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Nanocomposites: An In-Depth Exploration of Synthesis, Properties, Classification, and Prospective Application

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Abstract

Rapid advances in artificial intelligence (AI) and materials engineering have expanded options for high-performance materials, with nanocomposites—heterogeneous hybrids formed by incorporating nanoscale constituents—offering distinctive property combinations driven by composition, structure, and interfacial interactions. This study's objective is to synthesize current knowledge on how nanoscale constituents (e.g., nanofibers, nanoparticles, nanorods, nanotubes such as carbon nanotubes (CNTs), and graphene) modify mechanical, thermal, and electrical responses, and to highlight practical techniques for processing enhanced MBC, PBC, and CBC composites alongside procedures for efficient, result-oriented characterization. Methodologically, the work collates and organizes techniques and procedures reported in the literature, emphasizing processing routes and characterization protocols relevant to applications across sectors. Key findings indicate that the incorporation of nanomaterials—characterized by very high tensile strength and thermal/electrical conductivity and often eco-friendly attributes—tends to alter and improve composite performance; nanocomposites, as multiphase systems with one, two, or three dimensions on the order of 1 mm to 100 nm, are increasingly adopted from small- to large-scale industrial contexts including automobiles, construction, electronics, information technology, food packaging, and biomedicine. The study concludes that nanomaterial integration is a viable strategy for tailoring composite properties and enabling broader industrial deployment. The contribution and implication lie in consolidating processing techniques for enhanced MBC, PBC, and CBC systems, outlining characterization procedures that support reproducible evaluation, and mapping current and prospective application domains relevant to today's technology landscape.

Keywords: Nanocomposites; Nanomaterials; Polymer Matrix Composites (PMC); Metal Matrix Composites (MMC); Ceramic Matrix Composites (CMC); Processing Techniques; Materials Characterization

Introduction

In modern technology, a nanocomposite is a multiphase material where at least one of the constituent phases is on the nanoscale (less than 100 nanometers). These materials combine the properties of their individual components to create a material with enhanced characteristics not found in the original materials alone. These materials can be superior in their mechanical, electrical, and thermal properties with respect to their micro or macro materials, due to the unique properties at the nanoscale, such as high surface area and almost perfect crystal order. The nanocomposite material has been used to encompass a large variety of systems such as one-dimensional, two-dimensional, three-dimensional and amorphous materials made of distinctly dissimilar components and mixed at the nanometer scale. Polymer nanocomposites comprises nanoparticles. The methods used for preparing nanocomposites may vary from mechanical and chemical routes and vapor phase deposition, mainly depending on the type of matrix used. Chemical properties like resistance or passiveness to corrosion are very important. Being environment-friendly, few nanocomposites have the possibilities of clean technologies (Oyubu, A. O. and Nwabueze, C. A., 2023). Proper choice of nanofillers and matrix is key in achieving the desired multifunctional properties that are required for many aerospace applications. Therefore, unlike the individual materials, the composite materials exhibit a distinctive property. In terms of mechanical, thermal, electrical, and barrier properties, nanocomposites outperform conventional composites. They can also greatly reduce flammability while maintaining the polymer matrix's transparency.

These attractive properties lead to a wide range of potential industrial uses for polymer nanocomposites:

i. Automobile (exterior and interior panels, gas tanks, bumpers)
ii. Development (structural panels and building sections)
iii. Electrical and electronic engineering (printed circuit boards and electrical components)
iv. The aerospace industry (high-performance components and flame-retardant panels)
v. Packaging for food (wrapping films and containers) Injection molded items, fire retardants, coatings, adhesives, optical integrated circuits, microelectronic packaging, medical devices, medication delivery, membranes, consumer goods and sensors and can all benefit from polymer nanocomposite. Polymer nanocomposites (PNC) are polymers (elastomers, thermosets, or thermoplastics) reinforced with nanosized particles with high aspect ratios (L/h > 300) in modest amounts (less than 5% by weight.

Mostly, composite materials consist of at least two components including a continuous matrix phase and discontinuous reinforcement material while the other consists of one or more discontinuous phases dispersed in one continuous phase. Generally, a discontinuous phase has more advanced mechanical properties than a continuous phase. Continuous phase is known as "matrix", while discontinuous phase is called "reinforcement" or reinforcing material. Based on the size of reinforcement in the structures, composites are commonly divided into three basic classes, namely macrocomposites, microcomposites, and nanocomposites.

Nanocomposites Classification

In general, nanocomposites can be put under polymer and non-polymer classification. Non-polymer-based nanocomposites are of three types:

1. metal/metal nanocomposites;
2. metal/ceramic nanocomposites
3. ceramic/ceramic nanocomposite.

These are being researched on for wide range of applications, including electronics, aerospace, biomedical, and energy storage. Figure 1 shows types of nanocomposites according to matrix.

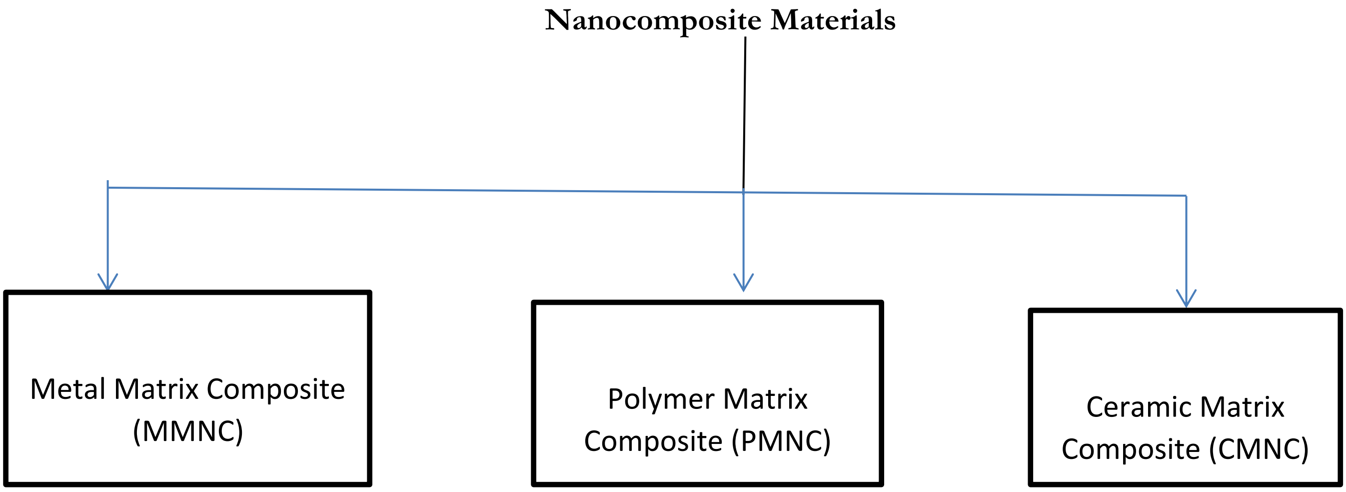

Figure 1: Types of nanocomposites according matrix.

Metal/metal nanocomposites

Metal matrix nanocomposites (MMNCs) are advanced materials composed of a ductile metal or alloy matrix reinforced with nanosized particles or materials. These materials combine the properties of both the metal matrix and the nanomaterial reinforcement, resulting in enhanced mechanical, physical, and thermal characteristics. Composition of MMNCs consist of a metallic matrix (e.g., aluminum, copper, magnesium) and a reinforcement phase that is typically a ceramic or another metal in the form of nanoparticles. Common reinforcements include carbides, oxides, and carbon-based nanomaterials like carbon nanotubes. Metal matrix composites (MMCs) like other composites, are made up of at least two physically and chemically different phases that are dispersed in such a way that they provide properties that neither of the separate phases can provide. In general, there are two phases spread in a metallic matrix: a fibrous or particulate phase. In power transmission lines a composite made from Al matrix reinforced with a continuous A12O3 fiber, the cutting tools and oil drilling inserts are made up from cobalt (Co) particulate and tungsten carbide (WC), and a composite made by reinforcing A1 matrix with SiC particle used in automotive, thermal management and aerospace applications are just a few examples. These nano composite MMNC are made up of a ductile alloy or metal matrix with nanosized reinforcing material. These materials have ceramic and metal properties, such as toughness and ductility, as well as high modulus and strength (P. H. C. Camargo, K. G. Satyanarayana, and F. Wypych 2009 & K. K. Chawla 2012).

As a result, these nanocomposites are highly suited for the creation of materials with high service temperatures and shear/compression strengths. They offer significant potential for usage in a multitude of disciplines, including the automotive and aerospace industries, as well as structural material manufacture (P. H. C. Camargo, K. G. Satyanarayana, and F. Wypych 2009)

Metal/Ceramic Nanocomposites: This type of nanocomposite has improved chemical, magnetic, electric and mechanical properties. Metal nanoparticles can be deposited on the ceramic supports by evaporating metal on the selected substrate meta nanoparticles or by dispersion using solvent chemistry. For complex nanocomposites, novel processing techniques such as template synthesis, scanning probe electrochemical methods, electrospinning, etc are employed (P.M. Ajayan, L.S. Schadler, P.V. Braun, 2003).

Polymer nanocomposites are materials consisting of a polymer matrix and the nanometer-size particles of different dimensionalities, usually smaller than 100 nm. Noteworthy, significant improvements in mechanical, electrical, thermal, and barrier properties in polymer nanocomposites can be observed even at low nanofillers load, below 5%–10%. There are basically two forms of nanodispersion: intercalated dispersion—generated if the nanodispersed filler is still ordered and exfoliated dispersion—occurring when filler is randomly dispersed in the polymer matrix Polymer nanocomposites that are intercalated have structures in which polymer chains enter into layered structures and occur in an orderly manner at nanometric distances. Exfoliated polymer nanocomposites are systems in which the separation of individual layers in the polymer matrix occurs according to average distances, depending on the amount of additive introduced into the polymer matrix. Such dispersion of the nanoadditive can affect the gas permeability, thermal deformation temperature, flammability, biodegradability, and mechanical properties compared to polymer microcomposites.

The polymer matrix is used to disperse agglomerated nanoparticles in reality. Functional nanocomposites with better physical properties open up new possibilities in micro-optics, electronics, energy conversion, and storage. In the majority of cases, the filler load correlates with the change in the sought characteristic. Due to shape or molding constraints, large solid loading is limited by composite flow characteristics, which results in property modification. Before the forming process of composites, the rheological properties (flow properties) should be measured using different tests to estimate the correct shear rate and temperature. Their rheological behavior is determined by the surface area and the ensuing large polymer-filler interfacial layer (T. Hanemann and D. V. Szabó, 2010). Polymer nanocomposites have opened a new horizon for a potential class of hybrid materials by introducing particle nanofiller into polymer matrices to improve the properties of neat polymers (R. K. Gupta, E. Kennel, and K.-J. Kim 2009). During the last decade, polymer nanocomposites have gained a lot of attention and curiosity around the world. The sol–gel process looks to be the most promising among the fabrication methods for polymer nanocomposites. At the molecular or near molecular level, the nanoparticles were dispersed before being combined with the polymer gel (M. C. Kuo, C. M. Tsai, J. C. Huang, and M. Chen 2005).

Polymer-based nanocomposites can be classified based on the type of nanomaterial used, their morphology, and the degree of dispersion within the polymer matrix. Common types include those with inorganic-inorganic, organic-organic, or hybrid compositions, as well as those using layered silicates or carbon nanotubes as fillers.

Based on Composition:

i). Inorganic-Inorganic: These nanocomposites incorporate inorganic materials like clay, silica, or metal oxides within a polymer matrix.

ii). Organic-Organic: These involve combinations of different organic polymers, sometimes with one acting as a matrix and the other as a reinforcing filler.

iii). Polymer/Ceramic: A polymer matrix is combined with ceramic nanoparticles or nanostructures.

iv). Inorganic/Organic Hybrid: These nanocomposites combine inorganic and organic components, often using functionalized nanoparticles to enhance interactions with the polymer.

Based On Morphology:

Conventional/Microcomposites: The nanoparticles are not well dispersed and exist as separate phases within the polymer matrix.

Intercalated Nanocomposites: The polymer chains are inserted between the layers of a layered material (like clay), resulting in a layered structure.

Exfoliated Nanocomposites: The layered material is completely dispersed into individual layers within the polymer matrix, maximizing the interfacial area and enhancing properties.

Based On Nanofiller Type:

i. Nanoplatelets: One nanoscale dimension (e.g., graphene, clay).

ii. Nanofibers: Two nanoscale dimensions (e.g., carbon nanotubes).

iii. Nanoparticles: All three dimensions are in the nanoscale (e.g., silica, metal oxides).

The Advantages of PMCs:

1. Lightweight: PMCs are generally lighter than traditional materials like metals.
2. High Strength-to-Weight Ratio: They offer excellent strength and stiffness for their weight.
3. Customizable Properties: The properties of PMCs can be adjusted by varying the type and amount of reinforcement, as well as the type of polymer matrix.
4. Corrosion Resistance: PMCs can be more resistant to corrosion than some metals.
5. Cost-effective: Certain PMCs, particularly those using natural fibers, can be more economical.

i). Ceramic Matrix Nanocomposites (CMNCs): are a type of advanced material that combines the desirable properties of ceramics with the benefits of nanomaterials. They are created by incorporating nanoscale reinforcements into a ceramic matrix, resulting in materials with enhanced mechanical, thermal, and sometimes even biocompatible properties.

Ceramic matrix nanocomposites (CMNC), particularly the aluminum oxide (Al2O3)/silicon carbide (SiC) system, have a lot of potential. All the investigation has proven that the addition of low volume fraction (~10%) of SiC with a specific size for Al2O3 matrix gives good improvement in the properties of matrix. The crack-bridging role of nanosized reinforcements has been used in certain research to explain this toughening mechanism. As a result of incorporating high-strength nanofibers into ceramic matrices, innovative nanocomposites with superior failure and high toughness characteristics have been developed in comparison to rapid failures of ceramic materials. The preparation of ceramic matrix nanocomposites has been described using a variety of approaches.

Conventional powder method; Vapor techniques (CVD and PVD); Spray pyrolysis; Polymer precursor route; and Chemical methods, which include the colloidal and precipitation procedures, template synthesis, and sol-gel process are the most prevalent methodology utilized for micro composites. The sol-gel process can be affected by a wide range of factors which permit control of the structure and chemical properties of the final material, such as solvent type, time, pH, water/metal ratio, precursor, and so on (M. Y. Wing, Y. Zhongzhen, X. Xaolin, Z. Qingxin, and M. A. Jun 2003)

ii). Ceramic/Ceramic Nanocomposites: These types of nanocomposites are used in artificial joint implants for fracture failure problems for extending the mobility of patients and eliminating the high cost of surgery. Example: Zirconia- toughened with alumina (W. Chaisan, R. Yimnirun, S. Ananta 2009)

Table 1: Different types of nanocomposites

Class	Examples
Metal	Fe-Cr/$Al2O3$, Ni/$Al2O3$, Co/Cr, Fe/MgO, Al/CNT, Mg/CNT
Ceramics	$Al2O3$/$SiO2$, $SiO2$/Ni, $Al2O3$/$TiO2$, $Al2O3$/SiC, $Al2O3$/CNT
Polymer	Thermoplastic/thermoset polymer/layered silicates, polyester/$TiO2$, polymer/CNT, polymer/layered double hydroxides

Types of Nanoscale Fillers

Nanoscale fillers, used to enhance the properties of materials, can be broadly categorized based on their dimensionality: one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D). Examples include carbon nanotubes (1D), graphene (2D), and nanoparticles (3D). These fillers can be further classified by their material type, such as carbon-based (e.g., CNTs, graphene), ceramic-based (e.g., silica nanoparticles), or organic (e.g., nanocellulose). Various forms of nanofillers are shown in figure 2.

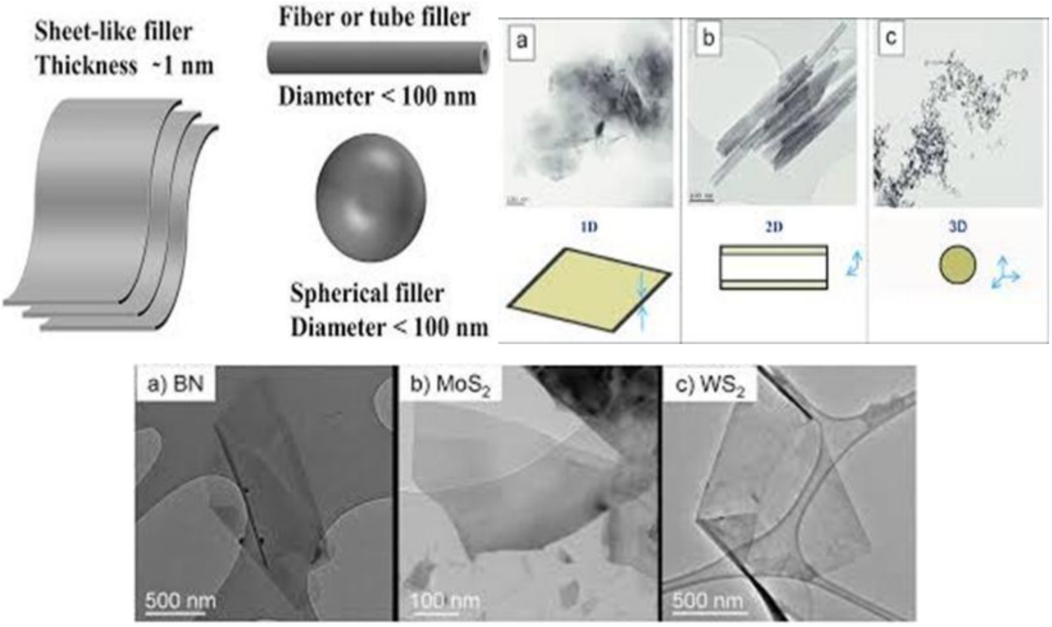

Figure 2: Various types of nanofillers.

i). Carbon-based Nanofillers:

Carbon Nanotubes (CNTs): These are cylindrical nanomaterials made of rolled-up graphene sheets. They can be single-walled (SWCNTs) or multi-walled (MWCNTs). CNTs exhibit exceptional mechanical, thermal, and electrical properties. Whereas single-walled carbon nanotubes (SWCNTs) are formed by a graphene sheet rolling alone. Covalently bound carbon atoms form a hollow structure in a single-walled carbon nanotube. Multiwalled nanotubes (MWNTs) come in a variety of shapes and sizes, depending on how they are made. Approximately 0.34 nanometers is the distance between neighboring graphene layers. The geometry and size of carbon nanotubes determine their mechanical and physical properties ((T. Ichihashi, "Erratum 1993 & V. Z. Mordkovich, M. Baxendale, S. Yoshimura, and R. P. H. Chang 1996). Single wall SWCNTs and MWCNTs carbon nanotubes are shown in figure 3.

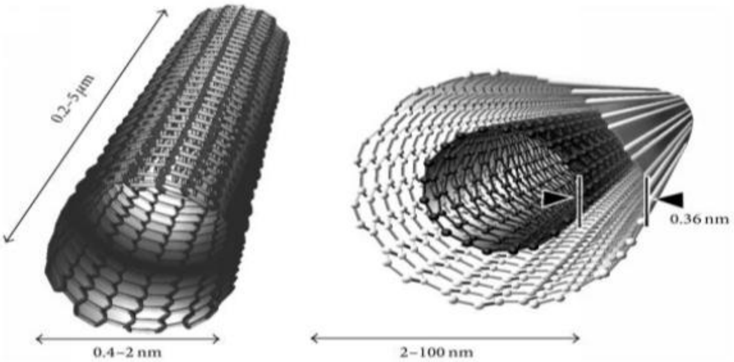

Figure 3: Single wall SWCNTs (left) and Multiwall MWCNTs (right) carbon nanotubes.

Nanoscale spherical fillers are particles with dimensions between 1 and 100 nanometers that are used to enhance the properties of various materials. They are a type of nanofiller, and their spherical shape is a key factor in their functionality. These fillers can be made from various materials, including ceramics, polymers, and metals. Pyrolysis has made carbon black available in a variety of surface areas, and spherical nanoparticles have existed since the 1900s. Particles with a surface area range from 20-500 m2g-1 have a size from 20-300 nm. To make silica accessible, researchers have utilized the wet chemical technique, the Ludox process (Dupont commercial procedure), and the flame process. For a long time, flame methods have been used to produce ultrafine powders, and they are still used today. The goal of several research projects is the creating of spherical nanoparticles with variable diameters. Particle size is influenced by the nanoparticle manufacturing process. This interest stems mostly from the impact of particle size on their properties. Nanoscale fillers when mixed with polymers it can give the ability to use these polymers in new applications due to the properties that nanoscale fillers. The fillers on nano scale can add properties to polymer matrices that micro fillers or other fillers cannot (S. Fu, Z. Sun, P. Huang, Y. Li, and N. Hu, 2019). ZnO nanoparticles in water TEM images are shown in figure 4 and 3D shape of spherical fillers dispersed in matrix is shown in figure 5.

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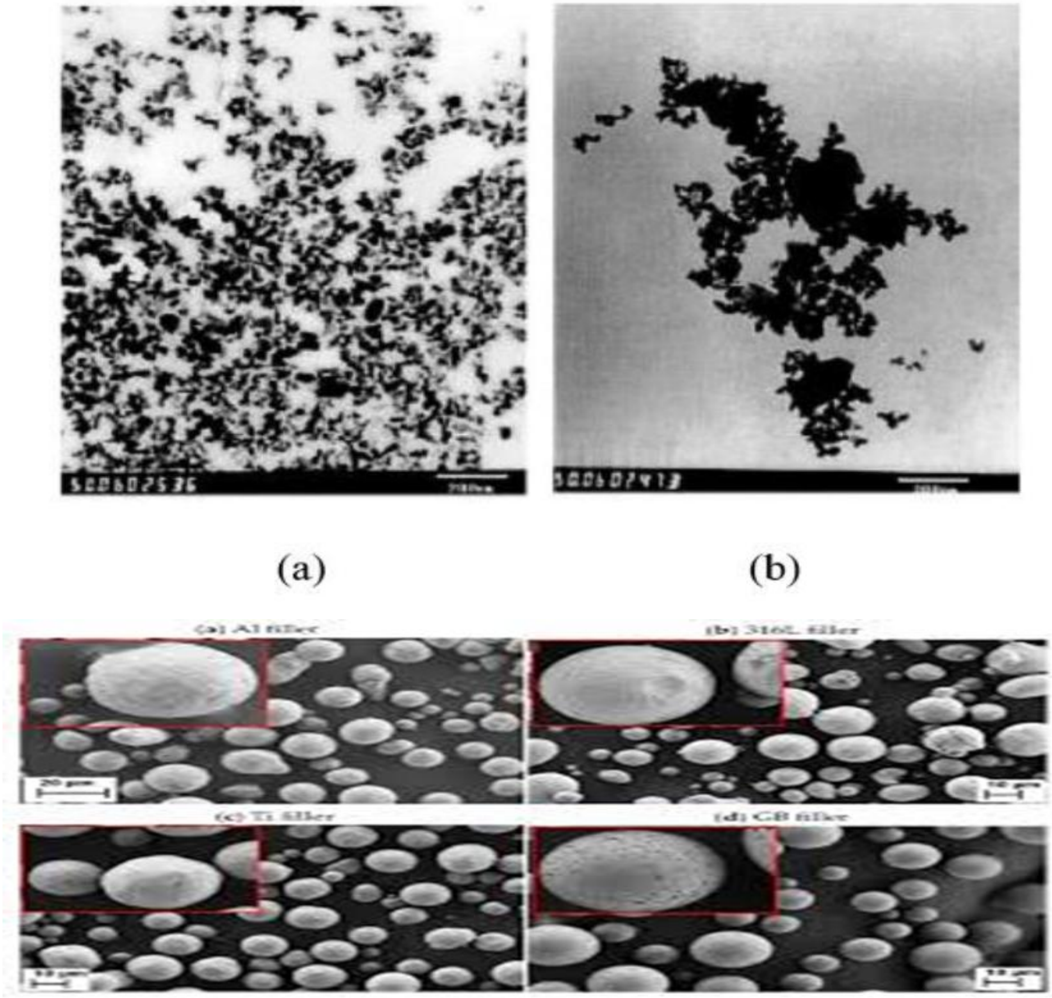

Figure 4: ZnO nanoparticles in water TEM images.

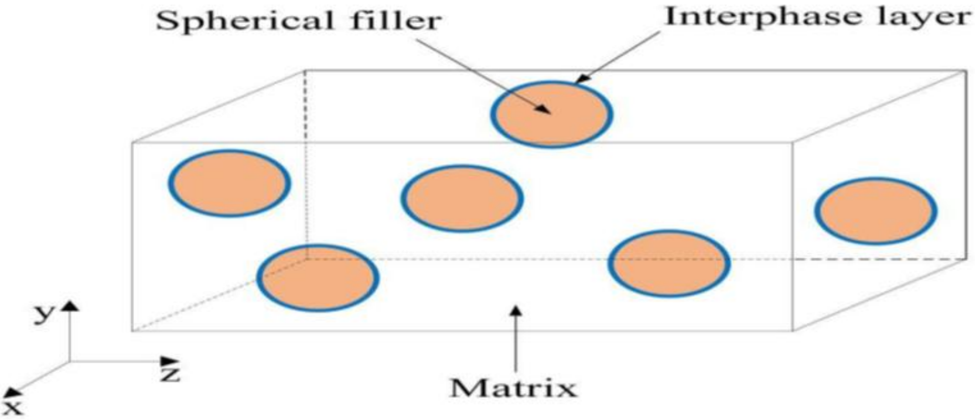

Figure 5: 3D shape of spherical fillers dispersed in matrix.

Sheet-like nanoscale fillers Sheet-like nanoscale fillers, often used in polymer nanocomposites, are materials with a layered structure, like layered silicates (e.g., montmorillonite, hectorite), where individual layers are only a few nanometers thick and can range from tens of nanometers to several micrometers in lateral dimensions. These fillers, due to their high aspect ratio and ability to align within the matrix, can significantly improve the mechanical, thermal, and barrier properties of the resulting nanocomposite. Two-dimensional layers make up their crystal lattice. Two outer silica tetrahedrons are fused to a core alumina or magnesia octahedral sheet, with the octahedral sheet's oxygen ions belonging to the tetrahedral sheets. The layers are approximately nm thick, and their lateral dimensions range from a few 10ths of nm to several μm or more. Between the "interlayers" or "inter-galleries," these sheets will stacks having Vander Waals spaces among them. This type of clay has a moderate positive exchange capacity, and because the charges of the layers vary, an average value measured over the entire crystal must be used (E. P. Giannelis, R. Krishnamoorti, and E. Manias 1999 & S. S. Ray and M. Okamoto 2003). Figure 6 shows the most commonly used silicate structure.

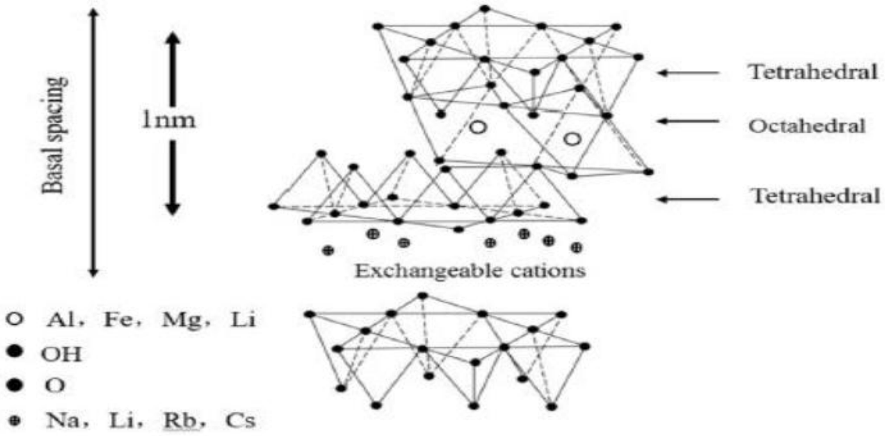

Figure 6: The most commonly used silicate structure

Properties of Nanocomposites

Nanocomposites materials with nanoscale-sized components dispersed within a matrix, exhibit unique properties compared to their bulk counterparts. These properties stem from the high surface area to volume ratio of the nanoparticles and their interactions with the matrix, leading to enhanced mechanical, electrical, optical, and barrier properties. In recent years, research on nanocomposites has gained more interest with significant efforts of controlling the nanostructures by suitable synthetic methods. Morphology and interfacial characteristics of the materials decide the properties of the nanocomposites such as temperature, magnetic properties, and charge capacity. As nano particles and nanolayers have high surface to volume and aspect ratio, they are ideal for usage along with the polymeric materials. Such structures combine the simplest properties of every component to possess enhanced mechanical & superconducting properties for advanced applications. This characteristic is taken into account to be the bottom for forming the matrices for the polymers in resulting hybrid nanocomposites. These inorganic nanocomposites are useful for electronic and charge transport properties. They also possess superior mechanical properties like high dielectric constants which are flexible, easy to process, and powerful. The most commonly used ceramic materials with a high dielectric constant are found to be brittle and are processed at high temperatures, polymeric materials though it can be easily processed, it have low dielectric constant.

Nanocomposites have improved properties over the quality material properties like mechanical properties like strength, modulus, dimensional stability, toughness, and electrical or thermal conductivity, decreased gas etc., Nanocomposites are clay, polymer, or carbon, or a mixture of those materials with nanoparticle building blocks. They need a particularly high surface-to-volume ratio (C.O. Charles, 2013, Oyubu, A. O and Nwabueze, C. A., 2023). Nanocomposites formations are shown in figure 7.

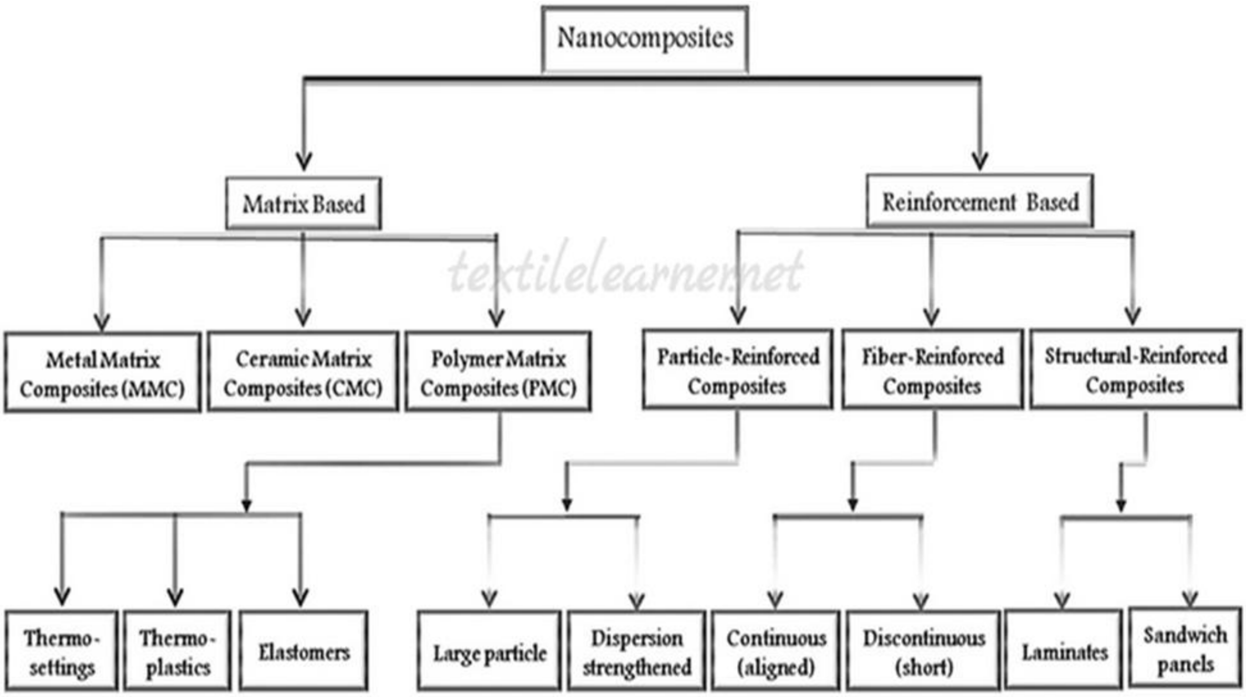

Figure 7: Nanocomposites formation

Potentials and Opportunities in Nanocomposites

Ceramics possess high thermal and chemical stability along with good wear resistance but they are brittle due to the low toughness strength. This can be overcome by converting into ceramic matric nanocomposite, resulting in the significant enhancement on mechanical properties which can be achieved. For example, the incorporation of energy-dissipating components like whiskers, fibbers, platelets, or particles within the ceramic matrix may cause increased fracture toughness. The reinforcements rebound the crack and create bridging elements, thus delaying the further opening of the crack. Toughening and strengthening processes is based on the crack bridging role of the nanosized matrix. Incorporation of high strength nanofibers into ceramic matrices led to advanced nanocomposites with high toughness.

Nanocomposites, materials with at least one component at the nanoscale, offer a wide array of potential applications due to their enhanced properties compared to traditional materials. These materials are finding use in diverse fields like biomedicine, aerospace, electronics, and environmental remediation, driven by their superior strength, lightweight nature, and tailored functionalities.

Key Potential Applications and Opportunities:

i). Enhanced Mechanical Properties: Nanocomposites can achieve high strength and stiffness while maintaining flexibility, making them suitable for lightweight structural components in vehicles, aircraft, and construction.

ii). Biomedical Applications: Their biocompatibility and ability to be modified for drug delivery, tissue engineering, and diagnostics open avenues in nanomedicine and healthcare.

iii). Electronics and Optics: Nanocomposites can be tailored for specific optical and electronic properties, leading to advancements in sensors, displays, and optoelectronic devices.

iv). Environmental Remediation: Their high surface area and reactivity make them effective in water purification, air filtration, and the removal of pollutants.

v). Sustainable Packaging: Biodegradable nanocomposites can improve the shelf life and barrier properties of food packaging, offering a more environmentally friendly alternative.

vi). Energy Storage: Nanocomposites can enhance the performance of batteries, fuel cells, and other energy storage devices.

vii). Automotive and Aerospace: Their lightweight and high-strength characteristics make them ideal for fuel-efficient vehicles and aerospace applications.

Key Drivers for Nanocomposite Development

i). Increased Demand: Growing awareness of the benefits of nanotechnology and the need for sustainable materials are driving the demand for nanocomposites.

ii). Advancements in Synthesis and Characterization: Improved methods for synthesizing and characterizing nanocomposites at the nanoscale are enabling the development of materials with tailored properties.

iii). Interdisciplinary Research: Collaboration between materials scientists, chemists, engineers, and other researchers is accelerating the development and application of nanocomposites.

Benefits of nanocomposites

Nanocomposites offer a wide array of benefits due to their unique nanoscale properties, including enhanced mechanical strength, improved thermal and electrical conductivity, and increased barrier properties. These advantages stem from the high surface area to volume ratio of the nanomaterials within the composite, leading to superior performance compared to traditional materials.

Enhanced Mechanical Properties

i). Increased Strength and Stiffness: Nanocomposites can exhibit significantly higher strength and stiffness compared to the base material, making them suitable for applications requiring robust and durable materials.

ii). Improved Toughness: The dispersion of nanoparticles within the matrix can enhance the material's ability to absorb energy before fracture, leading to increased toughness and resistance to impact.

iii). Enhanced Flexibility and Dimensional Stability: Nanocomposites can maintain their shape and size under stress, offering improved dimensional stability and resistance to deformation.

Improved Thermal and Electrical Properties

i). Increased Thermal Conductivity: Nanocomposites can effectively transfer heat, making them useful in applications like heat sinks and thermal management systems.

ii). Electrical Conductivity: The presence of conductive nanoparticles can improve the electrical conductivity of the composite material, enabling its use in electronic devices and energy storage systems.

In general, nanocomposites exhibit improvements in the barrier, flame resistance, structural, and thermal properties yet without significant loss in impact or clarity. Nanocomposites are tightly bound structure in a polymer matrix which will be impermeable to gases and liquids, due to this it has good barrier properties over the native polymer. Improved mechanical properties such as stability have contributed to an increase in heat deflection temperature, example polymer-clay nanocomposites have a large reduction in gas and liquid permeability and solvent uptake. Nanocomposites are used as insulators because of their high heat resistance and low flammability. Nanocomposites are less porous than plastics, hence they can be used in the packaging of foods and drinks, vacuum packs, and to protect medical instruments, film, and other products from external contamination. They possess significant weight reductions, greater strength, and increased barrier performance (C.O. Charles 2013)

Application Areas of Nanoparticles

Nanoparticles can be used in many different ways. Here are a few of the most significant.

Medical and drug Applications

Simple and complex inorganic nanoparticles have unique chemical and physical properties that make them an important component in the creation of innovative nanodevices for a variety of applications such as pharmacological, medical, biological, and physical applications. NPs have grabbed the interest of researchers across the medical field due to their ability to deliver medications in the right dosage range. As a result, therapeutic efficacy has increased, side effects have decreased and patient compliance has improved. NPs are used for their optical properties in biological and cell imaging applications, as well as photothermal therapeutic applications, to produce efficient contrast. Both the discrete dipole approximation approach and Mie theory could be used for the most common classes of NPs to evaluate the scattering and the absorption efficiency, as well as optical resonance wavelength (I. Khan, K. Saeed, and I. Khan, 2019).

Fuel cells

Fuel cell applications involve polymers in the proton exchange membrane, binder for the electrodes and matrix for bipolar plates. The electrodes are of carbon black particles with Pt catalyst particles and a polymeric binder (Nafion). Nanoparticles play a major part in fuel cells. Pt nanoparticles deposited onto single-walled carbon nanotubes with Nafion as a binder to improve performance over the conventional carbon black based electrodes. Nanoparticles incorporation in the proton exchange membrane has been noted in numerous publications to improve mechanical properties as well as to enhance proton conductivity. Nanoparticles have been used to reduce methanol crossover. Heteropolyacids have been added to proton exchange membrane to yield improved proton conductivity at a higher temperature. Silica nanoparticle in proton exchange membranes gave lower methanol crossover. Nano clay modified Nafion and montmorillonite membranes have been reported to offer improvements over the unmodified controls. Zirconium phosphate, Zirconium hydrogen phosphate, and $TiO2$ in proton exchange membranes exhibited promise in direct methanol fuel cells. These are mthe ain application of nanocomposites in fuel cells.

Biomedical applications

The use of nanocomposites in biomedical applications is one of the growing fields in nanotechnology. One area intense research involves electrospinning or producing bio restorable nanofiber scaffolds for tissue engineering applications. Another area involving nanofibers is the utilization of electrically conducting nanofibers based o conjugated polymers for regeneration of nerve growth in a biological system. Nanoparticle silver, silver oxide, and silver salts have been incorporated into polymer matrices to provide antimicrobial activity. Polymer nanocomposites based on hydroxyapatite [Ca10(PO4)6(OH)2] have been investigated for bone repair and implantation. Hydroxyapatite, a major constituent of hard tissue exhibits undesirable mechanical properties if directly employed thus polymer-based matrix nanocomposites are desired. Collagen derived gelatin and poly-2-hydroxyethyl methacrylate/poly (3- caprolactone) nanocomposites based on hydroxyapatite are examples of systems studied for bone repair systems. Electrospinning of biodegradable polymer solutions is a popular method to produce nanofiber scaffolds for tissue engineering applications. Poly (L-lactic acid)/exfoliated montmorillonite clay/salt solutions were electro spun followed by salt leaching/gas foaming. Polymer matrix nanocomposites have been proposed for drug delivery/release applications. Iron oxide nanoparticles have been used for various applications including drug delivery, magnetic resonance imaging contrast enhancement, immunoassay, and cellular therapy. Iron and cobalt nanoparticles encapsulated in polydimethylsiloxane have been noted for treating retinal detachment disorders.

Manufacturing Applications

Nanocrystalline materials are intriguing to examine because their characteristics differ in size from those of the bulk material. Manufacturing NPs have unique mechanical, electrical, optical and imaging characteristics in commercial, medical and environmental applications because of their physicochemical properties. The benefits of nanotechnology have been documented by many companies, and commercial products are now being mass-produced in fields like aerospace, microelectronics, and pharmaceuticals. Packaging and food processing industries have heralded nanotechnology as the next great thing (I. Khan, K. Saeed, and I. Khan, 2019 & O. H. Sabr, N. H. Al-Mutairi, and A. Y. Layla, 2021).

Mechanical Industries Applications

NPs can be used in a variety of mechanical applications, such as adhesives, coatings and lubricants, as evidenced by their mechanical properties, which include outstanding stress, strain and young modulus properties. Also, this property could be used for the manufacturing of nanodevices that are mechanically stronger for different applications. Tribological properties (surface properties) of the polymer or the metal matrixes could be enhanced by adding nanoparticles NPs to improve their mechanical strength, the added nanoparticles improve the lubrication in the contact area and reduce the wear and friction (I. Khan, K. Saeed, and I. Khan, 2019).

Electronic Applications

The prospect of low-cost electronics and large space for flexible screens and sensors, as opposed to typical silicon approaches, has sparked interest in printed electronic research in recent years. Printed electronics, which use a variety of functional inks containing NPs such as organic electronic molecules, metallic and ceramic NPs and carbon nanotubes CNTs, is expected to become a large-scale production technique for new types of electronic equipment in the near future. One-dimensional metals and semiconductors possess unique electrical, structural and optical properties, making them a key systemic component in a new generation of photonic, electronic and sensor materials (I. Khan, K. Saeed, and I. Khan, 2019).

Aerospace applications

In some applications, apart from being lightweight, high performance is of prime importance in aerospace structures e.g., equipment enclosures, aircraft interiors, coatings, cockpit, crew gear, space durable mirrors, nozzles and solar array substrates. Nanocomposite materials offer chemical stability and fire resistance apart from the advantage of low operating cost due to their lightweight. Aerospace structures are subjected to a diverse environment that includes variations in moisture and temperature. They are also subjected to contact with jet fuel, deicing fluid, and hydraulic fluid. The coatings should withstand lightning strikes, ultraviolet exposure, and erosion.

Current Status Challenges and Future Prospects

The field of nanocomposites holds an expansive potential for commercial application, yet the pace at which these applications are being implemented remains remarkably slow. Despite their promise, many nanocomposites fail to perform adequately in real-world conditions, potentially falling short of expectations due to mismatches like increased stiffness not correlating with the strength required in synthesized composites. This implies that certain properties of nanocomposites might be compromised. Therefore, the successful production and application of nanocomposites heavily depend on factors such as the chemistry involved in the modification of fillers, as well as the physics and thermodynamics relevant to filler dispersion. Presently, the evaluation of nanocomposites focuses on their structural and property aspects at a fundamental level, underscoring the importance of understanding the proper scientific theories and principles necessary for developing new materials. Equally, there is a need to delve into the rheological characteristics, processing techniques, and applications associated with these materials. A major challenge facing biodegradable nanocomposites is their use of natural polymers, which are prone to high water permeability and swelling behavior upon water contact, consequently diminishing their mechanical properties and complicating their suitability for packaging applications. Advances such as the integration of nano clay sheets into biopolymers have demonstrated positive effects on the water sensitivity and stability of bioplastics, with clay particles serving as barriers due to their non-permeable nature against small gas molecules, affecting molecular migration. These advancements suggest that nanocomposite materials with well-dispersed barrier elements can exhibit improved mechanical properties, enhanced stability, and potentially reduced aging effects. As research into nanocomposites across diverse scientific domains has surged in recent years, a wealth of theoretical and experimental techniques have evolved, fundamentally reshaping synthesis processes, analysis methods, and cost-control strategies for nanocomposites. Consequently, it is imperative to determine the most effective methodologies, culminating in the present work's aim to gain an overview of nanocomposites that encompasses their classification, characterization, and various applications.

Also, some of the challenges faced in the use of nanocomposites include: suitable reinforcements such as nanofibers with or without spinning, which will have higher strength properties, being lighter than their micro counterparts and hence appearing as superior structural components; use of nanofibers in different areas such as biomedical, electrical and optical, for various functional devices; conducting polymer-based nanomaterials for electrochemical applications; modification of the mechanical behavior of nanocomposites to get higher performances; surface modification of polymer nanofibers for their use in polymer matrices to overcome the poor interfacial bonding; modelling and simulation of mechanical properties of nanofiber-containing composites, etc. Other promising area for inexpensive reinforcements is the use of cheap and abundantly available reinforcing materials of natural origin for various applications. In this case, carbon nanotubes in larger extent can reduce the cost of nanocomposite products. Hence, efforts are essential to identify new formulations with materials of renewable resources such as polylactide, polyhydroxylalkanoates, etc., reinforced with easily available reinforcements based on common elements like hydroxides, layered double hydroxides and layered hydroxide salts. Selection of these will lead to a cleaner environment and ecology. Knowledge from the interdisciplinary areas such as physics, chemistry, biology, material science and engineering to obtain new nanoscale structures. Study of structure-property correlations in nanocomposites is challenging in the development of suitable fabrication techniques for dealing with the nanoscale materials, for their characterization and mechanics in order to understand the interactions (H. Pedro, C.K. Cury, S. Gundappa, W. Fernando 2009)

Future Prospects

Scalability and Cost

Scaling up the production of nanocomposites while maintaining their unique properties and controlling costs remains a challenge.

Long-term Stability and Durability: Ensuring the long-term stability and durability of nanocomposites under various operating conditions is crucial for their widespread adoption.

Environmental Impact

It is important to assess and minimize the potential environmental impact of nanocomposites throughout their lifecycle, from production to disposal.

Despite these challenges, the potential of nanocomposites is vast, with ongoing research and development efforts expected to lead to further breakthroughs and innovative applications in the years to come.

Conclusion

This paper discussed both nanotechnology and nanocomposites materials, definitions and their classifications. Nanomaterials have different types based on their shapes (particles, fibers, and sheets), also have different sizes with different nano dimensions (1D; only one dimension in nano-scale, 2D; two dimensions in nano scale, and 3D). In this context, nanocomposites are suitable materials to meet the emerging demands arising from scientific and technological advances. Processing methods for different types of nanocomposites (CMNC, MMNC and PMNC) are available, but some of these pose challenges thus giving opportunities for researchers to overcome the problems being encountered with nanosize materials. They offer improved performance over monolithic and microcomposite counterparts and are consequently suitable candidates to overcome the limitations of many currently existing materials and devices. Hence they are used for emerging demands. Because of their unique properties like very high mechanical properties even at a low loading of reinforcements, gas barrier, and flame related properties. Nanoparticles, nanowires, and nanotubes of various materials have already had an impact in the field of chemical sensors, ranging from gas sensors to glucose enzyme electrodes. Currently, nanocomposite-based protocols are being exploited for the detection of proteins, acids, toxic gases, etc. Nanocomposite-based sensors are expected to possess serious impact on clinical diagnosis, environmental monitoring, security surveillance, and ensuring the security of our food.

References

Ajayan, P. M., Schadler, L. S., & Braun, P. V. (2003). *Nanocomposite Science and Technology*. Wiley-VCH.

Camargo, P. H. C., Satyanarayana, K. G., & Wypych, F. (2009). Nanocomposites: Synthesis, Structure, Properties and New Application Opportunities. *Materials Research*, *12*(1), 1–39

Chaisan, W., Yimnirun, R., & Ananta, S. (2009). Preparation and Characterization of Ceramic: Nanocomposites in the PZT–BT System. *Ceramics International*, *35*(1), 121–124.

Charles, C. O. (2013). Nanocomposites – An Overview. *International Journal of Engineering Research and Development*, *8*(11), 17–23.

Chawla, K. K. (2012). Metal Matrix Composites. In *Composite Materials* (pp. 197–248). Springer.

Giannelis, E. P., Krishnamoorti, R., & Manias, E. (1999). Polymer-Silicate Nanocomposites: Model Systems for Confined Polymers and Polymer Brushes. *Polym. Confin. Environ.*, [Missing Volume(Issue)], 107–147.

Gupta, R. K., Kennel, E., & Kim, K.-J. (2009). *Polymer Nanocomposites Handbook*. CRC Press.

Hanemann, T., & Szabó, D. V. (2010). Polymer-Nanoparticle Composites: From Synthesis to Modern Applications. *Materials (Basel)*, *3*(6), 3468–3517.

Ichihashi, T. (1993). Erratum: Single-Shell Carbon Nanotubes of 1-nm Diameter. *Nature*, *364*(6439), 737.

Khan, I., Saeed, K., & Khan, I. (2019). Nanoparticles: Properties, Applications and Toxicities. *Arab. J. Chem.*, *12*(7), 908–931

Kuo, M. C., Tsai, C. M., Huang, J. C., & Chen, M. (2005). PEEK Composites Reinforced by Nano-Sized SiO_2 and Al_2O_3 Particulates. *Materials Chemistry and Physics*, *90*(1), 185–195.

Mordkovich, V. Z., Baxendale, M., Yoshimura, S., & Chang, R. P. H. (1996). Intercalation Into Carbon Nanotubes. *Carbon (New York, NY)*, *34*(10), 1301–1303.

Oyubu, A. O., & Nwabueze, C. A. (2023). Nanotechnology: A Concise View. *Engineering Science & Technology Journal (ESTJ)*, *4*(2), 18–28. http://www.fepbl.com/index.php/estj

Pedro, H., Cury, C. K., Gundappa, S., & Fernando, W. (2009). Nanocomposites: Synthesis, Structure, Properties and New Applications Opportunities. *Materials Research*, *12*(1), 1–39

Ray, S. S., & Okamoto, M. (2003). Polymer/Layered Silicate Nanocomposites: A Review From Preparation to Processing. *Progress in Polymer Science*, *28*(11), 1539–1641.

Sabr, O. H., Al-Mutairi, N. H., & Layla, A. Y. (2021). Characteristic of Low-Density Polyethylene Reinforcement With Nano/Micro Particles of Carbon Black: A Comparative Study. *Archives of Materials Science and Engineering*, *110*(2), 49–58.

Wing, M. Y., Zhongzhen, Y., Xaolin, X., Qingxin, Z., & Jun, M. A. (2003). Polymer Nanocomposites and Their Applications. *HKIE Transactions*, *10*(4), 67–73.