

A Comprehensive Review on Polymer Nanocomposites; Classification, Properties and Potential Applications

Ayesha Khan¹, Sadia Iqbal¹, Mehrab Khan¹, Fauzia Iqbal², Sara Musaddiq¹, Warda Masoom¹, Amna Sarwar¹

¹Department of Chemistry, the Women University Multan 66000, Pakistan

²Department of Physics, University of The Punjab, Lahore, Pakistan

Corresponding Email: drsara.chem@wum.edu.pk

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Abstract:

Polymer nanocomposites have been discovered in the last three decades. Recently, polymer nanocomposites have been making a large impact in the media and throughout several industries. Therefore, a systematic review on the classification, synthesis, and applications of polymer nanocomposites is extremely important. This review paper critically focuses on the three fundamental aspects, classification, properties, and applications to gain profound insights into polymer nanocomposites. It includes in-depth studies of the classification of polymer nanocomposites based on size, dimensions, and kinds of nanofillers. Various techniques are used to prepare polymer nanocomposites. This review also provides valuable applications in various engineering and medical fields.

Keywords: Polymer nanocomposites, Nanofiller, Polymer matrix, Tissue engineering, Drug delivery, Biosensors.

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1. Introduction

One of the most interesting composite materials are created by mixing polymer with inorganic and organic nanofillers and are called as polymer nanocomposites. Polymers are formed by combining monomers with different distinctive qualities, such as low specific gravity, flexibility high tensile strength, and plasticity etc. Since the properties of polymers is not very high, they have limited application in the formation of materials and structures on their own. For example, polypyrrole is highly conducting polymer which is used in biosensing devices, lithium batteries and actuators due to their optical and electric characteristics. However, the uses are limited due to poor mechanical characteristics of polypyrrole. In order to address these drawbacks polymer nanocomposites are created to improve the characteristics of polymers and broaden their applicability [1].

One billionth part of a meter is called a nanometer, and nanomaterials are substances with components that are less than 1 nm in at least one dimension. Physical properties change as particles grow from micro to nano size. Nanoscale materials have a vast surface region over volume proportion. Hence, many important chemical and physical interactions are controlled by surface properties. The surface area per unit volume of particles and fibers is inversely related to the size of the substance; the higher the surface area to volume ratio, the smaller the diameter [2]. As a result, as particle size decreases, a higher percentage of atoms are found at the surface than inside. Chemically, it increases the reactivity of materials and surface characteristics. Two main features that cause the characteristics of nano substances to differ significantly from other substances are large surface area and electromagnetic impacts [3].

Nanocomposites comprise at least two distinct composites having various physical and chemical characteristics. The incorporation of composite materials shows high-level performance and unique properties. Generally, they are composed of various phases divided by an intermediate layer. Because of this, a nanocomposite exhibits unique qualities that cannot be achieved using any of the components alone. The reinforcement process enhances the qualities of nanocomposites. The word "matrix" refers to the component which is present in a greater quantity. Nanomaterials in the form of reinforcement are similar to nano-fillers. Due to their constituents, nanocomposites exhibit anisotropy and inhomogeneity in the reinforcement. Alternatives that work around stoichiometry restrictions are nanocomposite materials. Nanocomposites are divided into categories, depending on their mode of construction. Different types of nanoparticles and matrix materials are used [4].

Nanocomposites are divided into three types by the type of matrix substance used. They are Ceramic Matrix Nanocomposites (CMNC), Metallic Matrix Nanocomposites (MMNC), and Polymer Matrix Nanocomposites (PMNC).

Table 1: Types of materials and their nanocomposites

Material	Nanocomposites
Metal	$\text{Al}_2\text{O}_3\text{SiC}$, SiO_2/Ni , $\text{Al}_2\text{O}_3/\text{SiO}_2$, $\text{Al}_2\text{O}_3/\text{TiO}_2$
Ceramic	Mg/CN , Co/Cr , $\text{Fe-Cr}/\text{Al}_2\text{O}_3$, Fe/MgO
Polymer	polymer/layered Category, silicates, polymer/CNT, Thermoplastic/thermoset, polyester/ TiO_2 , polymer/layered double hydroxides

Polymer nanocomposites are nano substances created by combining a polymer matrix and nanoparticles [5]. Monomers are combined to form polymers. Polymer nanocomposites are inorganic nanoparticles scattered all over the polymer matrix [6]. Through the synergistic interaction of the two constituent materials, these formations unite the finest qualities of all constituents. These involve improved chemical, electronic, mechanical, ionic, and other characteristics that can be used in various ways [7]. Polymer nanocomposites is one of the most studied and researched nanocomposites. Pie chart in figure 1 shows the % share of all kind of nanocomposites [8].

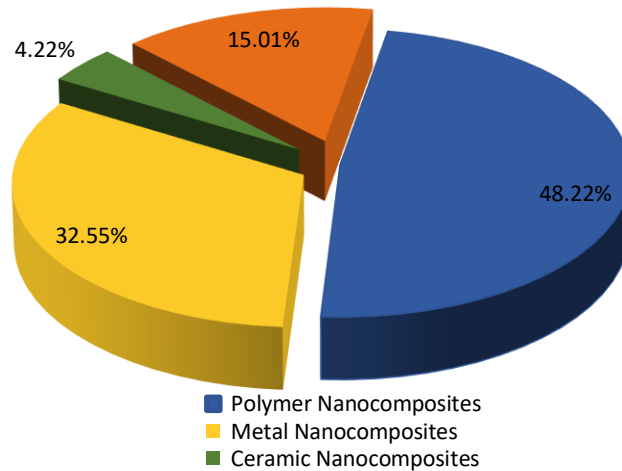


Fig. 1: Pie chart describing the % share of all types of nanocomposites.

Polymer nanocomposites can be created by mixing inorganic substances with various qualities with an organic polymer matrix's processability and flexibility. Polymer nanocomposites are made of a polymer matrix implanted with nanoscale materials. Combining monomers with flexible, light, and durable properties results in polymer nanocomposites [9].

2. Classification of polymer nanocomposites

Polymer nanocomposites are classified on the basis of size of nanofiller, kind of nanofiller, type of polymer matrix, method of fabrication.

2.1 Classification on the basis of the size of Nanofillers

We can divide nanofillers into three groups based on their size.

2.1.1 Zero-dimensional spherical nanofillers

These nano-sized particles have dimensions in any direction, e.g., silica nanoparticles and ZnO quantum dots. Their size does not extend any further than 100 nm. They are primarily spherical. They can be made of metal, ceramic, crystalline, or amorphous material. Researchers also developed CdS nanodot-/xanthan-agar-based nanocomposite. It removes organic dyes because of their luminescent properties [9].

2.1.2 Single-dimensional fibrous Nanofillers

Single-dimensional nanofillers, like nano-graphene platelets, nanotubes, and nano prisms, have dimensions in only one direction. They have the shape of a pointer. A gel made of alginate and single dimensional silver nanofiller has been used to make electronic devices. This nanofiller is in the form of nanosheets, nano clay, and nanorods [10].

2.1.3 Two-dimensional nanofillers

These nanofillers have dimensions in just two directions. Examples include layered silicates, graphene, MXene, carbon nanotubes, nano-whiskers and nanofibers. To observe the properties of the solution, -cyclodextrin-complexed montmorillonite nanocomposites were made [11].

2.1.4 Three-dimensional nanofillers

These are the nanofillers having nano range dimensions in three directions. Zeolites, nanogranules, nanoclays, and equivalent nanomaterials are excellent examples of three-dimensional nanofillers. Researchers have developed nickel hydroxide nanometals, including polymers reliant on nanocomposite electrodes. In green tea, it is used to detect late epigallocatechin-3-gallate [12].

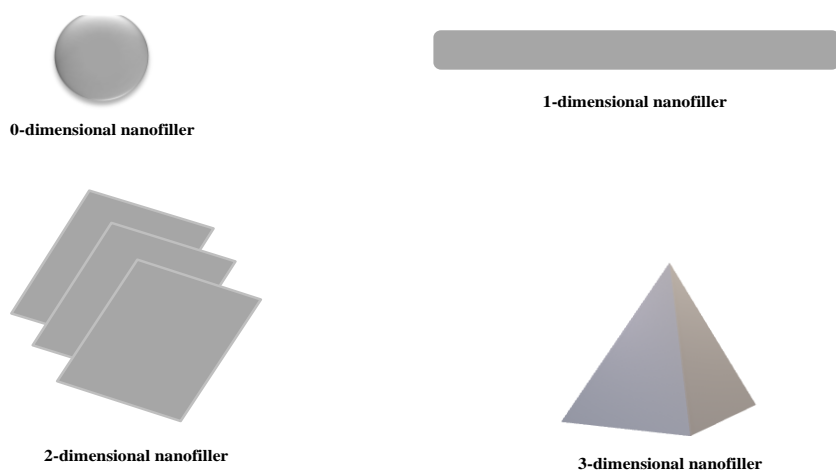


Fig. 2 Schematic diagram of kinds of nanofillers

2.2 Classification on the basis of kind of nanofiller

We can divide nanofillers into three groups based on their size.

2.2.1 Metal Sulfide/Polymer Nanocomposites

A metal sulfide nanomaterial improves a nanocomposite's thermal equilibrium more than a polymer matrix. It is because of the loss in the leavening of substances. Additionally, heat energy is slightly displaced in the polymeric network because metal sulfide fillers are present in the interstitial areas. Polymeric materials absorb metal sulfides like CdS, PbS, and ZnS, along with a low phase movement leading to chain transfer. There may be numerous ways to fabricate this type of nanocomposites. However, the best methods are hydrothermal and thermal degradation techniques. For example, developing a nanocomposite film based on zinc sulfide/sodium carboxymethyl cellulose [13].

2.2.2 Metal Hydroxide/Polymer Nanocomposites

These nanomaterials are famous for their flame inhibition activities. Nanofiller is widely used by magnesium and aluminium hydroxides in the form of cables and cords. The polymer composites can be poly (vinyl chloride), elastomers, polyphenols, and polyester. Endothermic decomposition of metal hydroxides begins with temperature rise. Compatible substances have incombustible elements such as water vapour and carbon dioxide that decrease the number of combustible gases. Moreover, magnesium oxide and aluminium oxide are referred to as resistant powders. Thus, this may disable the internal heat processing of the substance. Including these filters on the external face forms a ceramic barrier or translucent coating. They work as flame retardants because they disintegrate endothermically, trapping heat at a temperature near that of polymers. A recyclable poly (lactic acid) and zinc-aluminium double hydroxide-dependent nanocomposite were modified as fire retardants [14].

2.2.3 Metal or Metal oxide / Polymer Nanocomposites

The nanofillers utilized here also offer thermodynamic equilibrium as well as a flame reduction on built-in nanocomposites. Metal oxides can be prepared by sol-gel method, sonochemical, hydrothermal process, and measurement techniques. For instance, nanofillers include ferric oxide, aluminium oxide, titanium oxide, Silica, lead oxide, and copper. A composite of an electrochromic substance consisting of polyaniline based nanofiber wrapped around tin oxide containing antimony and titanium oxide nanofibers has also been synthesized [15].

2.2.4 Silicate/Polymer Nanocomposites

The clay medium retards the transference of weight; therefore, no thermal impact is seen as a result of nonconducting. Therefore, these materials have a built-in flame resistance. Ion exchange and coprecipitation methods are used to fabricate a nanocomposite. This nanocomposite is made of ferric oxide and polymer embedded in layered silicate magadiite. It is used for the recuperation of rock oil [16].

2.3 Classification Based on the Type of Polymer Matrix

Nanocomposites that are classified on the basis of type of polymer matrix are thermoplastic polymers, thermosetting polymers, elastomers, natural and biodegradable polymers.

2.3.1 Thermoplastic matrix based polymer

These polymers can get shapes regenerated in the heat, followed by cooling. They can be remolded because there is covalent bonding. They get pulpy when subjected to heat and become firm on cooling [17]. For example, thermoplastic networks are composed of polyamides, polyethene, polystyrene, and poly (vinyl chloride ride) [18].

2.3.2 Thermosetting matrix based polymer

These polymers are slightly different from thermoplastics. They have a three-dimensional structure that is covalently bonded and, as a result, unable to be rebuilt under the influence of the heating-cooling method. These cannot be rectified after treatment. Sharp rubber, polyester, epoxy resins, and polyurethanes constitute these polymers [19].

2.3.3 Elastomer matrix based polymer

These polymers are stretchable substances that can be significantly expanded without any modification. They are very slimy and, therefore, known as viscoelastic. Such substances have delicate intermolecular potential. They exhibit a lower rate of Young's modulus of elasticity and a significant pressure rate. Chloroprene, natural rubber, and polybutadiene are examples of non-saturated plastic. Epichlorohydrin, fluoro-silicone rubber, fluoro-elastomers, and polyacrylic rubber are examples of pure plastic [20].

2.3.4 Natural and biodegradable matrix based polymers.

These polymers are those that occur by nature. These are also called biopolymers. These can also be modified over time by using microorganisms, aerobic, and anaerobic mechanisms. Collagen, albumin, chitosan, carrageenan, starch, gelatin, hyaluronic acid, and alginate are examples. They are very resilient, and elastic compared to other substances.

2.4 Classification based on the method of fabrication

Polymer nanocomposites have been fabricated using a variety of ways so far. The homogeneous scattering of nanomaterials within the matrix is the most critical prerequisite. Because nanofillers have the potential to clump together, it is necessary to include such substances within a matrix. Suppose they are to create large-sized particles. A macro-sized particle should not be created by combining two smaller particles. The following are some of the most commonly used methods [21].

2.4.1 By Intercalation Method

The homogeneous scattering of nanoparticles, e.g., clay elements, inside the polymeric matrix is the main purpose of this procedure. An external adaption of nanosheets is required to make the nanocomposites. The following are the two techniques that were used. In the **chemical method**, nanoplatelets swell in the monomeric solution and then monomer polymerizes to incorporate the platelets. In **mechanical method**, nanoplatelets dispersed in a solvent and polymers dissolved in a co-solvent are mechanically mixed together. The solvent is replaced from occupied sites as polymer components are incorporated in nanoplatelets [21, 22]. Melt intercalation is a sub-type of intercalation method in which the constituents, such as nanoplatelets and polymer, are fused to mix their melt solution under shear tension. It is similar to injection molding and protrusion methods used by the manufacturing industry. Melt blending is based on the relatively same idea and includes adding nanoplatelets to a melted viscous polymer solution at high temperatures and shear strain. Fiber production, injection molding, or compression molding follow the process. The melt compounding process creates intercalated nanocomposites made of HDPE and zinc montmorillonite. It is then tested for antibacterial efficacy [23]. Figure 3 illustrates the melt intercalation process [24].

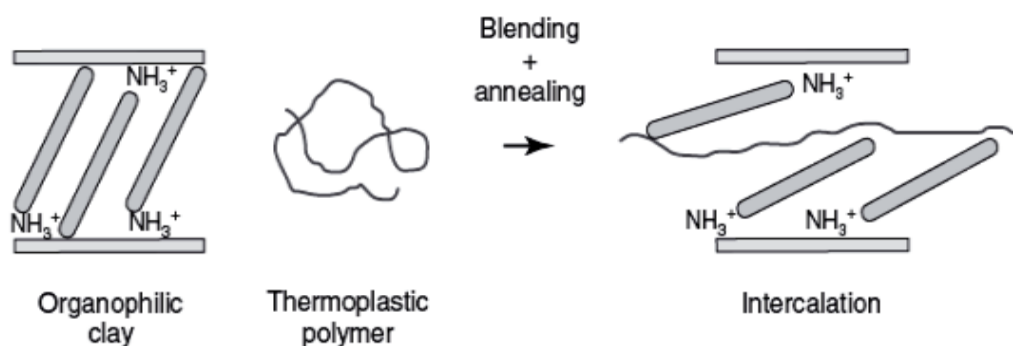


Fig. 3: Melt intercalation process

2.4.2 By In Situ Polymerization

This technique includes permeating monomer solution through the platelets as they enlarge. The monomer is then polymerized under heat, initiator, or UV light. As a result, exfoliated nanocomposite or layered nanocomposite is formed [22]. Another approach for controlling platelet size is in situ template synthesis. In this synthesis, polymer matrix and platelets are reflowed in water when subjected to high degree thermal energy with nucleation and diameter of platelets regulated by the polymer chain piercing them. However, this approach has the drawback of inducing polymer chain breakdown at high temperatures. To examine the electrochemical characteristics of polysaccharides and poly-pyrrole in the existence of COOH multi-layered carbon nanotubes, researchers developed the nanocomposites by in situ polymerization [25]. Figure 4 illustrates the In-situ polymerization method to make conducting and insulating polymers [26].

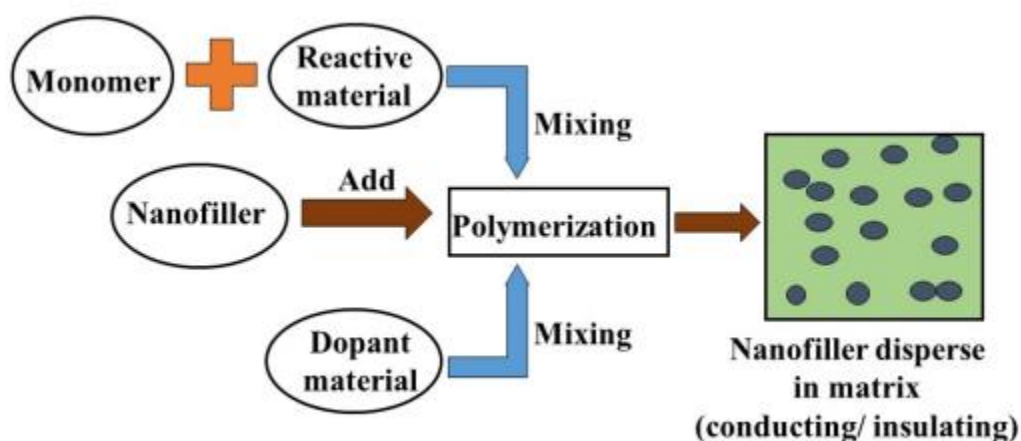


Fig. 4: In-situ polymerization method.

2.4.3 Sol-Gel Method

In this process, the fillers are disseminated in a monomer mixture called sol that penetrates the layers of filler. It leads to the creation of a polymer and nanoparticle network that is interconnected (called gel). As a result, polymer aids nanomaterial nucleation and growth. This strategy is a bottom-up strategy [21, 22]. Nanocomposite films were constructed by combining chitosan with salicylaldehyde and TiO₂ nanofillers [27].

2.4.3.1 Melt compounding

Melt compounding is the combining of nanofillers with polymer. It is done by keeping the polymer's glass transition temperature higher. The aggregated nanoparticles disperse as individual particles all over the polymeric matrix under the tensile force of molten and slippery polymer. This

approach does not necessitate the use of a solvent [22]. Figure 5 demonstrates the melt compounding method for fabrication of polymer nanocomposite [28].

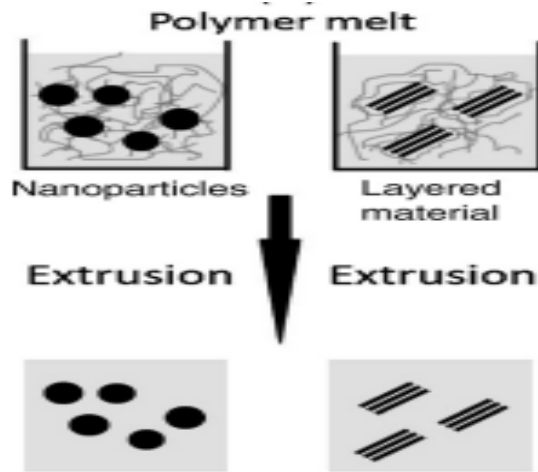


Fig. 5: Melt compounding method

2.4.3.2 Solvent extraction

It considers the nanoparticles' sono-chemical dispersion in a dissolvent, intermixing well with the soluble polymer in a co-solvent. The extract was vaporized or agglomerated towards the end to make nanocomposites. The shear stress is minor compared to the shear stress that appears when using the melt compounding method [22]. Figure 6 shows the solvent extraction method for making polymer nanocomposites [29].

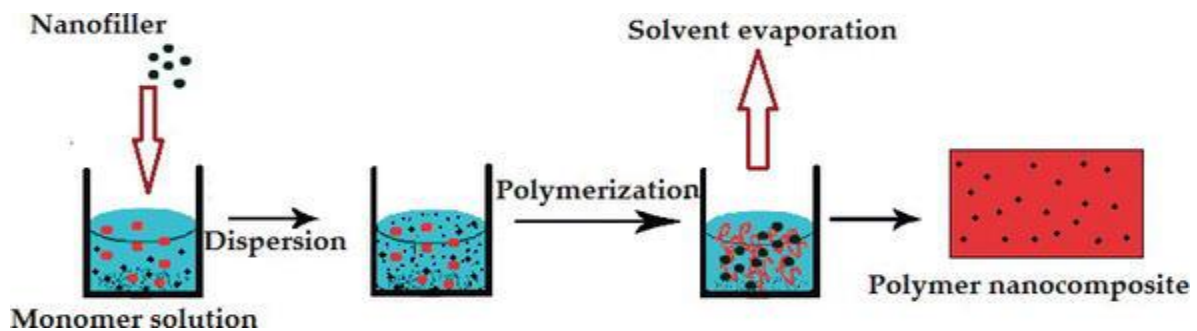


Fig. 6: Solvent extraction method

3. Methods for processing of Polymer Nanocomposites

There are a variety of ways to treat manufactured polymer nanocomposites. Some of them are thermoforming, calendaring, blow molding, injection molding, extrusion molding, casting, rotational molding, compression molding [21].

4. Properties of polymer nanocomposites

The characteristics of nanocomposites depend upon the method used in the fabrication of nanocomposites, types and orientations of filler materials, degree of two phases blending, adhesion type at matrix interface, the volume of nanoparticles used, properties of nanoparticles used, type of interphase that formed at the interface region, dimensions of the materials used as nanofiller, morphology of the system in addition to the characteristics of individual components [30, 31]. Nano-particles are evenly distributed throughout the matrix material to improve nanocomposites' qualities. Otherwise, there will be particle agglomeration, and the properties of nanocomposites will diminish. The nanoparticles should be evenly scattered throughout the matrix to obtain optimum property enhancement otherwise it will restrict the enhancement of the properties of the nanocomposite. Different types of nanoparticles in the matrix material are shown in figure 7. (a) good distribution but poor dispersion, (b) poor distribution and poor dispersion, (c) poor distribution but good dispersion, and (d) good distribution and good dispersion [32, 33].

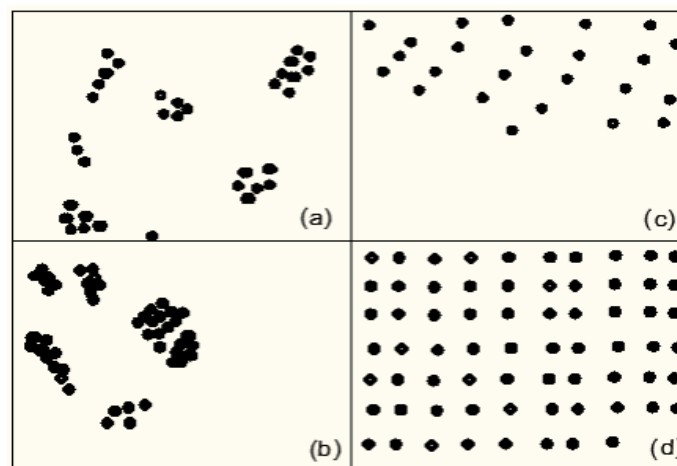


Fig.7 Distribution and dispersion of nanoparticles in the matrix

The type of interface between the matrix and the filler material significantly impacts the increase of the properties of nanocomposite materials. The development of an interface layer and the presence of a phase boundary between the matrix and filler material are the most prominent characteristics of polymer matrix nanocomposites. The interface's characteristics, composition, and microstructure are distinct from the matrix and filler and vary across the interface region. The overall characteristics of the nanocomposite will be more profound if the interface zone has good bonding between the matrix and filler material. The interfacial bond between the nano-filler and polymer matrix is strengthened. It can adjust the nanocomposite properties as most interphase properties depend on the bound surface. The ratio of filler to matrix surface area affects the interaction between the interconnecting phases. The large surface area of nanoparticles affects the

degree of interface phenomena which contributes to the characteristics of nanocomposites [34, 35].

Figure 8 shows that flexible polymer chains make up the structure of the space between the filler and the polymer matrix, often in sequences of adsorbed segments and unadsorbed segments. Unadsorbed segments exist as loops and tails that entangle with other polymer chains nearby and have no surface contact with the nanoparticle. Adsorbed segments have point contact with the nanoparticle surface in the form of anchors or trains. The degree of polymer chain entanglement, flexibility, and adsorption energy are just a few factors that impact the thickness of the interphase area. The interface structure determines the stress flow from matrix to filler [35]. Good polymer characteristics require excellent chemical or physical interactions between the host polymer and nanofiller. When interface adhesion is good, the interlaminar shear strength, corrosion resistance, dielectric characteristics, thermal properties, and flame retardancy all improve [34, 36, 37].

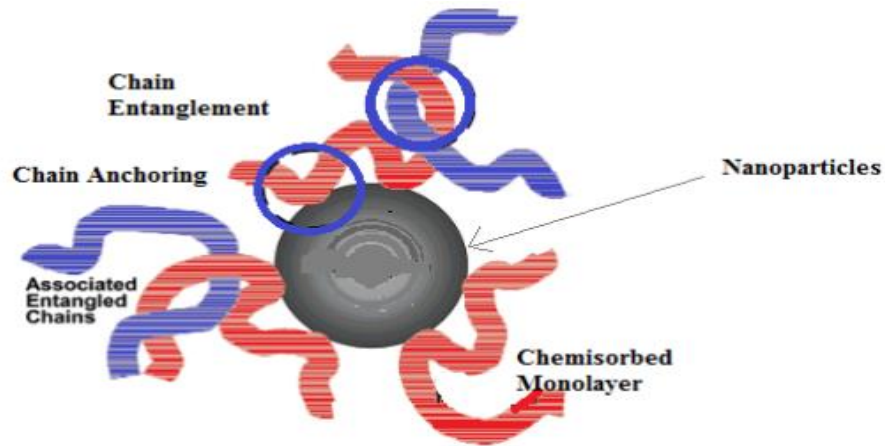


Fig.8: Interphase region between filler and polymer matrix

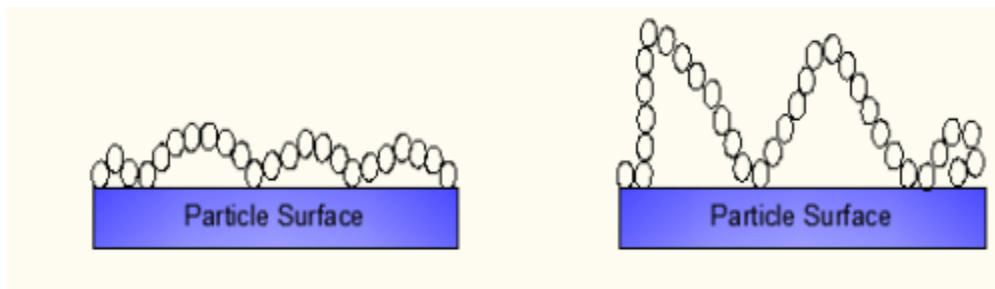


Fig. 9: Different type of polymer matrix adhesion with nanoparticle surface

Two different forms of polymer matrix adhesion with nanofiller material surfaces are depicted in figure 9 (a) Firm adhesion of polymer chains with nanoparticle surface and (b) Poor adhesion of polymer matrix with the nanofiller material surface [38].

A flat, dense layer covers the surface of nanoparticles due to the firm contact between polymer chains and the surface. Poor contact, however, causes a region of decreased density with polymer loops and tails extending into the matrix. According to the literature, when a particle's size is in the nano range, it is possible to see significant changes in the particle's attributes. Additionally, the contact at the phase boundary greatly enhanced as the dimension approached the nanoscale, improving the material's properties. Additionally, the aspect ratio, shape, and orientation of the nanoparticles affect how much the characteristics of the host polymer change. Nanoparticles with a high aspect ratio have a larger surface area than those with a low aspect ratio, and this aspect ratio is crucial for improving the characteristics of nanocomposites. Asymmetric nanoparticles, such as carbon nanotubes or layered silicates, significantly improve polymer characteristics (such as viscosity, shear modulus, and tensile strength) compared to symmetrical nanoparticles with spherical shapes, etc. Compared to highly symmetric nanoparticles and elongated rod-like

nanoparticles, sheet-like nanoparticles significantly improve polymers' mechanical and gas permeability [39, 40].

The microstructure of nanocomposites determines their characteristics. Structure-property relationships of polymer nanoplatelet composites are determined by their morphological characteristics. It is difficult to disperse nanomaterials in non-polar polymers, but homogeneous dispersion of nanoplatelets ensures high-quality composites. The microstructure of layered nanocomposites can be categorized as exfoliated, intercalated, and phase-separated. It depends on processing methods, component types (layered silicate, organic cation, and polymer matrix), dispersion methods, and the interaction between polymer matrix and layered nanomaterial (aggregated) [28]. When the polymer is unable to intercalate between the silicate layers, a phase-separated (aggregated) composite is created, and its properties are almost identical to those of traditional micro composites (Figure 10(a)). In intercalated nanocomposites, the polymer chains intercalate into the silicate layers in crystallographic regular order. This intercalation is regardless of the clay-to-polymer ratio. (Figure 10(b)) [41].

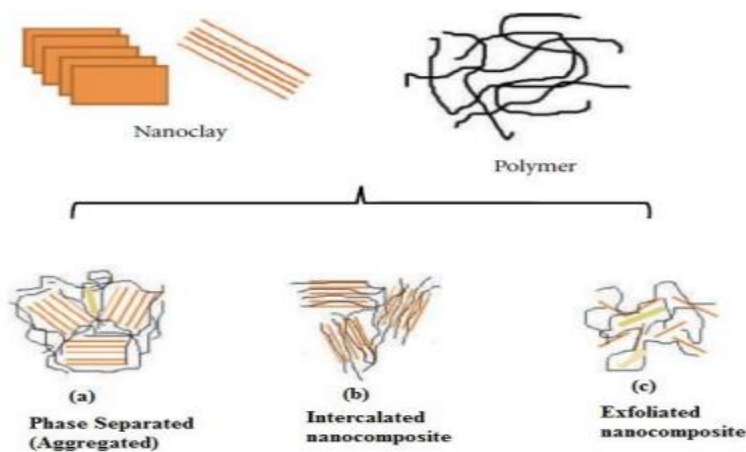


Fig.10 Different type of dispersion of clay layers in polymer nanocomposites

A well-ordered multilayer microstructure is generated using alternating polymeric and clay layers. The clay layers are entirely and uniformly disseminated in the polymer matrix of exfoliated nanocomposites. The average distance between the clay layers varies in a polymer matrix depending on the clay loading. An exfoliated nanocomposite typically contains fewer clay layers than an intercalated nanocomposite. Different kinds of clay layer dispersion in a polymer matrix are depicted in figure 10 [17, 42].

5. Applications of polymer nanocomposites

Polymer nanocomposites find their applications in almost every field of science and technology, from tissue engineering and drug delivery to high-speed cars and jets. It is impossible to cover all the applications of polymer nanocomposites, so only a few of them are discussed here.

5.1 Biosensors

Recently, polymer nanocomposites have increasingly drawn the attention of researchers for their use in the medical and biomedical fields. They have been exploited for a variety of biomedical applications, including biosensing devices. Biosensing devices, including immunosensors, aptamer sensors and glucose sensors, are discussed below.

5.1.1 Immunosensors

Due to quantum dots and metallic-based polymer nanocomposites, material scientists have recently become interested in electrochemical immune-sensing applications. In one study, graphene oxide nanosheet-polyaniline (GO-PANI-CdSe) to detect interleukin-6, nanowire-CdSe quantum dots) was developed. Polyaniline-graphene oxide nanocomposites have large surfaces, electrochemiluminescence properties, and high electrical conductivity. The sensor displayed enhanced selectivity and precision in finding interleukin-6 in humans [43]. PANI-AuNP PWEs (PANI-AuNP-altered paper working electrodes) have demonstrated biosensing applicability for detecting two tumor tissues. The first is a carcinoembryonic antigen, and the other is fetoprotein, both of which are present in human serum [44]. A Grp-AuNP-poly-DPB-AuNP-IL nanocomposite thin film-based immunosensor analyzes the microcystin-LR. The above sensor improves the $\text{Fe}(\text{CN})_6^{3-/4-}$ electron transport to the electrode [45].

5.1.2 Aptamer Sensors

An oligodeoxynucleotide or peptide created chemically is called an aptamer sensor. These can replace antibodies because they are more stable and have a higher affinity for the desired specific site than antibodies do. An illustration of an aptamer biosensor of daunomycin is AuNP-PS-aptamer-polyTTBA-AuNP-GCE [46]. Aflatoxin M1 was detected using Fe_3O_4 -PANI-IDE (interdigitated electrodes altered to PANI films incorporating Fe_3O_4). By using glutaraldehyde cross-linking, the aptamers were made immobile [47]. Poly(pyrrole-NTA)/ Cu^{2+} /HisTBA-Pt [poly (pyrrole-nitrilotriacetic acid) chelated with copper ions and histidine-riched thrombin sensor deposited on the surface of platinum]. It served as a tool for measuring thrombin levels. Aptamer sensors provide a wide range of different uses for polymer nanocomposites [48].

5.1.3 Glucose Sensors

Now the techniques for glucose sensing are using polymer nanocomposites more frequently. An electrochemically active polymer nano junction sensor for glucose detection was synthesized [49]. Researchers combined polyaniline hydrogel with Pt nanoparticles to create glucose enzyme biosensors. It efficiently catalyzes the breakdown of H_2O_2 , and glucose molecules get oxidized. Microporous PANI hydrogel immobilized the enzymes and absorbed them into water-soluble compounds. An ideal nanocomposite has a glucose sensitivity of $96.1 \mu A^3 mm^{-1} cm^{-2}$. At a detection limit of 0.7 M, the sensor's response time was 3 seconds [50]. Cu nanoparticle-based polymer nanocomposites were also created to identify enzymatic glucose. At a low detection limit, the glucose acuity was $1417.1 \mu A^3 cm^{-2} mM^{-1}$. Glucose sensors made of conducting polymer nanocomposites have excellent sensitivity, fewer detection limits, and a wide linear range and exhibit rapid response [51].

5.2 Tissue Engineering and Drug Delivery

The tissues that have been damaged are recovered through tissue engineering. By fusing the parent cells, this method creates new tissues [52]. The pore size of the substance must be optimized in scaffolds to provide the cells with the essential nutrients and eliminate metabolic waste from the cell body [53]. The creation of micro-engineered hydrogels uses a top-down strategy and a bottom-up method. A top-down approach primarily determines the micro-molding and shape-designing of scaffolds. This method makes use of relatively large hydrogel pieces on microscale features. On the other hand, the fabrication process uses a bottom-up approach by putting together smaller building blocks [54]. As bulking agents for urinary discomfort, collagen-based scaffolds that have been interlinked with glutaraldehyde are being used [55]. The most popular superabsorbent scaffolds for cartilage engineering are hydrogels made of alginate. These can either be implanted directly through injection or after being molded [56]. For in vivo and in vitro drug delivery systems, challenging issues include hydrogels with weak physical strength and considerable moisture-containing forms. These restrictions can be lifted by adding nanomaterials to the hydrogel's cross-linked matrix, including metal-based nanocomposites, graphene, and clay.

When the surface-area-to-volume ratio of nanomaterials grows, so does their surface reactivity to release bioactive components. Additionally, the nanomaterials' mechanical and biological qualities are improved [57]. Because nanomaterials can more easily enter tissues through epithelial cells, the therapeutic agent's ability to transport to the target through the lining and capillary sites could be improved for the most effective delivery [58].

Such materials show similarities with the extracellular cartilage matrix(ECM) [59]. Drugs can be released into the body in a controlled manner using hydrogel nanocomposites targeted infected tissue locations. Tyrosine-based silica-polycarbonate xerogel polymer nanocomposite is created for the controlled distribution of drugs. These nanomaterials combine ceramic fillers' mechanical qualities with biodegradable polymers' functionality [60]. Through a diffusion-controlled mechanism, the drug is delivered from the hydrogel matrix. The flow rate of the drug is wholly dependent upon the density gradient. The mechanism of drug diffusion is described in figure 11 [61].

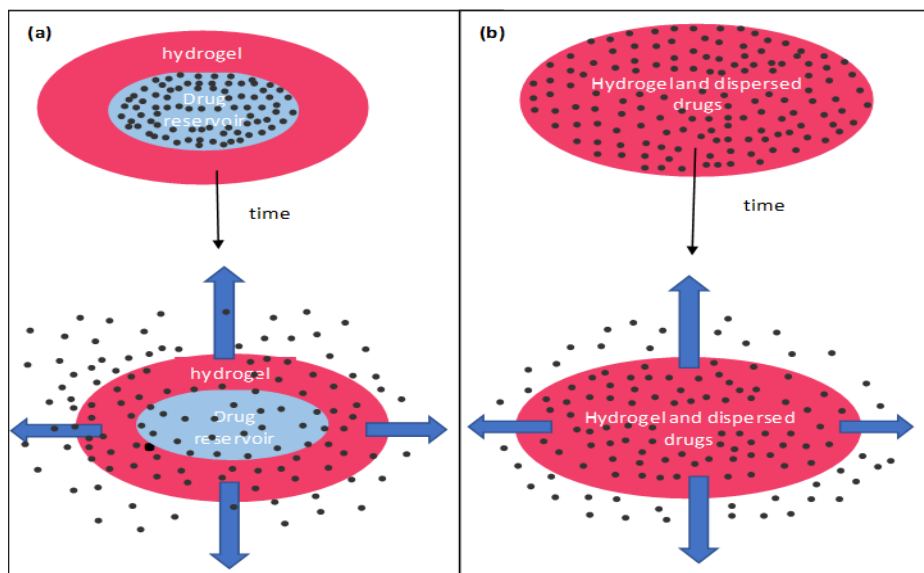


Fig. 11: Schematic diagram of drug release through hydrogel membrane in (a) reservoir system
(b) matrix system

5.3 Polymer Nanocomposites for Water Purification:

New materials are being found daily to extract harmful components from wastewater. Water contamination is mostly caused by industrialization, urbanization, and rising population levels [62]. All of the living things on our planet depend on water to survive. Thus, it is essential to filter out all contaminants from wastewater. From this perspective, the development of improved materials for cleaning water-soluble dyes and some other pigments has been made possible by polymeric nanomaterials [63]. Recent advances in nanocomposites have developed new techniques for removing and detoxifying organic and inorganic pollutants such as nutrients, heavy metals, cyanide, and biological pollutants from water [64].

Polymer nanocomposites are often used to remove organic contaminants from water and wastewater, such as medicines, personal hygiene products, pigments, microbes, agrochemicals, and humic and phenolic chemicals. Natural polymer nanocomposites reveal significant outcomes in removing organic pollutants from the surface, groundwater and wastewater. Various studies reveal a small number of pharmaceuticals (within the range of ng/L to mg/L) in the water. Long-term exposure to these pollutants may cause endocrine dysfunction and negatively affect humans and aquatic life. A graphite oxide/poly(acrylic acid) chitosan polymer nanocomposite was created by Kyzas et al. to remove dorzolamide from clinical wastewater [65].

Table 2: Polymer nanocomposites are used to remove different organic pollutants and their percentage removal efficiency.

Type of pollution	Source and name of pollutant	Polymer nanocomposite used for treatment	% Removal efficiency	(mg/m) Removal efficiency	Reference
Pharmaceuticals/ Personal care product	Dorzolamide	Graphite oxide/poly (acrylic acid) grafted chitosan nanocomposite		447	[65]
	Ciprofloxacin	Poly (styrene-block-acrylic acid) diblock copolymer/Fe ₃ O ₄ magnetic nanocomposite	97.5	15.52	[66]
	Fluoroquinolones	Magnetic mesoporous carbon/b-cyclodextrin chitosan	90.7 -99.7	130-165	[67]
	Benzophenone-3	Cellulose acetate/Zinc oxide-Zeolite nanocomposite	98%		[68]
Dyes	Methylene blue	Carbon dot @ zinc peroxide embedded poly vinyl alcohol (PVA/CZnO ₂) nanocomposite	98%	1972 ± 40	[69]
	Reactive Black 5	Starch/polyaniline nanocomposite	99	811.3	[70]
	Methyl orange	Glutaraldehyde cross-linked chitosan-coated Fe ₃ O ₄ nanocomposites	96 -98%	758	[71]
	Congo red	Chitosan/polyvinyl alcohol (PVA)/zeolite nanocomposite	94	5.33	[72]
Nutrients and Microorganisms	Bacillus subtilis	Polyvinyl-N-carbazole/single-walled carbon nanotubes	90%		[73]
	Staphylococcus aureus	Polyaniline/graphene nanosheets/carbon nanotubes nanocomposite	99.5		[74]
	Chemical oxygen demand	Multi-walled carbon nanotubes functionalized with amino polyethylene glycol and poly hydroxybutyrate	95.4 -99.7	950 -5000	[75]

	Escherichia coli	Qatarized chitosan organic rectorite intercalated composites	up to 90%		[76]
Pesticides/Herbicides	Atrazine	Poly(4-vinylpyridine-co-styrene)-montmorillonite	90 -99%		[77]
	Trifluralin	Polysulfide graphene oxide/TiO2 nanocomposite	73%	7.69	[74]
	Diuron	Nanocellulose organic montmorillonite nanocomposite	82.3%	69.04	[78]
	Permethrin	Chitosan zinc oxide nanocomposite	99		[79]
Humic and phenolic compound	Trinitrophenol	Poly-4-vinylpyridine-co-styreneemontmorillonite	90 -100	45.82	[80]
	4-nitrophenol	Polydimethylsiloxane carbon nanotubes porous nanocomposite	93%	25	[81]
	Humic acid	Poly (4-styrenesulfonate)ebentonite nanocomposite	87.6%		[82]

A wider range of polymers is employed in wastewater treatment operations to remove pollutants and particle debris. Numerous transition metal nanoparticles, including copper, titanium, iron, and palladium, are employed and examined for water filtration [83]. To extract reactive pigments and nickel ions from wastewater, Nguyen and Pho attached magnetic Fe₃O₄ nanoparticles to chitosan hydroxyapatite composite [84].

According to research, the interaction of amine groups with Au and Pd complexes and their coordination with oxygen and nitrogen atoms causes the adsorption of Au(III) and Pd(II). Amine groups were protonated in an acidic environment. Sand, fly ash, triethanolamine, tripolyphosphate, gold, silver, titanium, iron, and other materials have all been used to increase the adsorption capacity of chitosan nanocomposites. Sand, fly ash, alumina ceramic, triethanolamine, tripolyphosphate, gold, silver, titanium, iron, and other materials have all been used to increase the adsorption capacity of chitosan nanocomposites [85]

In addition to organic impurities, Table 2 shows different polymer nanocomposites used to remove various inorganic pollutants from wastewater along with their per cent efficiency removal.

Table 3: Polymer nanocomposites used to remove different inorganic pollutants and their percentage removal efficiency.

Source of pollutant	Name of pollutant	Polymer nanocomposite used for treatment	%Removal efficiency	(mg/m) removal efficiency	Reference
Heavy metals	Cadmium (II)	Polymerized acrylamide/2-acrylamido-2-methyl-1-propane sulfonic acid - montmorillonite	~100%	301.5	[86]
	Chromium (VI)	polyaniline/2-acrylamido-2-methyl propanesulfonic acid-capped silver nanoparticles/graphene oxide quantum dots	~100%	59.96	[87]
	Copper (II)	Layered double hydroxide/polydopamine/ α -amino phosphonate nanocomposite	-	105.44	[88]
	Cobalt (II)	Polyacrylamide (PAM)/sodium montmorillonite nanocomposites	98.67%	-	[89]
	Lead (II)	Poly(N-vinyl carbazole)-graphene oxide nanocomposite	97%	887.98	[90]
	Zinc (II)	Polypyrrole/sawdust nanocomposite	94.4-98.5	-	[91]
	Nickel (II)	Lignocellulose/montmorillonite nanocomposite		94.86	[92]
	Arsenic	Polyhydroxylbutyrate functionalized carbon nanotubes	100%	-	[93]
	Mercury	Nano-SiO ₂ -Crosslinked Chitosan-Nano-TiO ₂ nanocomposite	98-99.5%	1515.2	[94]
Non-metallic compounds	Nitrates	Polyethylene glycol/chitosan nanocomposite	-	50.68	[95]
	Fluorides	Polypyrrole/Fe ₃ O ₄ magnetic nanocomposite	-	17.6-22.3	[96]
	Perchlorate	Polypyrrole@CoNi-Layered double hydroxide	-	302	[97]
	Phosphates	Chitosan/Al ₂ O ₃ /Fe ₃ O ₄ nanofiber	-	135.1	[98]

5.4 High-speed Fibers

Very few tangled nanotubes resulted in the first attempt to make nanotubes, but this has sparked interest in these substances. More profound research resulted in the formation of methods for rotating nanotubes into nano fibers that are present in a polymer matrix, which is particularly interesting for use in the fabrication of both mechanical and electronic components [99].

Continuous sheets can be created by mixing a polymer with nanotube mats or knitted fibers, or it is possible to create films of a nanocomposite. The nanotubes will improve mechanical properties. Electrical conductivity, as well as the strength and stiffness of the film. Until recently, the only method of producing polymer fibers was extruding fibers with relatively large (micrometer diameter) sizes [100].

Recently, it was demonstrated that an electrospinning technique could effectively create pure composite material and polymer nanofiber with diameters ranging from 200 nm to 300 nm. More intriguing is the discovery of highly aligned nanoparticles in electro-spun nanofibers. Although no outcomes were reported, it probably significantly impacts the optical and physical characteristics. Due to their low cost and ease of mass production, polymer-based nanofibers are highly appealing for changing the refractive indices of interlinked optical fibers. They are used in various applications in the field of telecommunications as well as optical computing. It can be accomplished when nanofibers with different refractive indices are added to the polymer matrix [101]. Figure 12 shows the polymer nanocomposite fiber that is widely used in optical applications [102]

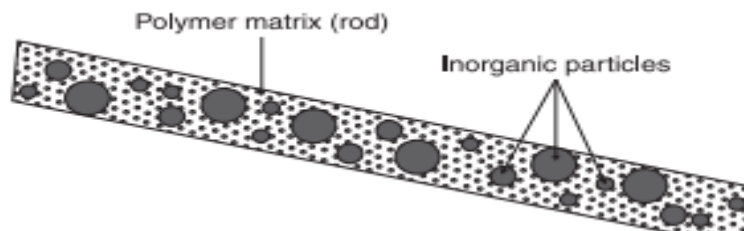


Fig. 12: Nanocomposite fiber.

5.5 Automotive Application

Polymeric nanocomposites exhibit superior physical characteristics, improved yield strength, impact resistance, enhanced abrasion resistance, excellent thermal properties, reduced cost, and reduced environmental effect [103]. They are suitable to replace materials in automobiles and other applications due to their warpage of components and improved impact resistance. The main factors influencing polymer use: The automotive industry uses parts with nanocomposite technology to reduce vehicle weight, superior performance, decrease CO₂ emissions, and increase

engine efficiency, which saves fuel (greater safety, increased comfort, and better drive ability) [104].

The industrialization of polymer nanocomposites began in 1991 with the release of nylon/clay nanocomposites by Toyota Motor Company, first for use in the production of timing belt covers for engines for their Toyota Camry automobiles. A step-assist automotive element produced polyolefin fortified with 3% nano clays, was introduced by General Motors in 2002. Polymer nanocomposites are advantageous for the automobile sector in several areas, including motors and power trains, shock absorbers and automatic braking, combustor pipes and carburetors, panels and components of the body, varnishes and protective coatings, grease, tires, and electronic equipment as shown in figure 13. Since then, numerous studies on nanocomposites have been conducted globally [105].



Fig. 13: Components of the car in which polymer nanocomposite are used

Conclusion:

In this review article, we have studied polymer nanocomposites in detail. Nanofiller components are included in polymer nanocomposites. It causes a "nano-effect" and significantly enhances the nanocomposite characteristics. The categorization of nanomaterials has been covered in this review, along with an explanation of each form of nanomaterial. The characteristics, manufacturing processes, and applications of several polymer nanocomposites are studied in

detail. This review paper also illustrates the various ways by which polymer nanocomposites can be prepared. There will be a considerable improvement in the polymer nanocomposites' characteristics, including their mechanical, gas barrier, flame-retardant, electrical conductivity, etc. Polymer nanocomposites have a lot of benefits over conventional nanomaterials. In this scenario, polymer nanocomposites are the materials most suited to satisfy growing demands from the scientific community. Polymer nanocomposites have enormous commercial potential. Applications for polymer nanocomposites have expanded due to the advancement of polymer nanocomposite technology. The development of polymer nanocomposites has led to an increase in the number of applications for these materials.

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