Recent Research Progress and Advanced Applications of Polymer Nanocomposites.

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Abstract

Materials containing two or more constituents that have distinctly different physical or chemical properties are referred to as composites. The heterogeneous hybrid materials known as nanocomposites are created when polymers are combined with other organic or inorganic components at the nanometric scale. The most common method for creating nanocomposites involves in situ biopolymer and inorganic matrix development and polymerization. Because of their adaptable shape, significant specific surface area, and simplicity of functionalization, polymer nanocomposites are frequently employed. On the basis of their scattered matrix and dispersed phase components, nanocomposites can be categorized. In addition to their many other applications, multi-functional hybrid materials have shown tremendous promise in the fields of optics, sensors, environmental cleanup, electronics, catalysis, soft robotics, storage, energy transformation, mechanics, electromagnetic interface shielding and drug delivery. This study focuses on describing recent advancements in preparation and structure characterization techniques, as well as the distinctive characteristics and applications of diverse polymeric nanocomposites.

Keywords: Nanocomposites, Polymer nanocomposties, Electrical properties, Mechanical Properties.

Introduction –

There is a lot of research interest in using nanomaterials in polymer matrices to create heterogeneous materials with distinct characteristics and enhanced performance. Polymer nanocomposites as a concept first emerged in the 20th century and have swiftly evolved alongside developments in nanotechnology and nanoscience [1-3]. Materials that contain two or more elements with noticeably differing physical or chemical properties are known as nanocomposites. While hybrid usually refers to the constituents at the nanoscale or molecular level, nanocomposites cover a wider variety of dimensions of mixing components. For the best performance in a variety of applications, including coatings, sensing, energy harvesting and storage, magnetism, and packaging, they have been designed, synthesized, and customized. Every aspect of our everyday lives has been greatly impacted by the revolution of new composites technology [4]. Composites can be divided into polymer composites, ceramic composites, carbon composites, and metal composites based on the matrix material. The most common types of nanofillers include three-dimensional porous nanofillers, metal nanoparticles and oxides, and carbon-based compounds [5,6]. The most prevalent carbon compounds with high aspect ratio, mechanical stability, and thermal and electrical conductivity are graphene (GPE) and carbon nanotubes (CNTs) [7, 8]. Both natural and artificial polymers are available. Natural polymers are those that can be derived from nature and used. Silk, wool, DNA, cellulose, and proteins are examples of water-based natural polymers [9]. On the other hand, synthetic polymers like nylon, polyethylene, polyester, Teflon, epoxy, etc. Polymer nanocomposites have special synergistic properties that cannot be attained when individual components are acting independently [10]. To produce a PNC with improved properties for a particular application, inorganic nanofillers such nanoclays, metal-oxide nanoparticles, carbon nanomaterials, and metal

nanoparticles can be included into a polymer matrix [11,12]. Due to their wide range of uses in environmental rectification and the treatment of many environmental problems, polymer nanocomposites have become more well-known in science [13]. This review's objective is to provide a thorough analysis of the current status of polymeric nanocomposites used as water remediation materials throughout the world. It does this by examining different polymer nanocomposites classifications, cutting-edge synthetic techniques, uses, benefits, drawbacks, and potentials. The review's search terms include "polymeric material," "polymer nanocomposite," "adsorbent," "photocatalyst," "organic pollutant," "heavy metal," "photocatalytic degradation," "adsorption," and "water treatment," and it is based on papers and books that have been published in SCOPUS and Web of Science.
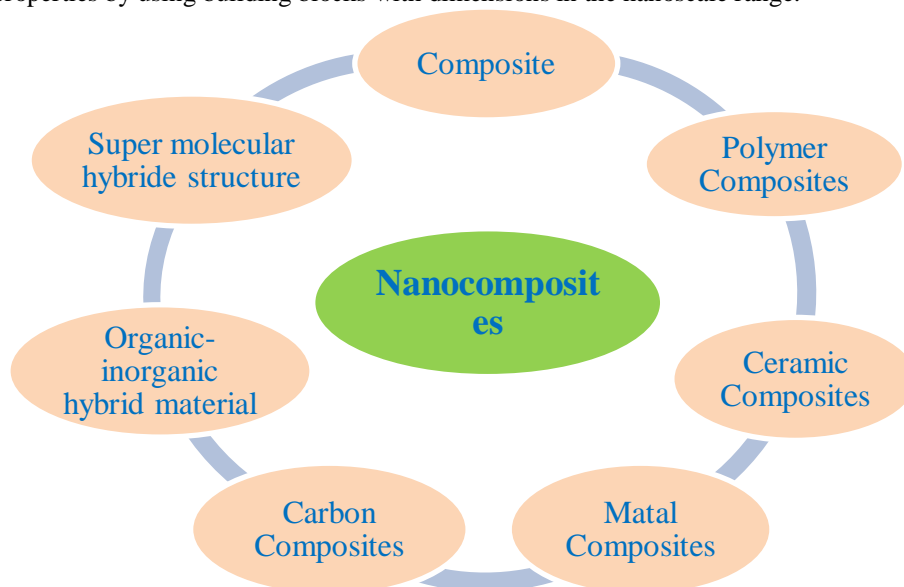
Composites –

In order to produce a new substance with better properties than the original materials in a particular finished structure, two or more different constituent materials, each of which has its own significant characteristic (physical or chemical properties), must be combined [14, 15]. Composites are engineered or naturally occurring solid materials that result from this process. They are frequently created to offer a variety of qualities and traits, some of which include:

➢ Low coefficient of expansion
➢ Stiffness and strength
➢ Resistance to corrosion
➢ Resistance against fatigue
➢ Simple repair of damaged structures
➢ Ease in manufacturing complex shapes

Nanocomposites –

As nanocomposites have multiphases, they are multiphase materials, at least one phase should have dimensions in between 10 to 100 nanometers to overcome problems associated with nanoscale morphology such as nanotubes, lamellar nanostructures or Nanoparticles. Today, nanocomposites have emerged as a means for overcoming the limitations of different engineering materials. These can be categorized according to the dispersed phase composition and dispersed matrix [16]. Modern synthetic approaches have enabled the development of many exciting new materials with novel properties with the help of this rapidly expanding field. The so-called found's traits were heavily influenced by the originals' interfacial and morphological qualities in addition to their own properties. Of course, we cannot discount the possibility that the parent constituent materials may not be aware of the newly produced feature in the material [17, 18]. Thus, the concept behind nanocomposite is to develop and produce new materials with remarkable flexibility and improvement in their physical properties by using building blocks with dimensions in the nanoscale range.

Types of nanocomposites –

Based on whether or not the composite contains polymeric material, the following categories of nanocomposite materials can be created. Non-polymer based nanocomposites are those in which the

compositions do not include any polymers or components generated from polymers. Inorganic nanocomposites are another name for non-polymer based nanocomposites. Additionally, they can be divided into ceramic based, metal-based and ceramic-ceramic based nanocomposites [19].

Polymer Nanocomposites –

a) **Ceramic Nanocomposites –**

Ceramic fillers and an organic polymer matrix, particularly polysiloxanes, make up polymer ceramic materials, which are inorganic-organic composites. The ability of functionalized resins to produce ceramic-like structures upon thermal curing is the basis for the creation of polymer ceramics. Polymer-ceramic composites could be used to build a variety of electro-technical components subject to high thermal loads. The development of connecting materials and foamed materials with excellent thermal stability and effective thermal isolation capabilities could also serve as evidence of the polymer-ceramics' wide range of applications.

b) **Inorganic / Organic Polymer –**

These substances may contain inorganic elements in side groups that are related to the organic network and have C-atoms in the main chain or network. Additional inorganic cross-linking is also conceivable here. Creamers are made by silylated oligomers or polymers being processed in a sol-gel method after the organic network has already been generated in the precursor.

c) **Inorganic / Organic Hybrid –**

In organic sensors, organic light-emitting diodes (OLEDs), organic field-effect transistors (OFETs), organic phototransistors, and organic photovoltaics (OPVs), organic materials, including both small molecules and polymers, have been extensively studied. The next generation of commercially produced electronics is expected to be organic electronics due to their high scalability, simple processing capability, flexibility, and low manufacturing cost.

d) **Layered silicate nanocomposites –**

Layered silicate minerals are readily available and inexpensive, but it is difficult to incorporate them on the nanoscale into polymer matrices. To get organically modified silicates or clay, which is subsequently more compatible with the organic polymer matrices, it is typically necessary to modify the surfaces of these materials.
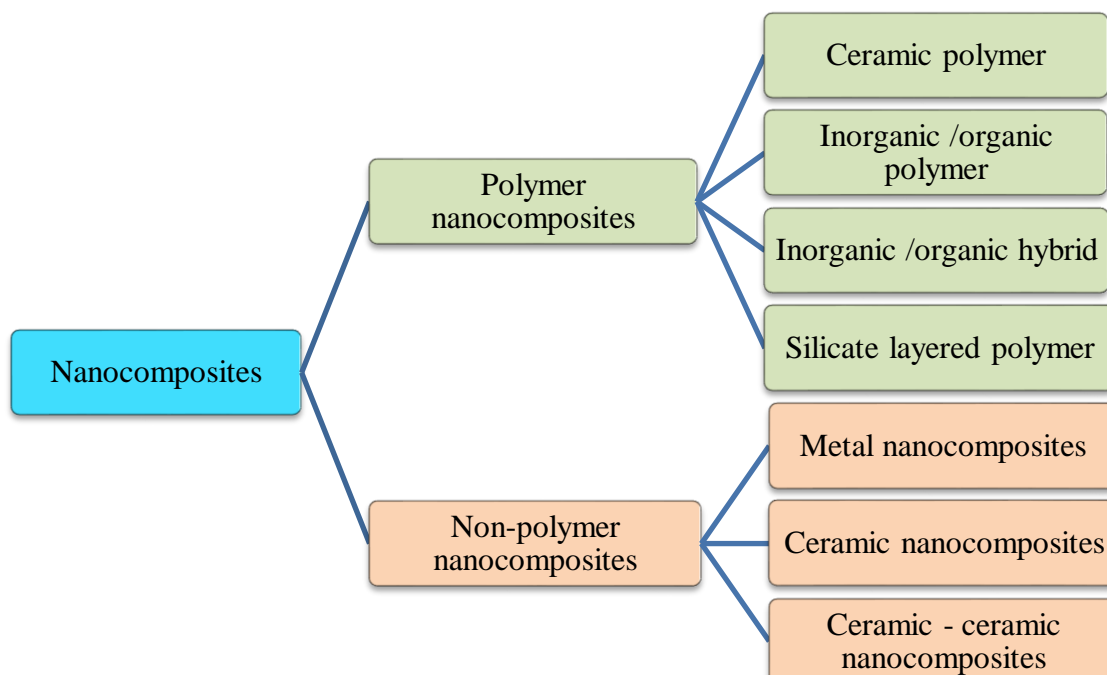
Non-polymer-based nanocomposites –

a) **Metal-based nanocomposites –**

Due to their improved catalytic characteristics and improvement in optical properties connected to individual and differentiated metals, bimetallic nanoparticles are being explored in depth in the form of alloy or core-shell structures. They are distinguishable by:

➢ Increased strength and hardness,
➢ Lower melting points,
➢ Super plasticity,
➢ Increased electrical resistivity,
➢ Improved magnetic properties, etc.

Metal/metal nanocomposites, such as Pt-Ru nanocomposites, are another category for non-polymer-based nanocomposites.

b) Ceramic-based nanocomposites –

Ceramic composites containing more than one solid phase, at least one of which has dimensions in the nanoscale range (50-100 nm), are referred to as ceramic-based nanocomposites. For instance, hydroxyapatite/titanium nanocomposites both phases of these composites combine magnetic, chemical, optical, and mechanical capabilities [20–22]. These can be identified by their increased Strength, ductility and hardness.

c) Ceramic-ceramic-based nanocomposites –

The nanocomposites of non-polymer based can also be categorized as ceramic-ceramic nanocomposites, which can be applied to artificial joint implants for fracture failures, might significantly lower surgery costs, and would increase the patient's mobility. Calcium sulfate-biomimetic apatite nanocomposites are another type of ceramic/ceramic nanocomposites [23]. The application of nonpolymer-based nanocomposites or inorganic materials, such as calcium phosphate, hydroxyapatite, and bioactive glass nanoparticles, which are metal or ceramics, are particularly advantageous in alveolar bone regeneration and enamel replacement, is where both metal-based nanocomposites and ceramic-based nanocomposites hold the most promise [24].

Polymeric Nanocomposites: Synthetic Techniques and Applications in Remedial Practice –

For the production of polymer nanocomposite materials, the selection of design, precursors, and synthetic techniques is crucial. To create Poly-Nanocomposites with the desired feature, one must select from a wide range of monomers, fillers, and other composite components as well as synthesis techniques [25]. This highlights how important the design and synthesis processes are in the production of poly-nanocomposites [11]. The most frequently used synthesis techniques include ultrasonication-assisted mixing, shear mixing, microwave-assisted synthesis, roll milling, in-situ polymerization, ball milling, selective laser sintering, double-screw extrusion, and 3D printing (additive manufacturing) [11,26]. Typically, direct compounding and in situ synthesis are the two processes used to create polymer nanocomposites [27]. It has been claimed that problems with nanoparticle aggregation in melt-mixing procedures can be resolved via atomic layer deposition and plasma-assisted mechanochemistry. A comparable role is also played by high frequency sonication in the disaggregation of nanoparticles during mixing processes. The production of thermodynamically stable nanocomposites is possible through in-situ polymerization, and the production of porous objects is effectively accomplished through electrospinning [28]. Nanofillers are increasingly being used in the creation of Poly-Nanocomposites because of their distinctive characteristics and numerous potential applications. Fillers with one dimension less than 100 nanometers are referred to as one-dimensional (1D) nanofillers [11].

They typically come in sheets with thicknesses varying from a few nanometers to thousands of nanometers. Montmorillonite clay and graphene nano-platelets are two examples of one-dimensional nanofillers. Polymer nanocomposites produced from various nanofillers and polymers are of interest to both academia and industry. Microwave-assisted synthesis is a new technology that is being employed in many areas of materials science and chemistry because of its consistent volumetric heating and the enormous improvement in reaction rate.

Functionalized polymer-based nanoadsorbents have also been produced using microwave-assisted manufacturing [29].

Advantages of designing novel nanocomposites –
A bulk matrix and one or more nanodimensional phase(s) that have different properties due to differences in structure and chemistry are called nanocomposites. Properties that have shown significant improvements include:

➢ **Mechanical characteristics (strength, bulk modules, limit of withstands, etc.) –**
The mechanical characteristics of materials are frequently described using their tensile strength, impact strength, elongation at break, and bending properties [30, 31]. Using the sol-gel process, Jiao et al. [32] created metal oxides/epoxy resin (EP) nanocomposites, and they discovered an increase in the tensile strength, elongation at break, impact strength, and flexural strength of EP composites. The strengthening process is connected to the fact that EP is more likely to experience stress concentration when metal oxides are present. On the one hand, when there is a concentration of stress, more deformation energy can be absorbed through the development of matrix cracks, and the toughness of EP rises in direct proportion.

➢ **Thermal stability –**
The breakdown temperature and mass fraction of SiO_2 in SiO_2/polymer nanocomposites have been determined using the thermogravimetric analysis (TGA), which may be used to study thermal stability [33, 34]. Saoud et al. [35] examined the impact of SiO_2 content on the thermal characteristics of a methacrylate polymer by adding varying amounts of SiO_2. Since the decomposition temperature of the composite rises with an increase in metal oxide content while the slope of the corresponding curve falls during the decomposition process, the presence of metal oxides in composites reduces the rate of decomposition and increases heat resistance and thermal stability. The crosslinking network topology restricts the polymer molecular chain's ability to migrate when heated.

➢ **Flame retadency –**
Flammable substances Reactive-type flame retardants, as previously mentioned, involve adding a monomer that can improve a polymer's fire resistance, either by creating a polymer that is flame-resistant or by adding a reactant to a polymer by chemically combining a flame-retardant substance at the side or terminal chain [36]. In the past, flame retardant chemicals have been utilized, but this approach suffers from low commerciality with polymer materials, leading to losses during manufacturing and use. In addition, the mechanical qualities of the polymers deteriorate as the amount of added flame retardant increases. By converting a portion of the main chain or a pendant group of the polymer into a reactive flame retardant, it is possible to permanently boost the fire performance and solve these issues [37]. Using this technique, reactive flame retardants are incorporated into the polymer as monomers or polymer precursors to create fire-safe polymers. Because there are covalent bonds between the flame-retardant compound and polymer, reactive flame retardants are therefore more effective than additive-type flame retardants in improving the fire performance of polymers. In these situations, the flame-retardant additive does not phase-separate or deplete. This group includes, among others, compounds containing phosphorus, nitrogen, boron, halogens, silicones, and mixtures of phosphorus-nitrogen and phosphorus-silica. These substances can be used in the synthesis of polymers as co-monomers or chain extenders [38].

➢ **Electrical conductivity –**
According to percolation theory, the electrical conductivity of composites comprised of a conducting phase dispersed in an insulating matrix is highly dependent on the filler loading.[39] A desirable filler for creating electrically conductive nanocomposites is carbon nanotubes (CNTs). Since the average distance between the filler elements is greater than their size when the filler concentration is low, the conductivity of the nanocomposite is quite similar to that of the pure insulating matrix. A "percolation" channel of connected fillers occurs when enough filler is supplied, enabling charge transmission through the sample. The percolation threshold, or critical concentration, is where the conductivity begins to abruptly and quickly rise. The value of the percolation threshold is determined by geometrical factors [40].

➢ **Optical properties –**
In composite materials, transparency and refractive index are the most crucial optical characteristics. The transparency of materials is frequently assessed using ultraviolet-visible spectroscopy. The amount of nano-metaloxide in the PVA matrix is growing, which increases the composite film's ability to absorb light. The strong hydrogen bonds between nano-metal oxide and the hydroxyl groups of PVA, which improved the binding effect between PVA and metal oxide, may be the cause of the absorbance increasing as metal oxide concentration rises.

Conclusion –

In order to create new materials for cutting-edge applications, the study of nanocomposites has grown in significance. Nanocomposites are the best option to meet the growing demand for multifunctional materials since they are varied class of materials and they have a better level of amalgamation. The development of thermodynamically stable polymeric nanocomposites is made possible by in-situ polymerization. Porous materials can be created effectively using electrospinning. Additionally, there are clear benefits to selective laser sintering for creating nanocomposites in terms of preventing aggregation.

It is a multidisciplinary field that requires expertise in both technological and scientific backgrounds to produce macroscopic designed materials that are obtained through nanoscale structures. These materials are appropriate for meeting the new demands brought on by technological and scientific advancements. The crucial aspect is that it offers many of our industrial sectors, including those in the biomedical, electrical, chemical, transportation, electronics, and electrical industries, which are endowed with properties like self-healing, self-cleaning, super hydrophobicity, multiple responses, and shape memory, a plausible benefit. Therefore, it is anticipated that these will have a significant impact on keeping the environment cleaner, greener, and safer in the years to come.

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