci, K. B., Genc, B., Ebin, B., Olmez-Hanci, T., and Gürmen, S. (2014). Photocatalytic studies of Ag/ZnO nanocomposite particles produced via ultrasonic spray pyrolysis method, *Journal of Alloys and Compounds*, **586**, pp. 267–273.
24. Ren, Q., Su, H., Zhang, J., Ma, W., Yao, B., Liu, L., and Fu, H. (2016). Rapid eutectic growth of Al₂O₃/Er₃Al₅O₁₂ nanocomposite prepared by a new

- method: Melt falling-drop quenching, *Scripta Materialia*, **125**, pp. 39–43.
25. Ogasawara, T., Ishida, Y., Ishikawa, T., and Yokota, R. (2004). Characterization of multi-walled carbon nanotube/phenylethynyl terminated polyimide composites, *Composites Part A: Applied Science and Manufacturing*, **35**, pp. 67–74.
 26. Alexandre, M. and Dubois, P. (2000). Polymer-layered silicate nanocomposites: Preparation, properties and uses of a new class of materials, *Materials Science and Engineering: R: Reports*, **28**, pp. 1–63.
 27. Rehab, A. and Salahuddin, N. (2005). Nanocomposite materials based on polyurethane intercalated into montmorillonite clay, *Materials Science and Engineering: A*, **399**, pp. 368–376.
 28. Hussain, F., Hojjati, M., Okamoto, M., and Gorga, R. E. (2006). Review article: Polymer-matrix nanocomposites, processing, manufacturing, and application: An overview, *Journal of Composite Materials*, **40**, pp. 1511–1575.
 29. Anandhan, S. and Bandyopadhyay, S. (2011). Polymer nanocomposites: From synthesis to applications. In: *Nanocomposites and Polymers with Analytical Methods* (Cuppoletti, J., Ed.) (InTech), pp. 3–28.
 30. Haraguchi, K. (2011). Synthesis and properties of soft nanocomposite materials with novel organic/inorganic network structures, *Polymer Journal*, **43**, pp. 223–241.
 31. Wang, R. M., Zheng, S. R., and Zheng, Y. (2011). *Polymer Matrix Composites and Technology* (Woodhead Publishing Ltd.).
 32. Bai, H. and Ho, W. S. W. (2009). New sulfonated polybenzimidazole (SPBI) copolymer-based proton-exchange membranes for fuel cells, *Journal of the Taiwan Institute of Chemical Engineers*, **40**, pp. 260–267.
 33. Bondeson, D., Mathew, A., and Oksman, K. (2006). Optimization of the isolation of nanocrystals from microcrystalline cellulose by acid hydrolysis, *Cellulose*, **13**, pp. 171–180.
 34. Saito, T., Kimura, S., Nishiyama, Y., and Isogai, A. (2007). Cellulose nanofibers prepared by tempo-mediated oxidation of native cellulose, *Biomacromolecules*, **8**, pp. 2485–2491.
 35. Lahiji, R. R., Xu, X., Reifengerger, R., Raman, A., Rudie, A., and Moon, R. J. (2010). Atomic force microscopy characterization of cellulose nanocrystals, *Langmuir*, **26**, pp. 4480–4488.
 36. Gong, G., Mathew, A. P., and Oksman, K. (2011). Strong aqueous gels of cellulose nanofibers and nanowhiskers isolated from softwood flour, *TAPPI Journal*, **10**, pp. 7–14.

37. Petersson, L., Kvien, I., and Oksman, K. (2007). Structure and thermal properties of poly(lactic acid)/cellulose whiskers nanocomposite materials, *Composites Science and Technology*, **67**, pp. 2535–2544.
38. Bondeson, D. and Oksman, K. (2007). Dispersion and characteristics of surfactant modified cellulose whiskers nanocomposites, *Composite Interfaces*, **14**, pp. 617–630.
39. Kvien, I., Tanem, B. S., and Oksman, K. (2005). Characterization of cellulose whiskers and their nanocomposites by atomic force and electron microscopy, *Biomacromolecules*, **6**, pp. 3160–3165.
40. Siqueira, G., Mathew, A. P., and Oksman, K. (2011). Processing of cellulose nanowhiskers/cellulose acetate butyrate nanocomposites using sol-gel process to facilitate dispersion, *Composites Science and Technology*, **71**, pp. 1886–1892.
41. Svagan, A. J., Jensen, P., Dvinskikh, S. V., Furó, I., and Berglund, L. A. (2010). Towards tailored hierarchical structures in cellulose nanocomposite biofoams prepared by freezing/freeze-drying, *Journal of Materials Chemistry*, **20**, pp. 6646–6654.
42. Goetz, L., Mathew, A., Oksman, K., Gatenholm, P., and Ragauskas, A. J. (2009). A novel nanocomposite film prepared from crosslinked cellulosic whiskers, *Carbohydrate Polymers*, **75**, pp. 85–89.
43. Etang Ayuk, J., Mathew, A. P., and Oksman, K. (2009). The effect of plasticizer and cellulose nanowhisker content on the dispersion and properties of cellulose acetate butyrate nanocomposites, *Journal of Applied Polymer Science*, **114**, pp. 2723–2730.
44. Kvien, I. and Oksman, K. (2008). Microscopic examination of cellulose whiskers and their nanocomposites. In: *Characterization of Lignocellulosic Materials* (Blackwell Publishing, Oxford, UK), pp. 342–356.
45. Sawyer, L. C. and Grubb, D. T. (1987). *Polymer Microscopy*, 1st ed. (Chapman and Hall, London).
46. Pei, A., Zhou, Q., and Berglund, L. A. (2010). Functionalized cellulose nanocrystals as biobased nucleation agents in poly(l-lactide) (PLLA)-crystallization and mechanical property effects, *Composites Science and Technology*, **70**, pp. 815–821.
47. Goldstein, J., Newbury, D. E., Joy, D. C., Lyman, C. E., Echlin, P., Lifshin, E., Sawyer, L., and Michael, J. R. (2003). *Scanning Electron Microscopy and X-Ray Microanalysis*, 3rd ed. (Springer, USA).
48. Goodhew, P. J., Humphreys, J., and Beanland, R. (2001). *Electron Microscopy and Analysis* (Taylor & Francis, London).

49. Braga, P. C. and Ricci, D. (2004). *Atomic Force Microscopy: Biomedical Methods and Applications (Methods in Molecular Biology 242)* (Humana Press).
50. Eaton, P. and West, P. (2010). *Atomic Force Microscopy* (Oxford University Press, USA).
51. Bandyopadhyay, S., Samudrala, S. K., Bhowmick, A. K., and Gupta, S. K. (2007). Applications of atomic force microscope (AFM) in the field of nanomaterials and nanocomposites. In: *Functional Nanostructures: Processing, Characterization and Applications* (Seal, S., Ed.) (Springer), pp. 504–568.
52. Brown, E. E. and Laborie, M.-P. G. (2007). Bioengineering bacterial cellulose/poly(ethylene oxide) nanocomposites, *Biomacromolecules*, **8**, pp. 3074–3081.
53. Aulin, C., Ahola, S., Josefsson, P., Nishino, T., Hirose, Y., Österberg, M., and Wågberg, L. (2009). Nanoscale cellulose films with different crystallinities and mesostructures: Their surface properties and interaction with water, *Langmuir*, **25**, pp. 7675–7685.
54. Ten, E., Turtle, J., Bahr, D., Jiang, L., and Wolcott, M. (2010). Thermal and mechanical properties of poly(3-hydroxybutyrate-co-3-hydroxyvalerate)/cellulose nanowhiskers composites, *Polymer*, **51**, pp. 2652–2660.
55. Cranston, E. D. and Gray, D. G. (2006). Formation of cellulose-based electrostatic layer-by-layer films in a magnetic field, *Science and Technology of Advanced Materials*, **7**, pp. 319–321.
56. Gindl, W., Emsenhuber, G., Maier, G., and Keckes, J. (2009). Cellulose in never-dried gel oriented by an ac electric field, *Biomacromolecules*, **10**, pp. 1315–1318.
57. Hoeger, I., Rojas, O. J., Efimenko, K., Velev, O. D., and Kelley, S. S. (2011). Ultrathin film coatings of aligned cellulose nanocrystals from a convective-shear assembly system and their surface mechanical properties, *Soft Matter*, **7**, pp. 1957–1967.
58. Thygesen, A., Oddershede, J., Lilholt, H., Thomsen, A. B., and Ståhl, K. (2005). On the determination of crystallinity and cellulose content in plant fibres, *Cellulose*, **12**, pp. 563–576.
59. Sugiyama, J., Vuong, R., and Chanzy, H. (1991). Electron diffraction study on the two crystalline phases occurring in native cellulose from an algal cell wall, *Macromolecules*, **24**, pp. 4168–4175.
60. Lee, Y. H., Lee, S. W., Youn, J. R., Chung, K., and Kang, T. J. (2002). Characterization of fiber orientation in short fiber reinforced

- composites with an image processing technique, *Materials Research Innovations*, **6**, pp. 65–72.
61. Yoshiharu, N., Shigenori, K., Masahisa, W., and Takeshi, O. (1997). Cellulose microcrystal film of high uniaxial orientation, *Macromolecules*, **30**, pp. 6395–6397.
 62. Bohn, A., Fink, H.-P., Ganster, J., and Pinnow, M. (2000). X-ray texture investigations of bacterial cellulose, *Macromolecular Chemistry and Physics*, **201**, pp. 1913–1921.
 63. Gindl, W. and Keckes, J. (2006). Drawing of self-reinforced cellulose films, *Journal of Applied Polymer Science*, **103**, pp. 2703–2708.
 64. Wada, M., Sugiyama, J., and Okano, T. (1993). Native celluloses on the basis of two crystalline phase (α/β) system, *Journal of Applied Polymer Science*, **49**, pp. 1491–1496.
 65. Iwamoto, S., Isogai, A., and Iwata, T. (2011). Structure and mechanical properties of wet-spun fibers made from natural cellulose nanofibers, *Biomacromolecules*, **12**, pp. 831–836.
 66. Bokobza, L. (1990). Investigation of local dynamics of polymer chains in the bulk by the excimer fluorescence technique, *Progress in Polymer Science*, **15**, pp. 337–360.
 67. George, G. A. (1985). Characterization of solid polymers by luminescence techniques, *Pure and Applied Chemistry*, **57**, pp. 945–954.
 68. Zammarano, M., Maupin, P. H., Sung, L.-P., Gilman, J. W., McCarthy, E. D., Kim, Y. S., and Fox, D. M. (2011). Revealing the interface in polymer nanocomposites, *ACS Nano*, **5**, pp. 3391–3399.
 69. Clough, J. M., Creton, C., Craig, S. L., and Sijbesma, R. P. (2016). Covalent bond scission in the Mullins effect of a filled elastomer: Real-time visualization with mechanoluminescence, *Advanced Functional Materials*, **26**, pp. 9063–9074.
 70. Dewimille, L., Bresson, B., and Bokobza, L. (2005). Synthesis, structure and morphology of poly(dimethylsiloxane) networks filled with in situ generated silica particles, *Polymer*, **46**, pp. 4135–4143.
 71. Cole, K. C. (2008). Use of infrared spectroscopy to characterize clay intercalation and exfoliation in polymer nanocomposites, *Macromolecules*, **41**, pp. 834–843.
 72. Zhang, X., Bhuvana, S., and Loo, L. S. (2011). Characterization of layered silicate dispersion in polymer nanocomposites using Fourier transform infrared spectroscopy, *Journal of Applied Polymer Science*, **125**, E175–E180.

73. Dazzi, A. and Prater, C. B. (2016). AFM-IR: Technology and applications in nanoscale infrared spectroscopy and chemical imaging, *Chemical Reviews*, **117**, pp. 5146–5173.
74. Marcott, C., Lo, M., Dillon, E., Kjoller, K., and Prater, C. (2015). Interface analysis of composites using AFM-based nanoscale IR and mechanical spectroscopy, *Microscopy Today*, **23**, pp. 38–45.
75. Peng, H. X. (2011). Polyurethane nanocomposite coatings for aeronautical applications. In: *Multifunctional Polymer Nanocomposites* (Leng, J. and Lau, A. K. T., Eds.) (CRC Press, Boca Raton), pp. 337–387.
76. Mahieux, C. A. (2006). *Environmental Degradation in Industrial Composites* (Elsevier, Chicago).
77. Martin, R. (2008). *Ageing of Composites* (Woodhead Publishing, Cambridge).
78. Bharadwaj, R. K. (2001). Modeling the barrier properties of polymer layered silicate nanocomposites, *Macromolecules*, **34**, pp. 9189–9192.
79. Ray, S. S., Yamada, K., Okamoto, M., and Ueda, K. (2002). Polylactide-layered silicate nanocomposite: A novel biodegradable material, *Nano Letters*, **2**, pp. 1093–1096.
80. Gilman, J. W., Kashiwagi, T., and Lichtenhan, J. D. (1977). Nanocomposites: A revolutionary new flame retardant approach, *SAMPE Journal*, **33**, pp. 40–46.
81. Kojima, Y., Usuki, A., Kawasumi, M., Okada, A., Fukushima, Y., Kurauchi, T., and Kamigaito, O. (1993). Mechanical properties of nylon 6-clay hybrid, *Journal of Material Research*, **8**, pp. 1185–1189.
82. Meenakshi, K. S., Sudhan, E. P. J., Kumar, S. A., and Umopathy, M. J. (2011). Development and characterization of novel DOPO based phosphorus tetraglycidyl epoxy nanocomposites for aerospace applications, *Progress in Organic Coatings*, **72**, pp. 402–409.
83. Park, J. G., Louis, J., Cheng, Q., Bao, J., Smithyman, J., Liang, R., Wang, B., Zhang, C., Brooks, J. S., Kramer, L., Fanchasis, P., and Dorough, D. (2009). Electromagnetic interference shielding properties of carbon nanotube buckypaper composites, *Nanotechnology*, **20**, pp. 1–7.
84. Inam, F., Bhat, B. R., Vo, T., and Daoush, W. M. (2014). Structural health monitoring capabilities in ceramic-carbon nanocomposites, *Ceramics International*, **40**, pp. 3793–3798.
85. Leaversuch, R. (2001). Nanocomposites broaden roles in automotive, barrier packaging, *Plastics Technology*, pp. 47–64.

86. Damm, C., Munstedt, H., and Rosch, A. (2008). The antimicrobial efficacy of polyamide 6/silver-nano- and microcomposites, *Materials Chemistry and Physics*, **108**, pp. 61–66.
87. Barbosa-Pereira, L., Angulo, I., Lagarón, J. M., Paseiro-Losada, P., and Cruz, J. M. (2014). Development of new active packaging films containing bioactive nanocomposites, *Innovative Food Science and Emerging Technologies*, **26**, pp. 310–318.
88. Campos-Requena, V. H., Rivas, B. L., Pérez, M. A., Figueroa, C. R., and Sanfuentes, E. A. (2015). The synergistic antimicrobial effect of carvacrol and thymol in clay/polymer nanocomposite films over strawberry gray mold, *LWT-Food Science and Technology*, **64**, pp. 390–396.
89. Costa, C., Conte, A., Buonocore, G. G., and Del Nobile, M. A. (2011). Antimicrobial silver montmorillonite nanoparticles to prolong the shelf life of fresh fruit salad, *International Journal of Food Microbiology*, **148**, pp. 164–167.
90. Costa, C., Conte, A., Buonocore, G. G., Lavorgna, M., and Del Nobile, M. A. (2012). Calcium-alginate coating loaded with silver-montmorillonite nanoparticles to prolong the shelf-life of fresh-cut carrots, *Food Research International*, **48**, pp. 164–169.
91. Fernández, A., Picouet, P., and Lloret, E. (2010). Cellulose-silver nanoparticle hybrid materials to control spoilage-related microflora in absorbent pads located in trays of fresh-cut melon, *International Journal of Food Microbiology*, **142**, pp. 222–228.
92. Lloret, E., Picouet, P., and Fernández, A. (2012). Matrix effects on the antimicrobial capacity of silver-based nanocomposite absorbing materials, *LWT-Food Science and Technology*, **49**, pp. 333–338.
93. Manikantan, M. R. and Varadharaju, N. (2011). Preparation and properties of polypropylene-based nanocomposite films for food packaging, *Packaging Technology and Science*, **24**, pp. 191–209.
94. Xie, L., Lv, X. Y., Han, Z. J., Ci, J. H., Fang, C. Q., and Ren, P. G. (2012). Preparation and performance of high-barrier low density polyethylene/organic montmorillonite nanocomposite, *Polymer-Plastics Technology and Engineering*, **51**, pp. 1251–1257.
95. Follain, N., Belbekhouche, S., Bras, J., Siqueira, G., Marais, S., and Dufresne, A. (2013). Water transport properties of bio-nanocomposites reinforced by *Luffa cylindrica* cellulose nanocrystals, *Journal of Membrane Science*, **427**, pp. 218–229.

96. Lagarón, J. M., Cabedo, L., Cava, D., Feijoo, J. L., Gavara, R., and Gimenez, E. (2005). Improving packaged food quality and safety. Part 2: Nanocomposites, *Food Additives and Contaminants*, **22**, pp. 994–998.
97. Arunvisut, S., Phummanee, S., and Somwangthanaroj, A. (2007). Effect of clay on mechanical and gas barrier properties of blown film LDPE/clay nanocomposites, *Journal of Applied Polymer Science*, **106**, pp. 2210–2217.
98. Horst, M. F., Quinzani, L. M., and Failla, M. D. (2012). Rheological and barrier properties of nanocomposites of HDPE and exfoliated montmorillonite, *Journal of Thermoplastic Composite Materials*, **27**, pp. 106–125.
99. Zeng, Q. H., Yu, A. B., Lu, G. Q., and Paul, D. R. (2005). Clay-based polymer nanocomposites: Research and commercial development, *Journal of Nanoscience and Nanotechnology*, **5**, pp. 1574–1592.
100. Anadao, P. (2012). Polymer/clay nanocomposites: Concepts, researches, applications and trends for the future. In: *Nanocomposites: New Trends and Developments* (Ebrahimi, F., Ed.) (InTech), pp. 1–16.
101. Bumbudsanpharoke, N. and Ko, S. (2015). Nano-food packaging: An overview of market, migration research, and safety regulations, *Journal of Food Science*, **80**, R910–R923.
102. Vanderroost, M., Ragaert, P., Devlieghere, F., and Meulenaer, B. D. (2014). Intelligent food packaging: The next generation, *Trends in Food Science and Technology*, **39**, pp. 47–62.
103. Rahaman, M. and Yao, A. (2007). Ceramics for prosthetic hip and knee joint replacement, *Journal of the American Ceramic Society*, **90**, pp. 1965–1988.
104. Menezes, R. R. and Kiminami, R. H. G. A. (2008). Microwave sintering of alumina–zirconia nanocomposites, *Journal of Materials Processing Technology*, **203**, pp. 513–517.
105. Nevarez-Rascon, A., Aguilar-Elguezabal, A., Orrantia, E., and Bocanegra-Bernal, M. H. (2009). On the wide range of mechanical properties of ZTA and ATZ based dental ceramic composites by varying the Al_2O_3 and ZrO_2 content, *The International Journal of Refractory Metals and Hard Materials*, **27**, pp. 962–970.
106. De Aza, A. H., Chevalier, J., Fantozzi, G., Schehl, M., and Torrecillas, R. (2002). Crack growth resistance of alumina, zirconia and zirconia toughened alumina ceramics for joint prosthesis, *Biomaterials*, **23**, pp. 937–945.

107. Nawa, M., Nakamoto, S., Sekino, T., and Niihara, K. (1998). Tough and strong Ce-TZP/alumina nanocomposites doped with titania, *Ceramics International*, **24**, pp. 497–506.
108. Uchida, M., Kim, H. M., Kokubo, T., Nawa, M., Asano, T., Tanaka, K., and Nakamura, T. (2002). Apatite forming ability of a zirconia/alumina nano-composite induced by chemicals treatment, *Journal of Biomedical Materials Research*, **60**, pp. 277–282.
109. Tanaka, K., Tamura, J., Kawanabe, K., Nawa, M., Oka, M., Uchida, M., Kokubo, T., and Nakamura, T. (2002). Ce-TZP/ Al_2O_3 nanocomposites as a bearing material in total joint replacement, *Journal of Biomedical Materials Research*, **63**, pp. 262–270.
110. Philipp, A., Fischer, J., Hammerle, C. H., and Sailer, I. (2010). Novel ceria-stabilized tetragonal zirconia/alumina nanocomposite as framework material for posterior fixed dental prosthesis: Preliminary results of a prospective case series at 1 year of function, *Quintessence International*, **41**, pp. 313–319.
111. Kong, Y. M., Bae, C. J., Lee, S. H., Kim, H. W., and Kim, H. E. (2005). Improvement in biocompatibility of $\text{ZrO}_2\text{-Al}_2\text{O}_3$ nano-composite by addition of HA, *Biomaterials*, **26**, pp. 509–517.
112. Vallet-Regi, M. (2010). Evolution of bioceramics within the field of biomaterials, *Comptes Rendus Chimie*, **13**, pp. 174–185.
113. Paul, W. and Sharma, C. P. (2006). Nanoceramic matrices: Biomedical applications, *American Journal of Biochemistry and Biotechnology*, **2**, pp. 41–48.
114. Rho, J. Y., Kuhn-Spearing, L., and Zioupos, P. (1998). Mechanical properties and the hierarchical structure of bone, *Medical Engineering and Physics*, **20**, pp. 92–112.
115. Wel, G. and Ma, P. X. (2004). Structure and properties of nano-hydroxyapatite/polymer composite scaffolds for bone tissue engineering, *Biomaterials*, **25**, pp. 4749–4757.
116. Wang, Y., Liu, L., and Guo, S. (2010). Characterization of biodegradable and cytocompatible nano-hydroxyapatite/polycaprolactone porous scaffolds in degradation in vitro, *Polymer Degradation and Stability*, **95**, pp. 207–213.
117. Nejati, E., Firouzidor, V., Eslaminejad, M. B., and Bagheri, F. (2009). Needle-like nano hydroxyapatite/poly(L-lactide acid) composite scaffold for bone tissue engineering application, *Materials Science and Engineering C*, **29**, pp. 942–949.

118. Hong, Z., Reis, R. L., and Mano, J. F. (2008). Preparation and in vitro characterization of scaffolds of poly(L-lactic acid) containing bioactive glass ceramic nanoparticles, *Acta Biomaterials*, **4**, pp. 1297–1306.
119. Rajan, M., Murugan, M., Ponnamma, D., Sadasivuni, K. K., and Munusamy, M. A. (2016). Polycarboxylic acids functionalized chitosan nanocarriers for controlled and targeted anticancer drug delivery, *Biomedicine and Pharmacotherapy*, **83**, pp. 201–211.
120. Dhanavel, S., Nivethaa, E. A. K., Narayanan, V., and Stephen, A. (2017). In vitro cytotoxicity study of dual drug loaded chitosan/palladium nanocomposite towards HT-29 cancer cells, *Material Science and Engineering C*, **75**, pp. 1399–1410.
121. Rajan, M., Raj, V., Al-Arfaj, A. A., and Murugan, A. M. (2013). Hyaluronidase enzyme core-5-fluorouracil-loaded chitosan-PEG-gelatin polymer nanocomposites as targeted and controlled drug delivery vehicles, *International Journal of Pharmaceutics*, **453**, pp. 514–522.
122. Rasoulzadeh, M. and Namazi, H. (2017). Carboxymethyl cellulose/graphene oxide bionanocomposite hydrogel beads as anticancer drug carrier agent, *Carbohydrate Polymers*, **168**, pp. 320–326.
123. Reddy, N. N., Varaprasad, K., Ravindra, S., Reddy, G. S., Reddy, K. M. S., Reddy, K. M., and Mohana Raju, K. (2011). Evaluation of blood compatibility and drug release studies of gelatin based magnetic hydrogel nanocomposites, *Colloids and Surfaces A*, **385**, pp. 20–23.
124. Dhivya, R., Ranjani, J., Bowen, P. K., Rajendhran, J., Mayandi, J., and Annaraj, J. (2017). Biocompatible curcumin loaded PMMA-PEG/ZnO nanocomposite induce apoptosis and cytotoxicity in human gastric cancer cells, *Materials Science and Engineering C*, **80**, pp. 59–68.
125. Zheng, X. T., Ma, X. Q., and Li, C. M. (2016). Highly efficient nuclear delivery of anti-cancer drugs using a bio-functionalized reduced graphene oxide, *Journal of Colloid and Interface Science*, **467**, pp. 35–42.
126. Rao, K. M., Nagappan, S., Seo, D. J., and Ha, C. S. (2014). pH sensitive halloysite-sodium hyaluronate/poly (hydroxyethyl methacrylate) nanocomposites for colon cancer drug delivery, *Applied Clay Science*, **97**, pp. 33–42.
127. Han, S., Liu, F., Wu, J., Zhang, Y., Xie, Y., and Wu, W. (2014). Targeting of fluorescent palygorskite polyethyleneimine nanocomposite to cancer cells, *Applied Clay Science*, **101**, pp. 567–573.

128. Baibarac, M. and Gomez-Romero, P. (2006). Nanocomposites based on conducting polymers and carbon nanotubes: From fancy materials to functional applications, *Journal of Nanoscience and Nanotechnology*, **6**, pp. 1–14.
129. Sandler, J. K. W., Kirk, J. E., Kinloch, I. A., Shaffer, M. S. P., and Windle, A. H. (2003). Ultra-low electrical percolation threshold in carbon-nanotube-epoxy composites, *Polymer*, **44**, pp. 5893–5899.
130. Kothurkar, N. K. (2004). Solid state, transparent, cadmium sulfide-polymer nanocomposites, University of Florida.
131. Omar, G., Salim, M. A., Mizah, B. R., Kamarolzaman, A. A., and Nadlene, R. (2019). Electronic applications of functionalized graphene nanocomposites. In: *Functionalized Graphene Nanocomposites and Their Derivatives*, 1st ed (Elsevier), pp. 245–263.
132. Wu, Z., Chen, X., Zhu, S., Zhou, Z., Yao, Y., Quan, W., and Liu, B. (2013). Enhanced sensitivity of ammonia sensor using graphene/polyaniline nanocomposite. *Sensors and Actuators B Chemical*, **178**, pp. 485–493.
133. Al-Mashat, L., Shin, K., Kalantar-Zadeh, K., Plessis, J., Han, S., Kojima, R., Kaner, R., Li, D., Gou, X., Ippolito, S., and Wlodarski, W. (2010). Graphene/polyaniline nanocomposite for hydrogen sensing, *The Journal of Physical Chemistry C*, **114**, pp. 16168–16173.
134. Shi, X., Nguyen, T. A., Suo, Z., Liu, Y., and Avci, R. (2009). Effect of nanoparticles on the anticorrosion and mechanical properties of epoxy coating, *Surface & Coatings Technology*, **204**, pp. 237–245.
135. Introzzi, L., Blomfeldt, T. O., Trabattoni, S., Tavazzi, S., Santo, N., Schiraldi, A., Piergiovanni, L., and Farris, S. (2012). Ultrasound-assisted pullulan/montmorillonite bionanocomposite coating with high oxygen barrier properties, *Langmuir*, **28**, pp. 11206–11214.
136. Habouti, S., Kunstmann-Olsen, C., Hoyland, J. D., Rubahn, H. G., and Es-Souni, M. (2014). In situ ZnO-PVA nanocomposite coated microfluidic chips for biosensing, *Applied Physics A: Materials Science and Processing*, **115**, pp. 645–649.
137. Liu C. and Zhao, Q. (2011). Influence of surface-energy components of Ni-P-TiO₂-PTFE nanocomposite coatings on bacterial adhesion, *Langmuir*, **27**, pp. 9512–9519.
138. Toor, A., So, H., and Pisano, A. P. (2017). Improved dielectric properties of polyvinylidene fluoride nanocomposite embedded with poly(vinylpyrrolidone)-coated gold nanoparticles, *ACS Applied Materials & Interfaces*, **9**, pp. 6369–6375.

139. Zhou, Y., Zhang, H., and Qian, B. (2007). Friction and wear properties of the co-deposited Ni-SiC nanocomposite coating, *Applied Surface Science*, **253**, pp. 8335–8339.

Multiple Choice Questions

- Al alloys for engine/automobile parts are reinforced to increase their
 - Strength
 - Wear resistance
 - Elastic modulus
 - Density
- Composite materials are classified based on
 - Type of matrix
 - Size and shape of reinforcement
 - Both (a) and (b)
 - None
- Nanocomposites have barrier properties for
 - Oxygen
 - Water vapor
 - Ethylene
 - All of these
- Which type of nanocomposites are mostly used for orthopedic implants?
 - Polymer nanocomposite
 - Graphene nanocomposite
 - Ceramic nanocomposite
 - None of these
- The major load carrier in dispersion-strengthened composites is
 - Matrix
 - Fiber
 - Combination of (a) and (b)
 - Cannot be defined
- Which co-drugs are loaded together on chitosan/palladium-5% nanocomposite by Dhanavel et al.?
 - 5-Fluorouracil/graphene
 - ZnO/curcumin
 - 5-Fluorouracil/curcumin
 - None of these
- The factor rendering ceramics unsuitable for load bearing is
 - Brittleness
 - Instability
 - Density
 - All of these
- Thermodynamically, formation of nanocomposites is
 - Endothermic
 - Exothermic
 - Both (a) and (b)
 - None of these

9. The way to determine colloidal stability using calorimetry in a nanoparticle system is
 - (a) UV/Vis spectroscopy
 - (b) FT-IR spectroscopy
 - (c) Electrokinetic measurements
 - (d) None of these
10. The technique used for ascertaining CNT crystallization is
 - (a) Raman spectroscopy
 - (b) Non-polarized optical microscopy
 - (c) Solid-state NMR spectroscopy
 - (d) Polarized optical microscopy Raman spectroscopy
11. The spatial resolution in IR limits imposed by diffraction is lowered by
 - (a) Combination of AFM and IR techniques
 - (b) Combination of SEM and IR techniques
 - (c) Combination of TEM and IR techniques
 - (d) Combination of XRD and IR techniques
12. The interfacial dispersion in polymer nanocomposites is investigated by
 - (a) Förster resonance energy transfer (FRET)
 - (b) Scanning electron microscopy (SEM)
 - (c) Fourier-transform infrared spectroscopy (FT-IR)
 - (d) Fluorescence quenching measurement
13. The nanocomposites having maximum interactions among the constituent phases are
 - (a) Polymer matrix composites
 - (b) Layered nanocomposites
 - (c) Lamellar nanocomposites
 - (d) Nanoclays
14. Which of the following is the most used method for making CMNC?
 - (a) Polymer precursor method
 - (b) Powder procedure
 - (c) Ball milling
 - (d) Sol-gel process
15. The properties of metal matrix nanocomposites making them useful for aerospace and automotive industries are
 - (a) High ductility
 - (b) Low brittleness
 - (c) High toughness and strength
 - (d) High toughness, strength, and Young's modulus

16. Which of the following is not a type of nanocomposites?
- (a) Ceramic matrix nanocomposites
 - (b) Linear matrix nanocomposites
 - (c) Metal matrix nanocomposites
 - (d) Polymer matrix nanocomposites
17. Which of the following is a type of nanocomposite?
- (a) Ceramic matrix nanocomposites
 - (b) Metal matrix nanocomposites
 - (c) Polymer matrix nanocomposites
 - (d) All of the above
18. Which of the following is the processing method of ceramic matrix nanocomposites?
- (a) Spray pyrolysis
 - (b) Polymer precursor
 - (c) Melt interaction
 - (d) Ultrasonication
19. Which of the following is the processing method of metal matrix nanocomposites?
- (a) Polymer precursor
 - (b) Melt interaction
 - (c) Powder procedure
 - (d) Spray pyrolysis
20. Which of the following is the processing method of polymer matrix nanocomposites?
- (a) Sol-gel
 - (b) Melt interaction
 - (c) Ultrasonication
 - (d) Polymer precursor
21. _____ is the type of spectroscopic characterization.
- (a) Impedance
 - (b) Nuclear magnetic resonance
 - (c) Scanning electron microscopy
 - (d) None of the above
22. Which one of the following is a commercial-grade nanocomposite used for coating juice bottles?
- (a) Imperm[®]
 - (b) Biomaster[®]
 - (c) Durethan[®] KU2-2601
 - (d) Agion[®]
23. Imperm[®], a commercial-grade nanocomposite, is used for _____
- (a) Beer and carbonated drink bottles
 - (b) Coating juice bottles

- (c) Beer bottles
(d) None of the above
24. Advantage/s of nanocomposites in food packaging is/are _____
(a) Enhanced conductivity, mechanical strength, and stability
(b) Gas barrier properties
(c) Lighter and biodegradable
(d) All of the above
25. Pullulan-based nanocomposites are used for _____
(a) Anticorrosion (b) Biosensor
(c) Oxygen barrier (d) Dielectric

Answer Key

1. (c) 2. (c) 3. (d) 4. (c) 5. (a) 6. (c) 7. (a)
8. (b) 9. (c) 10. (d) 11. (a) 12. (a) 13. (c) 14. (d)
15. (d) 16. (b) 17. (d) 18. (b) 19. (d) 20. (b) 21. (b)
22. (c) 23. (a) 24. (d) 25. (c)

Short Answer Questions

1. What are the limitations for composite materials?
2. What should be the major characteristics of nanocomposites used in the aerospace industry?
3. Can ceramic nanocomposites be considered a special kind of polymer nanocomposites? If not, then please cite suitable justification(s).
4. Illustrate the mechanism of nanocomposite fabrication with improved inflammable prospects.
5. How the requirements of nanocomposites for biomedical purpose are distinct from those of aerospace?
6. How CNTs and fullerenes can be utilized to improve the performance of nanocomposites intended for drug delivery?
7. Outline the salient attributes of zirconia–alumina nanocomposites making them favored for designing orthopedic implants.
8. What is the basic difference between Young's modulus and elastic modulus? Cite suitable application-oriented examples.
9. How nanocomposites can be used to prolong the food material shelf life and natural essence?

Long Answer Questions

1. What are the applications for nanocomposites?
2. Differentiate between polymer and ceramic nanocomposites with respect to their applications?
3. Explain the application-specific method selection for polymer nanocomposites.
4. Elucidate the significance of atomic force microscopy over other microscopic techniques for nanocomposite development.
5. Explain the salient attributes of nanocomposites to be used for tissue engineering keeping the risk of in vivo toxicity and cross-reaction in mind?

