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Synthesis, Characterization and Applications of Polymer Nanocomposites

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Abstract - For specialized applications in today's modern world, a variety of multifunctional materials with suitable mechanical, thermal, electrical, and chemical properties are required. Composites are a type of material that offers a lot of potential for developing multifunctional innovative materials that are needed for new technological developments.

Composite materials can provide a desirable set of qualities that can be adjusted to meet the unique requirements for a given application by mixing two chemically or physically distinct materials. Traditional materials such as metals, ceramics and metal alloys, polymers, and other materials cannot achieve such a mix of qualities. Lately, polymer nanocomposites have been making waves in the media and in a variety of industries. There has been a lot of interest in tailoring the structure and composition of materials on a nanometer scale in the last several years. As a result, a thorough examination of the synthesis, characteristics, and applications of polymer nanocomposites is critical. Polymer nanocomposites are divided into several types based on a variety of factors. Sol gel process, in-situ polymerisation, solution mixing process, melt mixing process, and in-situ intercalative polymerisation are some of the preparation processes. Mechanical, optical, rheological, flame retardancy, and dielectric behaviour of nanocomposites have all been thoroughly examined. Finally, the major uses of nanocomposites as well as their future prospects have been discussed.

Keywords - Composite materials, nanocomposites, polymerization, flame retardancy

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INTRODUCTION

For specialised applications in today's modern world, a variety of multifunctional materials with suitable mechanical, thermal, electrical, and chemical properties are required. Composites are a type of material that offers a lot of potential for developing multifunctional innovative materials that are needed for new technological developments.

Composite materials can provide a desirable set of qualities that can be adjusted to meet the unique requirements for a given application by mixing two chemically or physically distinct materials. Traditional materials such as metals, ceramics and metal alloys, polymers, and other polymers are unable to provide such a mix of qualities.

COMPOSITES

A composite material is a multiphase material made up of two or more unique materials that has bulk properties that are significantly different from the individual components.

Generally, composites consist of two phases

a) **Matrix Phase**:

The primary continuous phase retains and supports the distributed discontinuous phase or filler material. It gives composites their basic structure, look, and environmental tolerance, among other things.

Dispersed In a discontinuous form, the secondary phase is embedded in the matrix. Because the dispersed phase imparts specific qualities that strengthen the matrix, it is also known as the reinforcing phase. In general, the dispersed phase is stronger and stiffer than the matrix phase, and it often provides the composites with good thermal, electrical, and other properties.

The diverse components of composites do not blend together, remaining separate and distinct at the microscopic level, despite working together to provide the composite material unique qualities that could not be produced independently.

Composites have been utilised in the form of mud bricks packed with chopped straw, bows formed of glued layers of wood, bone, and horn, and concretes made of gravels, cement, and sand since ancient times. Wood made of cellulose fibres in a lignin matrix, human bones made of hydroxyapatite and fibrous protein (collagen), sponges with a fibrous skeleton and silica or calcium carbonate spicules, and so on are examples of composite materials.

Composite material development for a variety of advanced technical applications is a constantly growing field. The most extensively utilised materials are various composite materials with exceptional characteristics. For structural, electrical, thermal, electrochemical, electroptical, environmental, and medicinal applications, they are widely employed. Because of their superior mechanical strength, chemical resistance, increased flexibility, low weight, low power consumption, and cost effectiveness, composites have considerable potential for structural applications. For use in the electrical industry, composites can be engineered to have integrated electrical, optical, power generating, and magnetic capabilities. Biomedical applications benefit from composites with specialised mechanical and biological qualities.

b) **Phase**:

NANOCOMPOSITES

Nanocomposites materials have gotten a lot of interest in the contemporary nanotechnology era because of their unique combination of features that make them superior to traditional composite materials.

Nanocomposites are composite materials in which the dispersed phase has at least one dimension in the nanoscale range. Nanocomposites provide a number of advantages over traditional composites, including:

i) Lighter weight due to low filler loading

ii) Low cost due to lower amount of filler use

iii) Show substantial enhancements in following properties at very low loading offiller

- Mechanical strength, modulus
- Decreased permeability to gases
- Thermal stability
- Flame retardancy
- Chemical resistance
- Improved surface appearance
- Electrical conductivity

In comparison to typically filled polymers, optical clarity Because of the enormous surface area to volume ratio of the nanoscale dispersion phase or nanofillers, nanocomposite materials have a unique set of good features that make them multifunctional. The high interfacial area between the polymer and the nanoparticle is important in determining the characteristics of the nanocomposite. Because surfaces and surface properties regulate many chemical and physical interactions, a nano-dimensional material will have significantly different properties than a larger-dimensional material of the same composition. As a result, the resulting nanocomposites have increased multifunctional characteristics while using less nanofiller and costing less. The transition from microparticles to nanoparticles, according to Hussain et al., has a significant impact on the physical characteristics of polymers. Kubaca et al. (2019) found that polymer nanocomposites containing TiO2 nanoparticles as a filler have a greater cytocompatibility than microsized TiO2 particles. These nanocomposites have a wide range of applications in electronics, ionics, mechanics, energy, the environment, biology, optics, medicine, functional smart coatings, solar cells, fuel cells, catalysts, sensors, and other fields.

POLYMER NANOCOMPOSITES

Polymer nanocomposites are fast growing as a multidisciplinary research endeavour with the potential to widen polymer applications to the benefit of a wide range of industries. Researchers' attention has switched to polymer matrix based nanocomposites as the demand for light weight and versatile materials grows. Metal and ceramic nanocomposites are significantly less common than polymer nanocomposites. Because of the following fundamental qualities that are not found in metals and ceramics matrix materials, polymers are considered to be suitable hosting matrices for composite materials with a wide variety of inclusions such as metals, semiconductors, carbon nanotubes, and magnetic nanoparticles.

- Polymers with low densities.
- The polymers are easy to produce and fabricate.
- Because of the minimal energy input, a low processing and curing temperature reduces manufacturing costs significantly.
- The large range of polymers available, each with its own unique characteristic feature, makes them appealing for building composites with a variety of qualities.
- The ability to modify and

functionalize the surface.

- Excellent corrosion resistance
- Color effects that are pleasing to the eye

Polymeric materials have a wide range of qualities, allowing them to be used in a wide range of applications, including structural applications, cars, electronic items, optical devices, biological materials, aircraft components, and many more. Figure 1 illustrates some polymer instances. However, as compared to metals and ceramics, polymers have several drawbacks, such as weak mechanical and electrical properties. Consider the following scenario: Polypyrrole is a conductive polymer with favourable chemical and electrical properties that is limited in its usage as biological, electrochemical, and sensing devices due to its low mechanical strength. Many polymers, including homopolymers, co-polymers, blended polymers, and others, are insufficient to compensate for these qualities. Reinforcing polymers with multiple organic/inorganic fillers is one technique to increase the performance of the virgin polymer. Heat resistance, thermal conductivity, and electrical conductivity can all be increased with this method while critical aspects of the polymer matrix are preserved. Improved For polymers loaded with various types of nanoparticles, catalytical, electrochemical, mechanical, magnetic, electrical, optical, and biological properties have been reported.

Many research organisations have attempted to develop nanocomposite materials and have seen success in enhancing various qualities. Barari et al. [2019] developed polymer nanocomposites including Si, SiO_2, and SiC with excellent high temperature and abrasion resistance capabilities, as well as the polymer matrix's flexibility. Polystyrene-clay nanocomposites were found to have better thermal and mechanical properties in another study. The addition of 4 percent TiO_2 nanoparticles improves the mechanical characteristics of unsaturated polyester resin significantly. Bircuk et al. (2020) found an increase in thermal conductivity in epoxy-CNT nanocomposites. Using extremely small amounts of nanofillers, Bharadwaj et al. [2018] demonstrated that the transparent qualities of polymers may be maintained in polymer nanocomposites with sufficient improvement in mechanical and heat resistance capabilities. Chen et al. (2019) discovered that it is possible to create composite materials with emissivities lower than the basic elements. Morgan et al. [2016] shown that naocomposites of polymers with nanoclays increase flammability qualities significantly.

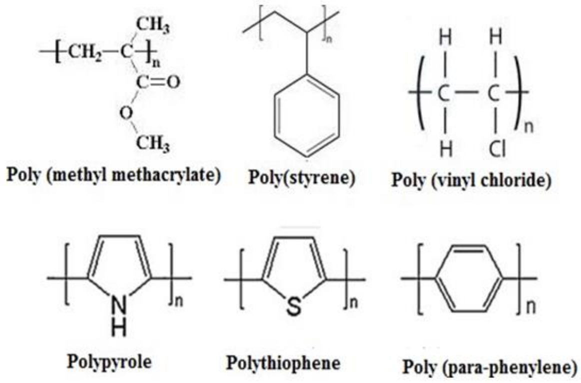

Figure 1: Examples of Polymers

Switching from an insulating to a conducting polymer matrix cleared the way for novel polymer nanocomposites applications in the electronic area, including conductive paints, memory switches, electromagnetic shielding, rechargable batteries, nanoelectronics, smart materials, and so on. Conducting polymers combine the electrical properties of metals with the benefits of polymers, such as ease of manufacture and low cost. Because of the multifunctional features generated from both the polymer and the nanoparticle, research on conjugated polymer nanocomposites has already gained international attention. The electrical and magnetic characteristics of nanocomposites of conjugated polymers with metal oxides such as Fe_2O_3 are particularly fascinating. The electrical and mechanical properties of nanocomposites comprising conducting polymers and carbon nanotubes (CNTs) have been discovered to be greatly improved. A number of studies have focused on combining metal nanoparticles (Au, Pt, etc.) with conducting polymers to create nanocomposites for opto-electronic devices that take advantage of metal nanoparticles' optical capabilities.

CONDUCTING POLYMER NANOCOMPOSITES

Because of their potential application in the technical sphere, scientists are becoming increasingly interested in the electrical properties of polymer nanocomposites. Conducting polymer nanocomposites are polymer nanocomposites in which at least one of the phases is an electrical conductor and shows electrical characteristics. As illustrated in Figure-2, it can be made with a conducting polymer matrix or a non-conducting polymer matrix with a conducting filler (metal nanoparticles, carbon, graphite, CNT, etc.).

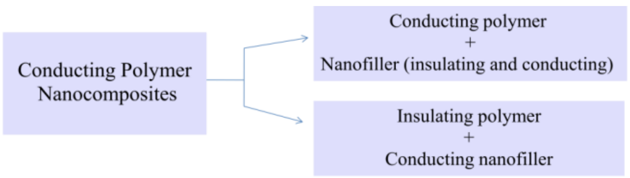

Figure 2: Constituents of Conducting Polymer Nanocomposites

Because of its low density, design flexibility, ease of processing, excellent conductivity at low filler loadings, and ability to integrate a wide variety of functions on a single platform, conducting polymer nanocomposites have piqued the interest of many scientists across the world. There have been numerous reports on the use of these polymeric nanocomposites in nanoelectronic devices, optoelectrical devices, sensors, and ion selective electrodes. For such applications, appropriate conductivity is usually required, which can be achieved through careful selection of filler/matrix materials and manufacturing conditions. Because the whole library of polymers and nanofillers is available, chemistry and processing may be used to regulate both electrical and mechanical properties.

METHODS OF SYNTHESIS OF POLYMER NANOCOMPOSITES

The enormous potential of polymer nanocomposites in a wide range of sectors has sparked a lot of interest in their manufacturing. The following are the methods for synthesising polymer nanocomposites that have been documented in the literature:

- **Direct Mixing Method**:

Direct dispersion of nanoparticles in the polymer matrix increases the viscosity of the polymer, making the composite moulding process more challenging. Low viscosity thermosetting matrices, such as epoxy resins, are commonly utilised in this process.

- **High Shear Mixing:**

To deagglomerate and disseminate the nanofillers, high-shear forces are used to mix them with the polymer resin. These shear forces are insufficient to adequately disseminate the nanofiller in the polymer matrix.

- **Melt Processing Method:**

The nanofillers are directly incorporated into the molten polymer employing high shear stresses in this approach. Because of its ease of use, economic viability, and capacity to produce vast quantities of materials at once, the melt processing method is the most often utilised technology in industry. The downside of this method is that the nanoparticles may shatter during blending, such as extrusion, and lose their high aspect ratio.

- **Solvent Processing Method:**

Solvent processing consists of three steps: dispersing the filler in a suitable solvent (typically with the addition of external energy, such as ultrasonication), adding the polymer (which must also be soluble in the solvent), and evaporating the solvent. This technology is straightforward and delivers greater nanofiller dispersion inside the polymer matrix, which is also repeatable due to the easy procedure. With tiny sample sizes, it works nicely. However, this process necessitates the polymer's solubility in one or more solvents, complete solvent elimination during drying, and the resulting film is not easily scalable.

- **In situ Polymerisation Method:**

The fillers are often combined with monomers using ultronic forces, high shear forces, and other techniques, with or without the use of a solvent. The polymerization procedure is then carried out by introducing an initiator and controlling variables like temperature and pressure. This method is said to create a strong bond between the polymer and the nanofillers. It offers many of the same advantages of good dispersion but without the need for a solvent to dissolve the polymer. Carbon-based nanomaterials such as CNTs, nanographite, and other carbon-based nanomaterials can potentially participate in the polymerization process using this approach. Nanotubes can be begun by an initiator (AIBN) to open their -bonds, which can then participate in polymerization and generate covalent bonds between the nanotubes and the PMMA matrix, according to Jia et al.

- **Functionalisation of the Nanofiller or the Polymer Matrix:**

Enhancing interfacial interactions by functionalizing either the nanofiller surface or the polymer matrix increases the quality of the interface between two components of the nanocomposite.

APPLICATIONS OF CONDUCTING POLYMER NANOCOMPOSITES

Polymer nanocomposites have a wide range of possible applications, spanning from automotive to packaging to electrical and electronic industries, due to their exceptional characteristics. The following are some of the electrical applications of conducting polymer nanocomposites:

- **Polymer Nanocomposite as Nanoelectronic Devices**

Electrically conducting polymer nanocomposites are becoming a hot topic in study for applications in light weight flexible electronics such as liquid crystal displays (LCD), light emitting diodes (LED), and so on.

- **Polymer Nanocomposites as Catalysts**

Because the conductive polymer matrix promotes and enhances the passage of electronic charges to the catalytic centres, polymer nanocomposites with metals have been found to be effective catalysts. Huang et al., for example, produced a PANI/Au nanocomposite modified electrode with improved electro catalytic activity for NADH oxidation.

- **Polymer Nanocomposites as Energy Devices**

Many conducting polymer nanocomposites have been used in energy conversion and storage devices such as solar cells and fuel cells.

a) Solar panels Conducting polymer nanocomposites with metal oxide inclusions are of special relevance for solar cell production because they combine the light-absorbing properties of metal oxides with the hole-transporting properties of conducting polymers, potentially improving photovoltaic efficiencies. P3HT/ZnO composites, PEDOT:PSS/CNT composites, and other conducting polymer nanocomposites solar cells are examples.

b) Fuel cells Conducting polymer nanocomposites, such as PPy-Co-MWCNTs nanocomposites, are utilised as cathode elctrocatalysts in a polymer electrolytic fuel cell to reduce oxygen.

c) Lithium-ion Batteries- Lithium-ion batteries, which are lighter and have a higher capacity than traditional nickel-metal hydride batteries, are commonly used in cell phones, computers, and other electronic devices. Conducting polymer nanocomposites have recently been shown to be good materials for Li-ion battery electrodes because they have a wide surface area in contact with the electrolyte.

d) Supercapacitors These energy storage systems are the most promising for a wide range of commercial and military uses. PEDOT/CNT nanocomposites, which are conducting polymer nanocomposites like PANI/CNT nanocomposites, have been reported to be excellent supercapacitor materials.

- **Microwave Absorption and EMI Shielding**

Electromagnetic interference shielding materials made of conducting polymer nanocomposites have been discovered to be effective in protecting electronic equipment from electromagnetic interference. PANI/CNT nanocomposite, for example, can be used for shielding.

- **Polymer Nanocomposites in Biomedical Field**

Drug delivery, nanomedicine, bioimaging, and possible cancer therapy are just a few of the biomedical applications for polymer nanocomposites. Because of their enormous surface area and reversible electrochemical reaction, conducting polymers like PEDOT/PLGA have been employed for controlled medication release.

- **Polymer Nanocomposites as Sensors**

Polymer nanocomposites showed to be a potential choice for detecting a range of compounds due to the conductance altering as a function of the extent of surface adsorption or chemical contact, large specific area. The tidy conducting polymers are good sensing materials in and of themselves, and the addition of high aspect ratio nanomaterials such as CNTs, metals, and other materials improves the sensing characteristics even more. PPy/MWCNT as an NH_3 sensor, PANI/In_2O_3 as an H_2, CO, NO_2 sensor, P3HT/MWCNT as a chloromethane gas sensor, and so on are some examples of conducting polymer nanocomposite sensors. PANI/Fe_3O_4/CNT nanocomposite doped with enzyme for glucose detection and other conducting polymer nanocomposites have also been employed as biosensors.

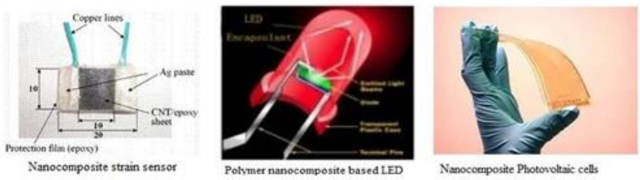

Figure 3: Examples of Applications of Polymer Nanocomposites

Figure 3 depicts some instances of polymer nanocomposite as electronic devices. Conducting polymer nanocomposites may be used to make chemical sensors and are a great tool for doing so. Researchers have made significant progress in the manufacture of sensors utilising conducting polymer nanocomposites, leading to the rapid development of polymer nano composites as sensors.

CONCLUSION

Controlling the dispersion of nanoparticles in polymeric matrices is the most significant impediment to the development of high-performance polymer nano composites, because the dispersion of these particles and their interfacial interactions with the polymer matrix are the most important factors affecting the nanocomposites' optimal properties. When nanofillers are disseminated in a polymer matrix, they are more likely to agglomerate, resulting in poor interfacial mixing and preventing nanocomposites from reaching their full potential. Polymer/CNT nanocomposites were severely weakened due to insufficient CNT dispersion. The dispersion of clay particles in the matrix is connected to the storage modulus and thermal stability of polypropylene-clay nanocomposites, according to the findings. Because of their layered structure, high aspect ratio, inert nature, and poor wettebility towards polymer matrix, nanographitic platlets, like other nanofillers, are prone to restacking. The key to achieving a high aspect ratio, huge interfacial area, and strong interfacial contacts between nanofillers and polymer matrices is overcoming the massive van der Waals-like forces between nanoparticles. To improve the properties of polymer nanocomposites, the most difficult problem is to disperse nanoparticles well in polymer matrices and optimise polymer-nanoparticle interaction at their interface.

As a result, developing a simple and processable method for dispersing nanofillers uniformly in the polymer matrix has become a major difficulty.

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