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REVIEW PAPER

Functional nanocomposites and their potential applications: A review

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Abstract

Herein, the review aims to compile some reportable work of researchers carried concerning the use of nanomaterials in the polymeric composites for significant improvements in the properties and to report the application areas of such nanocomposites. Carbon nanotubes, cellulose nanoparticles, titanium dioxide, and other nanoparticles are used in the polymeric composites to enhance their mechanical, electrical, inter-laminar, optical, chemical, electrochemical, electromagnetic shielding, and ballistic properties. Such nanocomposites have a wide range of applications in structural, biomedical, electronics, automobiles, aircraft, oil pipelines, gas pipeline construction, electromagnetic shielding, and protected areas. According to the reported results of researchers, the incorporation of nanomaterials into polymers significantly enhance their properties, which make them able to widen their application areas.

Keywords Nanomaterials · Nanocomposites · Carbon nanotubes · Cellulose nanoparticle · Biomedical properties · Energy harvesting

Introduction

Overview of nanotechnology

Nanotechnology is the field of applied science which deals with matter in the molecular and atomic scale, usually, 100 nm or smaller, and its usage in devices or materials lie in this range. Products are made from atoms and their properties depend upon the atomic arrangement. Further, Fig. 1 shows classifications and applications of nanotechnology [1–4].

Normally, nanomaterials size ranged from 1 to 100 nm. Its size is about 10^{-9} or one billionth of a meter. In the present scenario, these materials attract the attention of researchers due to their high surface to volume ratio which brings exceptional properties. The field in which the study of

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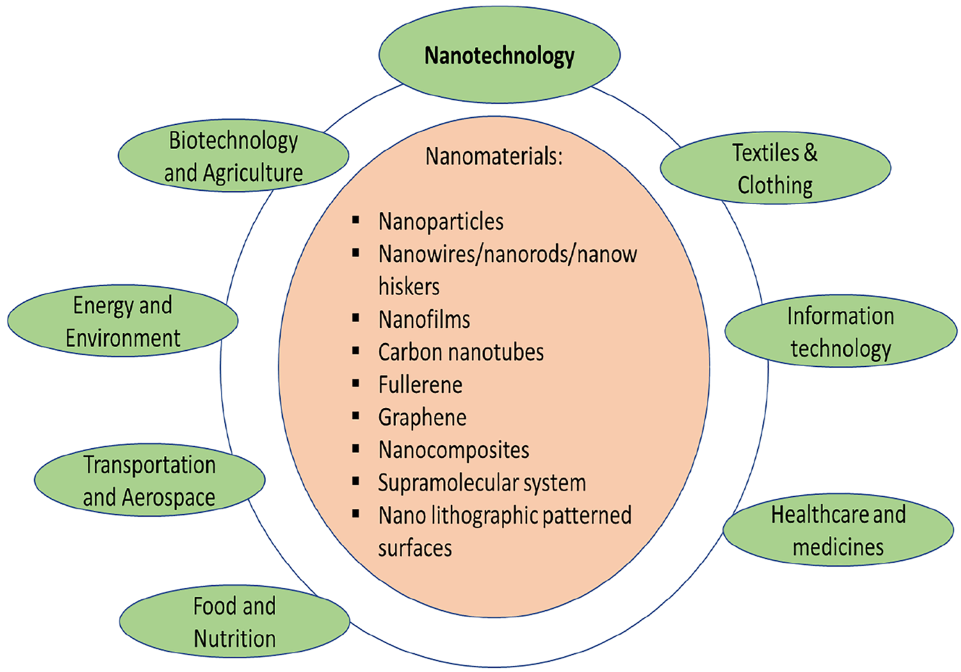

Fig. 1 Classification and application of nano technology

nanomaterials takes place or the applied science field which worked based on controlling the size of matter in molecular and atomic scale is known as nanotechnology [5–8]. It can be classified based on dimensions e.g. nanowires and nanorods with one dimension less than 100 nm, fibers, tubes, and plates having two dimensions less than 100 nm, and quantum dots, particles, and spheres with 3 dimensions less than 100 nm [9, 10]. Based on phase composition nanomaterials can be classified as single-phase solids, matrix composites, and multiple composites [11].

Nanomaterial which have one dimension in the nanoscale range is called nanoparticles [12, 13]. It has further classified into various types like nano clay which is one of the most popular and are widely used in polymer nanocomposites. It can be obtained from natural mineral clay and its structure e.g. sheet-like hydrous silicates [14–17]. Three decades ago, carbon exists in only two allotropic forms which are graphite and diamond. The third allotropic form of carbon having the name fullerene was discovered in 1985. Afterward, a single wall and multi-wall carbon nanotubes were discovered [18, 19]. Graphene was discovered later by the micromechanical cleavage of graphite. Various allotropic forms of carbon are shown in Fig. 2. Graphite structure like sheet e.g. phyllosilicates. Graphene is a layer that contains sp^2 hybridize bonds arranged in a honeycomb-like lattice [20–22].

Carbon Nanotubes [CNT's] are a unique material that was recently discovered having exceptional structural, electronic, and thermal properties like high thermal and electricity conductivity like copper and diamond [23–25]. Possible future applications are computer nanoelectronics devices and circuits. The strength of CNT's is 100 times greater than 1/6th weight of steel [26]. Researchers are working to use CNT's in transistors in electronics and other microprocessors. Many researchers found single-walled and multi-walled CNT's has successfully impart functionalization in reactions. Such reactions can be divided into two categories, one of them is the direct attachment of graphite surface with functional groups and the use of nanotubes bound carboxylic acid [27]. The attachment of the large functionalization groups to the nanotubes results the stabilization of CNT's [28]. Polymeric and oligomer

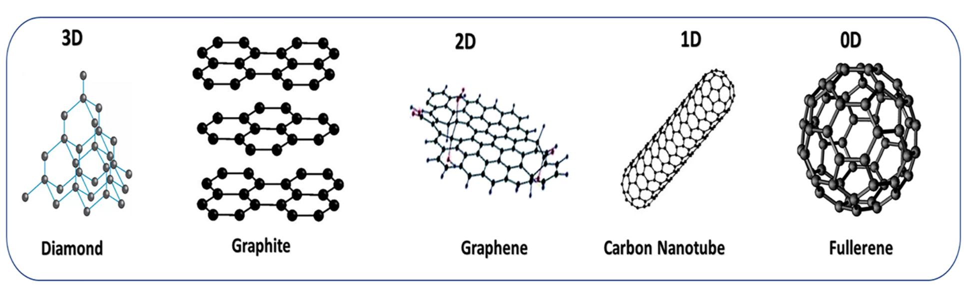

Fig. 2 Allotropic forms of carbon

compounds are used for the solubilization of CNT's in water or organic solvents. Nano bundles are break during functionalization which is much necessary for solubility [29]. The major commercial applications of multi-walled CNT's are used in polymeric conductive composites. Addition of 5% CNT's concentration results increase in conductivity from 0.01 to 1 S/cm. It also depends upon the type of polymeric matrix. Low-level loading of the multi-walled CNT's into nanofibers allow electrical conductivity [30]. It can be used as a conductive plastic automotive parts like mirror housing [31–33]. Hyperion et al. worked with an automotive manufacturer, plastics compounders, and plastic producers to develop more and more applications of nanotubes. By the addition of nanotubes into plastics provide structural materials with dramatic improvement in strength and modulus [34, 35].

Nanocomposites

Multiphase solid in which one of the phases having dimensions 1, 2, or all 3 are less than 100 nm is called nanocomposites [36, 37]. It has been further classified into polymer matrix nanocomposites, polymer-layered silicate nanocomposite, ceramic-polymer nanocomposites, inorganic–organic polymer nanocomposites, and inorganic–organic hybrid polymer nanocomposites.

Polymer matrix nanocomposites are materials in which inorganic nanoscopic particles having one dimension in range 10-100A must be dispersed in a polymer matrix. Such composites result in a significant improvement in the mechanical and physical properties when compared to pure polymers or regular polymer composites [38]. When CNT's are embedded in polymer matrices to form nanocomposites which has one of the most popular topics in CNT's research. The dispersion of nanotubes in the polymer is a challenging task. The use of solubilized CNT's has offered significant advantages in most cases. Hence CNT's are used in nanocomposite as a filler [39, 40]. Biological potential applications of CNT's have attracted much attention these days. Biocompatibility is an issue in various places during using CNT's for biological purposes. Researchers use CNT's for the helical crystallization of the protein to take advantage of exceptional rigidity and shape. The chemical modification and functionalization offer the utilization of CNT's for various nanocomposites with enhanced properties [41]. Constituents of polymer matrix nanocomposites are shown in Fig. 3. In recent years polymer nanoparticles have attracted great attention from researchers. In bulk as well as in solution the materials offer unique thermal, optical, mechanical, and electrical properties. Such significant improvement in the properties is due to the presence of nanoparticles and their interaction with polymers and the state of dispersion [42]. The use of macro-sized particles as a reinforcement agent scatter light, reduce the optical clarity and light transmittance. While using nano-sized particles as reinforcement in combination with polymer particles the interfacial adhesion reduces scattering and develops very strong transparent film membranes and coatings [43].

It shows great improvement in properties like electrical conductivity, chemical resistance, high thermal stability, good optical properties, high flame retardancy, high solvent resistivity, and high strength, etc. [44, 45].

Currently, polymer/layered silicate nanocomposite attracts great attention of both industrialists and academia due to the significant improvements in material properties when compared to conventional macro/micro composite and virgin polymer. Schematic representation of polymer layers silicates nanocomposites and the

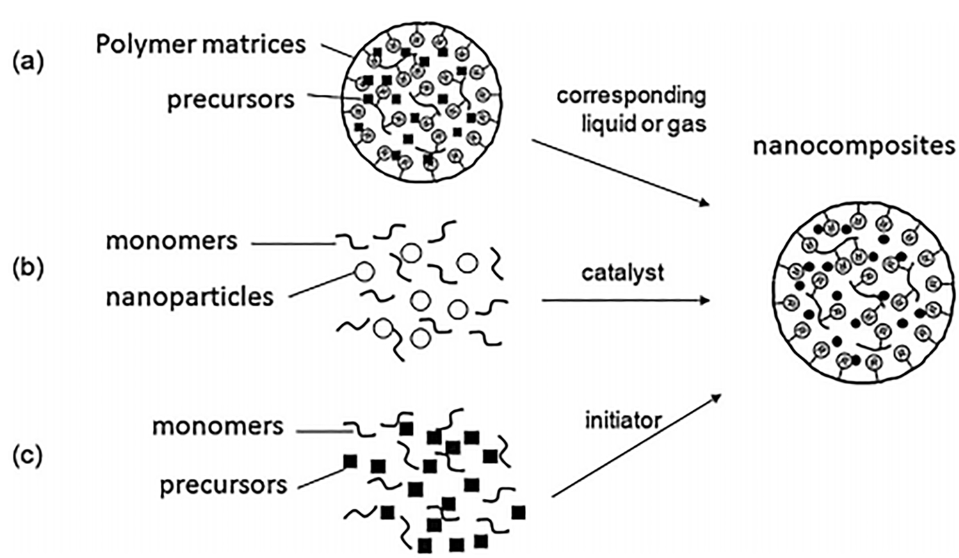

Fig. 3 Different Constituents of polymer Matrix Nano Composites [46]

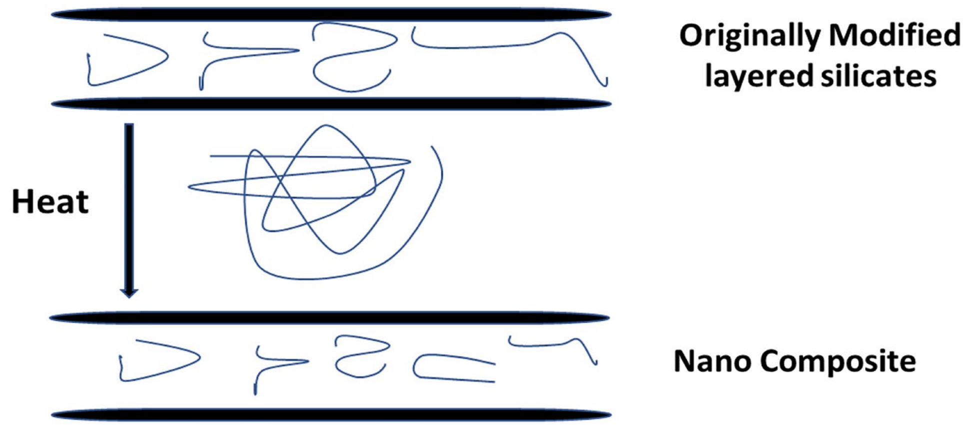

Fig. 4 Schematic representation of polymer layer silicate nanocomposites [50]

structure obtained by using layered silicates are shown in Fig. 4 and Fig. 5, respectively. Due to the hybrid and synergistic properties, polymer nanoparticles composites attract the attention due to its outstanding mechanical, optical, and ease of fabrication have led them toward the fabrication of many materials. Polymer/ceramics nanocomposites combine the flexibility of polymer and high dielectric constant of ceramic powder hence it can be used for embedded capacitors [47]**.** Composite with a polymer matrix that has at least one dimension less than 100 nm are called nanocomposites. The fillers can be high aspect ratio nanotubes and low aspect ratio nanoparticles [48, 49].

Ceramic/polymer nanocomposite consists of a single layer of ceramics with a thickness of 1 nm which has homogeneously dispersed in the continuous matrix. Due to dipole–dipole interactions, the ceramics layer arranges themselves parallel to each other. The synthesis of SiCN-MoS_2 composite from the in-situ pyrolysis of polysilazane molecules is shown in Fig. 6.

Inorganic/organic polymer nanocomposite attracts attention due to unique properties like metal clusters which have dispersed in the polymer matrix of size 1-10 nm. Properties of nanoparticles and clusters like transport of electron, spectral properties, and bandgap show a huge difference from those of bulk materials [53]. Moreover, when the organic and inorganic components of nanocomposites are mixed then it is called inorganic/organic hybrid nanocomposites [54]**.**

Nanocomposites have numerous applications like metals that are used in gas and oil pipelines having high corrosive nature with a high failure rate. Nanocomposites are the best candidate which improves the microscopic properties of the products significantly. Nanocomposites have much better mechanical properties due to their very high surface to volume ratio. It has also been found that the addition of CNT's increases electrical and thermal conductivity. The addition of another type of nanoparticles cause to enhance the resistivity to wear and damage mechanical properties like stiffness and strength. Mechanical properties of nanocomposites as shown in Fig. 7.

Azonanoa et al. found that the magnetic multi-layer materials are also the most important aspect of the

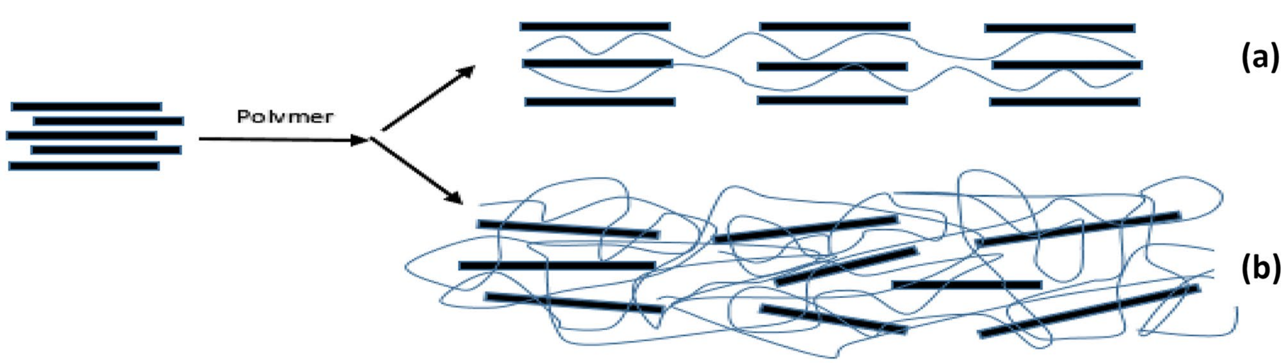

Fig. 5 Composite structures obtained by using layered silicates. Rectangular bars show silicate layers. **a** Single polymer layers **b** Composites obtained by delamination of silicate particles and the dispersion in a continuous polymer matrix [51]

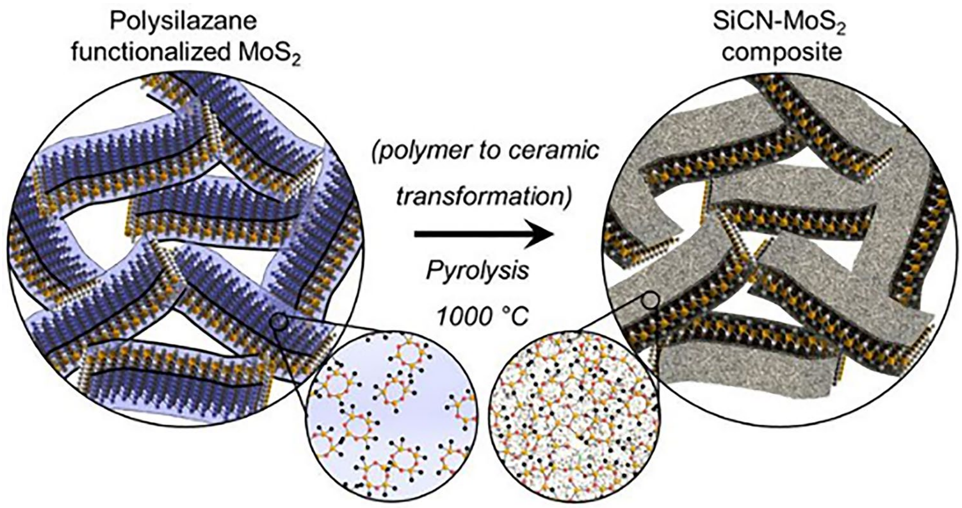

Fig. 6 Graphical representation of the synthesis of SiCN-MoS2 composite from the in-situ pyrolysis of polysilazane molecules [52]

nanocomposite, as they have significant improvements in storage media. Experimental work showed that all classes of nanocomposites result in a significant improvement in properties as compared to their counterparts. Therefore, it has applications in many areas such as sensors, lightweight composites, nanowires, optics, battery cathodes, and other systems. Nanocomposites have good mechanical properties; hence, it can also be used in the automotive and construction industries. In automotive it has great potential for utilization in mirror housing, vehicle belt covers, door handles manifolds and engine covers. Furthermore, general applications include, use as impellers and blades for a vacuum cleaner, portable electronic covers, and power tools housings, etc. Plastic products are provided by monomers nano-clays which can be used for packaging like rigid containers food and nano food films [55].

Use of different nanomaterials in composites

Silica nanoparticles

Silica/silicon dioxide (SiO_2) is the oxide of silicon. The addition of silicon nanoparticles significantly improves the properties of polymer composites [56, 57].

Researchers investigated about ballistic properties of silica nanoparticles thermoplastic hybrid composites. Nano silica is very commonly used as a nanofiller in aramid multi-axial fabric composites which have significant applications in ballistic. Agglomeration is one of the main problems when using nanomaterials as a filler in composites. In this research for the presentation of the agglomeration of silica nanoparticles, the coupling agent silica was used. Nano-silica is treated with silane and used as a matrix during the manufacturing of hybrid

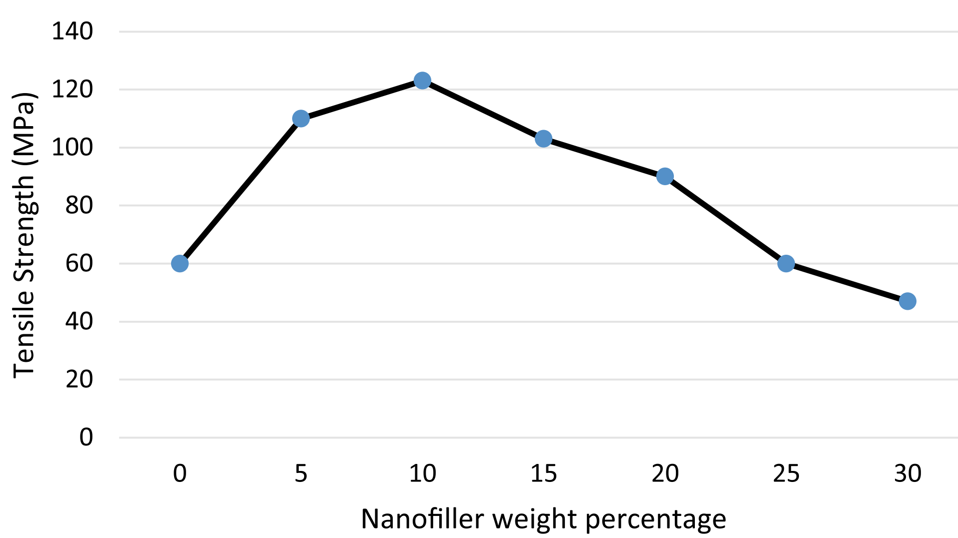

Fig. 7 Mechanical properties of nano-composite samples

composites. They prepare four samples which are coated with aminopropyl triethoxlisilane (AMEO Silane)/ ethanol solution. Two samples were impregnated with 30% by weight of silane-modified silica nanoparticles which are used as a reinforcement. They found that the impregnation of AMEO silane and modified silane nanoparticles have significantly contributed toward the improvement of mechanical properties [58–60].

Saba et al. investigated the polymer nanocomposites which has significantly encouraged research area for researchers since the last decade and continuously gained much more attention due to unique properties like exceptional mechanical properties which have applications in composite based industries, food packaging, medical sciences, and cosmetics. The matrix, polymers, and nanoparticles which are used as a filler at nanoscale significantly improved the properties. The reinforcement of nanoparticles greatly improves the performance as well as many other properties [15, 61].

Nanofillers are additives in the solid form which shows differences in terms of structure and composition from the polymer matrix. They are mostly inorganic materials and can also rarely be organic materials. There are two types of fillers e.g., active fillers and inactive fillers. The active fillers bring improvements in the physical and mechanical properties while inactive fillers raise the quantity by lowering the prices [6, 62].

Zapata et al. found that polyolefin does not have polar groups, so great efforts have been made for the improvements of organic fillers dispersion like silicon and clay in polyolefin, which is used as a matrix and will help to prepare effective polyolefin nanocomposites. According to significant research conducted on nanocomposites by government and industrialists the most commonly used polymers are polyurethanes, polyamides, polybutylene, terephthalate, polypropylene, acrylic, polyethylene, epoxies, styrene, polycarbonates, vinyl and resins. Montmorillonite clay is mostly used as a filler due to their unique structure having unit thickness of one nanometer or less and its aspect ratio is 100:1. The nanocomposite is expected to enhance and improve in barrier properties, modulus, heat distortion temperature and flexural strength, etc. [63].

Nano clay

Kumar et al. investigated the effect of nanomaterials on polymer composites. They studied the nanocomposites with nano-clays, nanoparticles, nanotubes, and nanofibers. Materials listed previously are used as nanofiller in the composites. They investigated that the better dispersion of filler within the matrix provides high-performance nanocomposites. They also found that there is a chance of agglomeration of nanomaterials inside the matrix when no proper dispersion takes place. It may result in stress concentration which can be avoided by proper mixing through mechanical mixtures, shear mixture, or ultrasonic mixture [64].

Brittleness of composites laminates shows reduction by adding nanofillers. However, chemical and corrosion resistance, tensile, compression, flexural, inter-intralaminar fracture toughness shear stress, toughness, electrical and thermal properties show significant improvement. Moreover, the vacuum-assisted technique can eliminate voids issues to a great extent [65].

The nanoscale dimensions significantly improve physio-chemical, chemical interaction, and interfaces in materials significantly. Morphology obtained from nanocomposites can modify the interface which is very essential to enhance various properties. Mixing and surface treatment are two key factors that enhance the performance of materials. Different varieties of combinations between matrix, classical additives, and nano-fillers allow a wide range of materials specifications improvements in the different properties like a reaction to fire, electrical properties, optical properties, mechanical and thermal properties. Improvement of fillers' quality significantly improves the diffusion of such nanocomposites which has a wide range of applications [5].

Marc et al. investigated the effect of nanoparticles on the mechanical properties of polymer composites. They found that the addition of the nanofillers significantly reduces the coefficient of fraction value as compared to pristine epoxy. Besides, if 1% by weight nanofillers surprisingly shown better results than 3% weight of nanofillers, which was not expected. It may be due to particle agglomeration which leads to the bad dispersion in the epoxy matrix. Good wear performance is achieved due to the very strong interface bonding between matrix and nanotubes. When polyamide is reinforced with carbon shoot it shows enhancement in tensile tests, toughness, and ultimate stresses. Acrylonitrile butadiene styrene shows a decrease in overall mechanical properties. During acrylonitrile butadiene styrene manufacturing process produces uncountable cracks which led them toward bad mechanical properties [66].

Carbon nanotubes (CNT's)

Nowadays nanocomposites attract great attention in the manufacturing of multifunctional lightweight composites for engineering applications. Polymeric nanocomposites, especially with CNT's, are much attractive for good structural characteristics of conductive composites. One of the main problems in the commercialization of CNT composites is agglomeration that prevents uniform dispersion of filler. It is due to high melt viscosity and interfacial tension between the polymer and CNT's as compared to thermosets. Schulte et al. claimed that carbon nanotubes are the most available composite strengthening option. According to Schulte, CNT's increase strength up to 11.6 GPa when they analyze properties versus cost relation and compared to carbon fibers. [39].

Properties imparted to the composites by nanomaterials

Electrical properties:

The addition of CNT's on composites contributes significantly to enhance the electrical conductivity of the composite as shown in Fig. 8. It is also reported that, the addition of CNT's results in significant improvement in the mechanical and thermal properties of composites.

Multiscale reinforcement with CNT's significantly enhances thermal and electrical properties. The conventional fillers like carbon and glass fibers for the promising solution toward the development of multi-functional composites [68].

By incorporation of different nanoparticles like CNT's into endless fiber-reinforced composites and neat thermoplastic significantly enhance properties. The addition of carbon black and CNT's has led to enhance the electrical conductivity of the polymer film and organic sheet as shown in Fig. 8. Electrical conductivity depends on various factors that involve the amount or quantity of conductive fillers used in the polymers. Semi-crystalline polyamide shows less electrical conductivity than amorphous polycarbonate. During the processing of polymer films into an organic sheet the nanofibrils agglomeration cause increase in electrical conductivity [20].

Conductive nanocomposites can conduct an electric current. Polycarbonate is an insulator material that can be made conductive. It is an inexpensive plastic that is known for mechanical and optical properties and finds application in the future in a more important and newer horizon. Polycarbonate is a poor conductor, but researchers amended this property by adding CNT's, hence it becomes highly conductive nanocomposites. By adding a suitable amount of CNT's in plastic it becomes ultra-high electrically conductive. Such inexpensive plastic is used for making optical discs that are used in high-end military air crafts to protect them against building electrical changes and the pulses which cause failure. By changing the amount of CNT's in polycarbonate the conductivity of nanocomposites also changes [14, 69, 70]

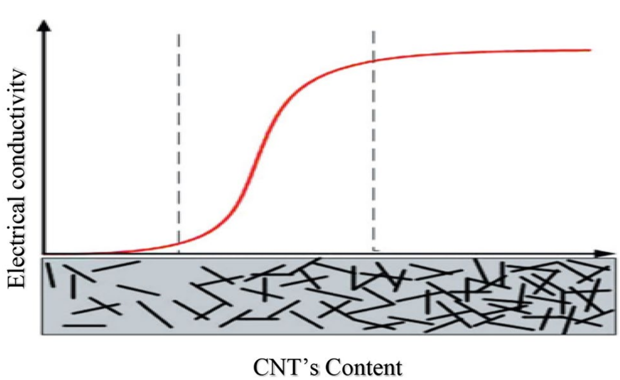

Fig. 8 CNT content versus electrical conductivity of composite [67]

The addition of conductive particles in polymer revealed a strong impact on the dielectric properties of the composites. By the integration of electronic devices e.g., capacitors, resistors, and others into the printed circuit boards, the developed composites have applications in the following areas.

- In the case of integrated capacitors performed huge functionality like large capacitance
- Industrial PCB fabrication process compatibility
- Having a low cost
- Abandonment of lead-containing materials
- More life cycles
- Highly reliable

When there is a need to increase the dielectric constant of composite then it is suitable to add ferroelectric ceramics to polymers that have high permittivity value just like $BaTiO_3$ [71].

Maria et al. investigated the combination of graphene/polymer nanocomposite and its applications in solar cells. They found that graphene, graphene oxide, and reduced graphene oxide are ideal candidates for solar cell applications due to their good thermal conductivity, flexibility, high transparency, large specific surface area, exceptional strength, mechanical, electrical properties, and 2D structure. For improving processability, electrochemical and chemical properties, and to vast their usage graphene nanomaterials are blended with polymers. This blend will be useful for using in devices parts interfacial layers, transparent electrodes, and active layers [72–74].

Flexible thermoelectric material is prepared by melt mixing technique. By adding CNT's inside the polypropylene matrix electrical network is built which can transport charges easily. CuO effect is determined by CNT's concentration. When CNT's concentration is high above the percolation threshold the small changes take place in thermoelectric properties [75–78].

Various types of materials like silicon inorganic semiconductor nanoparticles organic dyes, conducting polymers, graphene, graphene derivatives are used as photovoltaic materials. All the above-mentioned materials have some advantages and drawbacks. Organic conducting polymers has a different variety of structures and has some important properties like easy processing, recyclability, low cost and sustainability. An inorganic semiconductor has better electronic properties like high thermal stability high charge mobility and high electric constant. Nanoparticles of inorganic semiconductors have improved luminescent and photo conducting properties. By combining both conducting polymers and inorganic semiconductor has to make hybrid nanocomposites which became a prominent candidate for photovoltaic cells [79].

With the use of different materials to form a hybrid composite, the best performance is achieved by the combination of a nanotube array of TiO_2 and P_3HT in terms of power conversion efficiency. Certain factors affect the hybrid system and need to keep optimized for improving the systems. The charge transportation along both components can determine the current density which affects overall performance. Overall, the nanotubes array and nanorods based hybrid system perform better [80, 81]. Secondly, contact between organic and inorganic components and the interfacial area determines the charge separation efficiency. The nano tubes-based array shows better performance. Moreover, the energy level alignment at interfaces is also one of the most critical factors for the optimum hybrid systems. So, there is a need for great care during the selection of components.

The authors suggested some guidelines which should be carefully followed for improving the system.

- The right combination of inorganic and inorganic semiconductor should be taken
- For the charge separation process, such nanostructure should be used which provide a large interface
- Good contact between inorganic and organic components
- Nanostructure network will be more helpful in hybrid systems [82]

TiO_2 is amongst one of the materials which are very widely used in our daily life [83]. Ceramic piezoelectric e.g., lead zirconate titanate is widely used in microsystems technology. They can use in micro-actuators which convert electrical energy into mechanical energy. By applying an electric field which results in an effective mechanical response. It can also be used for exploiting pyroelectric properties and energy harvesting applications. The only commercially available piezoelectric material is polyvinylidene fluoride (PVDF).

Bloss et al. investigated the composites contain lead zirconate titanate (PZT) and PVDF tetrafluoroethylene for their piezoelectric behavior. They found that mechanical properties and dielectric constant affect the composite properties [74, 84].

Multifunctionality

Multi-functional nanocomposites are widely used as efficient sensors that perform multi-functionality [85]. Zang et al. fabricate Au (Pt) functionalize α Fe_2O_3, multi-functional nano spindles for co-oxidation, and gas sensing applications. Catalytic activity was measured in a fixed bad stainless-steel tubular reactor, while the gas sensing measurement system performs a gas sensing test. They found that the functionality of all nanoparticles results in higher activity in both applications compared to α Fe_2O_3. The reason for result improvement is due to the active AuNP,s which act as a catalyst for sensing the surface reactions and it also shows high reactivity at low-temperature co-oxidation [7, 86].

Lim et al. in 2010 grew uniform and densely packed radially oriented nanorods of oxide on the fiber to form the conductive fabric having a good resistance against washing cycles and stress. The conductive and non-toxic fabric shows excellent multiple sensing (optical and gas) performance at room temperature which is applicable for environmental, military, and health care applications [87].

Polymeric materials attract great attention due to their enhanced properties and functionality to use in various industries. For structural applications, thermoset polymers are very important such as marine, forming automotive, aeronautical, etc. Most importantly high specific strength thermoset polymers make it compatible with metallic materials and make replacement of various places. Thermoset polymers are very easy to process therefore it is widely used. With the recent developments of nanotechnology, nanocomposites offer various advantages over conventional composites materials like more sustainability, lightweight, and toughness. Nanocomposites grip great attention due to enhanced mechanical properties which have increased toughness. Various materials are used for the manufacturing of thermoset nanocomposites. Most commonly used particles are carbon nanoparticles and nano clays. The dispersion of nanoparticles is one of the biggest challenges [88].

Nanocomposites contain 10% to 12% nano-clays has higher tensile and flexural strength than nano calcium-based composites. In nano-clay composites, exfoliated and intercalated nanoparticles were observed. This enhances the mechanical and physical introduction of filler and matrix interface which greatly help in the dissipation of stresses and enhance the mechanical properties of nanocomposites [89, 90]. King et al. used the sol–gel process technique to disperse silica into the epoxy resins.

Liu et al. investigated the comparison of the high-pressure mixing and direct mixing for observation of the difference in the dispersion of nano clays. They found that high-pressure mixing is more efficient than direct mixing due to the breakages of clay layers. Sumfleth et al. use titanate modifications for better dispersion of nanoparticles [91]. Due to impressive mechanical properties, low filler load requirement, reinforcing capability, low weight abundance, and biodegradable nature of nanoparticles which are obtained from bio-resources like cellulose which make it ideal for the development of environmentally friendly polymers composites. Many researchers focused on the qualitative surface modifications, extraction, and mechanical performance of filling the polymers matrixes at different ratios. There are certain challenges in the fabrication of nanocomposites like difficult dispersion in organic solvents, agglomeration tendency, and hydrophilic nature. Due to increasing environmental concerns, regulations have put great interest in direction of developing eco-friendly materials. Natural fibers have advantages over synthetic due to their environmentally friendly nature, but by using natural fibers we cannot achieve strength in composite like synthetic fibers composite [65].

Nanocrystals of cellulose used structurally and geometrically designed models' cellulose fillers in various practically useful products. Commercially microcrystalline cellulose as a colloidal system is available in an aqueous suspension at very high solid concentrations like Celish (A trade name from Daicel Corporation) which provides a 10% slurry of cellulose nanofibers [92].

In 1961 Smith and Battista described the thixotropic gel system through patent. Solidified crystals of liquid have been applied in various optical applications used in security papers. The organic light-emitting diode can also be produced from wood cellulose nanocomposites for display substrates. Researchers worked and successfully produced optically transparent wood cellulose nanocomposites with low young modulus and low thermal expansion. Furthermore, they successfully deposited electroluminescent on flexible transparent wood cellulose nanocomposites which results in a low coefficient of thermal expansion.

To avoid dispersion ionic conductivity, cellulose whiskers (below 10% concentration) can also be used in low thickness polymers electrolytes which are used in lithium batteries. Loudspeaker membrane with low density and high young modulus can be obtained from melamine–formaldehyde and micro-fibrillated cellulose. Electrospun cellulose nanofibers are used as an affinity membrane that permits the purifications and clarifications of the molecules based on the biological functions or physical or chemical properties instead of the molecule's weight or size [93].

Oksman et al. investigated the cellulose nanofiber-based materials. Cellulose nanofibers are an excellent candidate for biomedical applications due to their load-bearing components, low toxicity, excellent mechanical properties, biodegradability, and biocompatibility. Cellulose nanocomposites are obtained from softwood pulp by the mechanical fibrillation process. Conducting composite can also be manufactured from whiskers and semiconducting polymers [94].

Nanocomposites are very helpful in the manufacturing process of sustainable materials with improved functionality and mechanical properties. Scientists are trying to modify thermoset nanocomposites to use vegetable oil-based Polyols and chemicals instead of bio-based resins for sustainability and minimization of dependency on petroleum-based resins. According to recent studies the nanocomposites can also be manufactured from vegetable oil-based resins which are environmentally friendly.

Haq et al. investigated the processing techniques of bio-based unsaturated polyester and clay nanocomposites. They determined the process limits, efficiency, and tensile properties. They also studied the properties of up/clay nanocomposite with various techniques and determined the optimum concentrations. Mayagawa et al. investigated the fracture surface of vegetable oil-based nanocomposites. They found that increasing epoxidized linseed oil and nanotube content modulus shows a significant increase [95].

Mechanical properties

Previously thermoplastic materials have been used with nano cellulose materials which shows the advantage of high fracture toughness and recyclability. In this study, the authors discussed some mechanical characteristic results for nano cellulose thermoset composites. The strength and stiffness properties of composites are highly improved by using nano cellulose in thermoplastic composites particulate or distributed composite base on nano cellulose benefits from interaction with the resin and relatively high aspect ratio of cellulose particles or fibers. The effect of fiber content on the mechanical and thermal expansion properties of bio-composites based on CNF has also been reported. It is observed that up to 40% fiber content a laminar increase in fiber modulus was observed using phenolic resin.

By incorporation of CNF in the epoxy, a great increase in glassy storage modulus was found. With 5% CNF epoxy film at 30 °C modulus shows an increase from 2.6GPa to 3.1GPa. Above the glass transition temperature, a high increase is reported. For 5% weight CNF's epoxy film at 130 °C, the rubbery storage modulus shows an increase from 9.7 MPa to 37.3 MPa [96, 97].

Ruiz et al. found that mechanical properties of composites show significant improvement by adding CNF up to 2% weight while further addition of CNF reduces mechanical and thermal properties due to agglomeration. Okubo et al. studied the dispersion of CNF reinforcement around bamboo fibers in the polylactic acid (PLA) matrix, they found that by addition of CNF also improves the fracture properties which prevent sudden crack growth. When CNF is added 1% weight cause to increase fracture energy by 200%. Researchers investigated that proper processing of CNF can lead to a safe environment, lightweight composites which has unique properties like barrier and transparency properties which have many applications in electronics, sensors, energy storage devices, packaging, medicines, and automotive manufacturing. Nano cellulose films can be used as a barrier material. Furthermore, high porosity aerogels can be used to allow the flow of gases while absorbing moisture, it is all due to its hydrophobic nature [98].

Nylrom et al. coated wood-based nano cellulose with poly pyrarole using in-situ polymerization, they obtained an electrically conductive composite. Nano cellulose composites provide transparency for various applications including armor applications and flexible display devices. Light and strong composite are possible by using CNF. 80% or more transparency has been reported for composites using CNF [99].

Bio-medical properties

Some new materials are developed for biomedical applications. It can be substituent in living tissues. Materials used for the biomedical application must fulfill structural, biological, physical, chemical, and mechanical behavior i.e., compatibility to roundabout host tissues. As mechanical properties are concerned especially elastic modulus, load transmission, stiffness and strength are of particular interest. Metals, polymers, and ceramic composites allow for tailoring the aspired physical properties. Some examples of polymer filler composites are given below.

- ***Repairing of bone fracture***: For external fixators, epoxide carbon fiber composite
- ***Screws and bone plates***
- ***Replacements of joints***: Carbon fibers (PEEK) are used for total hip replacement [21, 100]

Optical properties

Kleissl et al. investigated the influence of particle treatment on the optical properties of the nanocomposite. In-situ sanitization of nano-sized Al_2O_3 dispersed in Methyl methacrylate (MMA) resin and the subsequent polymerization yield better optical transmittance value in near infrared reflectance (NIR) than untreated Al_2O_3 [101]. M. Abdelrazek et al. explored the incorporation of gold nanoparticles (Au NPs) into polyethylene oxide / polyvinyl pyrrolidone (PEO/PVP) composites. Results revealed that by increasing Au NPs into composite the values of the optical parameters like refractive index, urbach energy, and optical energy gap shows significance increase [102].

Magnetic properties

Two types of composites show magnetic properties, one having metal nanoparticles and the other with ferrite nanoparticles. Mostly the nanoparticles are free from hysteresis which indicates superparamagnetic material. Ziolo et al. investigated the polymer nanocomposite contains 2.8% of Fe_2O_3 concentration. They found that their materials are free of hysteresis at room temperature and optically transparent. They further found that nanocomposites which contain γ-Fe2O3 nanoparticles in electromagnetic polymer matrix were also free of hysteresis [103]. M. T. Ramesan et al. incorporated nickel oxide (NiO) nanoparticles into Poly (vinyl cinnamate) and investigated their magnetic properties. They found the ferromagnetic nature of polymer nanocomposites. Furthermore, the increase in remanence, magnetic response, and hysteresis values were found by the incorporation of NiO nanoparticles into polymer [104]. Moreover, a wide range of functional nanocomposites applications is shown in Table 1.

Applications of functional nanocomposites

Structural applications

Polymeric materials are mostly studied and used materials in structural applications due to the area of its vast application from domestic to aerospace. The same vast applications are expected from polymer matrix nanocomposites. Inorganic materials are usually used as a reinforcement with polymers. Polymeric nanocomposite has exceptional mechanical properties and good electrical conductivity. Hence it has the best choice for structural applications [181–185].

Development of high-performance composites

M. Bauer et al. investigated the applications of nanotechnology in high-performance composites to reduce weight and increase strength considerably. They mainly focused on increasing strength which reduces weight automatically. They worked on the toughness of the nano modified thermoset composites. Fracture toughness is the main problem of highly cross-linked brittle thermosets. They focused on the effect of

Table 1 Applications of functional nanocomposites

Sr	Polymer	Nanomaterials	Applications	Ref#
1	Polyethylene glycol (PEG)	Quantum Dots (QDs)	Drug Delivery	[105]
2	DNA Molecule	Quantum Dots / Gold Nanoparticles	Biosensing	[106]
3	DNA	Carbon Nanotube (CNT's)	Biosensing	[107]
4	DNA	Graphene / Graphene Oxide	Biosensing	[108]
5	Poly (diallyldimethylammonium chloride) (PDDA)	QDs	Biosensing	[109]
6	1,4,7,10,tetraazacyclodocecane-N,N,N,N-tetraacetic acid (DOTA)	QDs	Bio imaging	[110]
7	(D,L-lactic-co-glycolic acid)	CdSe/ZnS nanocrystals	Drug Delivery	[111]
8	Chitosan	QDs /Drug	Drug Delivery	[112]
9	poly (acrylic acid)	QDs /drugs	Drug Delivery	[113]
10	Poly(ethylene glycol) (PEG)	Nanohydroxyapatite (nHA)	Injectable fillers for Orthopedic	[114]
11	Cellulose Acetate	Silver nanoparticles	Anti-microbial property /Biomedical Applications	[115]
12	polyether-based thermoplastic aliphatic polyurethanes	silver particles	Anti-microbial property/ Biomedical Applications	[116]
13	Polycaprolacton (PCL)	$CaCO_3$ Nanoparticle	Scaffold / Biomedical Applications	[117]
14	Polylactic acid (PLA)	calcium phosphate nanoparticles	Tissue Engineering	[118]
15	Polylactic acid (PLA)	Hydroxyapatite Nanoparticles	Enhanced Cell attachment / Tissue engineering	[119]
16	Gelatin	Hydroxy-apatite nanocrystals	Bones Regeneration	[120]
17	Polylactic acid (PLA)	Clay Nanoparticles	Tissue Regeneration	[121]
18	Poly (styrene sulfonate)	Co_3O_4 (Tri-Cobalt tetra Oxide) nanoparticles	Humidity Sensing	[122]
19	Poly (allylamine hydrochloride)	Graphene Oxide	Enhanced Mechanical Properties	[123]
20	Polypyrrole (PPy)	Titanium dioxide (TiO_2)	Gas sensor Applications	[124]
21	Polyaniline (PANI)	Halloysite	Supercapacitor Applications	[125]
22	poly-L-lysine	Graphene Oxide	Bio-scaffold coating	[126]
23	Gelatin	Graphene	Cellular imaging / Drug Delivery	[127]
24	Sodium alginate	Graphene Oxide	Tissue Engineering	[128]
25	Chitosan	Graphene	Tissue Engineering	[129]
26	Chitosan	Reduced Graphene Oxide	Biosensing	[130]
27	Polyethylene glycol (PEG)	Graphene Oxide	Drug Delivery	[131]
28	poly(lactic-co-glycolic acid)	Graphene Oxide	Enhance Mechanical and Thermal properties	[132]
29	Poly(ε-caprolactone) (PCL)	Reduced Graphene Oxide	Tissue Engineering	[133]
30	Polyurethane (PU)	Graphene Oxide	Enhance Mechanical and Thermal properties	[134]
31	Poly(propylene fumarate)	Graphene Oxide	Tissue Engineering	[135]
32	Poly (ethylene terephthalate) (PET)	Graphene	Enhanced mechanical, thermal, and electrical conductivity	[136]
33	Poly (vinyl alcohol) (PVA)	Reduced Graphene Oxide	Biomedical Applications	[137]
34	polyvinylidene difluoride (PVDF)	Graphene/ZnO	Temperature Sensing Applications	[138]
35	hydroxypropyl-β-Cyclodextrin (HPCD)	Graphene Oxide	Hemoglobin Sensing applications	[139]
36	Polyethylenimine (PEI)	Graphene	Glucose Sensing Applications	[140]
37	Chitosan	Graphene	Uric Acid Sensing Application	[141]
38	Poly (ethylene terephthalate) (PET)	Graphene	Cancer Cells Detection	[142]
39	Guargum	Silver Nanoparticle	Sensing of aqueous Ammonia	[143]
40	Polyaniline (PANI)	Copper Nanoparticle	Sensing of chloroform Vapor	[144]
41	Polypyrrole (PPy)	Gold Nanoparticles	Sensing of ammonia gas	[145]
42	Polyaniline (PANI)	Gold Nanoparticles	Sensing of glucose oxidase	[146]

Table 1 (continued)

Sr	Polymer	Nanomaterials	Applications	Ref#
43	Polyvinyl diene Fluoride (PVDF)	Single Wall Carbon Nanotube (SWNT)	Enhance Piezoelectric Response	[147]
44	Polyvinyl diene Fluoride (PVDF)	Reduced Graphene Oxide (rGO)	Energy Harvesting	[148]
45	Polyvinyl diene Fluoride (PVDF)	Reduced Graphene Oxide (rGO)	Increase Dielectric Constant	[149, 150]
46	P(VDF-TrFE)	Graphene Oxide	enhanced piezoelectric energy harvesting capability	[151]
47	Polyvinyl diene Fluoride (PVDF)	polyaniline-grafted-graphene oxide (G-graft-PANI)	Enhance Conductivity	[152]
48	Polyvinyl diene Fluoride (PVDF)	(Fe-RGO)/ CNT	Enhance Piezoelectric Performance and Conductivity	[153]
49	P(VDF-TrFE)	Zinc Oxide (ZnO)	Enhanced Piezoelectricity	[154]
50	Polyvinyl diene Fluoride (PVDF)	Nano Zinc Oxide (ZnO)	Increase output voltage, Piezoelectric charge constant and piezoelectric voltage constant	[155]
51	Polyvinyl diene Fluoride (PVDF)	Aluminum (Al)-doped ZnO	Increase in the dielectric constant	[156]
52	P(VDF-TrFE)	Silver nano-fillers (nanoparticle and nanowire)	Enhance output voltage and Piezoelectricity	[157]
53	Polyvinyl diene Fluoride (PVDF)	Silver nanoparticles (Ag-NPs)	Enhance tensile strength and thermal stability	[158]
54	Polyvinyl diene Fluoride (PVDF)	rGO/ZnO	Enhance thermal stability and piezoelectric properties	[159]
55	Polyvinyl diene Fluoride (PVDF)	TiO_2 /MWCNT's	Enhanced dielectric constant and breakdown strength	[160]
56	Polyvinyl diene Fluoride (PVDF)	TiO_2/ MWCNT's	Increase piezoelectric coefficient	[161]
57	Polyvinyl diene Fluoride (PVDF)	Fe-doped rGO	Enhance Piezoelectricity	[162]
58	Polyvinyl diene Fluoride (PVDF)	rGO and TiO_2 nanolayers	Higher β phase content, Enhance Tensile strength, and Young Modulus	[163]
59	Poly Vinyl Alcohol (PVA)	Barium titanate ($BaTiO_3$)	Enhance Piezoelectric Properties	[164]
60	Cellulose	Zinc Oxide (ZnO)	Increased piezoelectricity and mechanical Property	[165]
61	Poly Amide 11	Sodium niobate nanowire ($NaNbO_3$ NW)	Enhanced dielectric permittivity	[166]
62	Poly Amide 11	Lead Zirconate Titanate (PZT)/CNT's	Enhance dielectric permittivity	[167]
63	Poly Amide 11	Barium titanate ($BaTiO_3$)	Enhance dielectric Constant	[168]
64	Polyurethane	Lead Zirconate Titanate (PZT)	Increase d33 value	[169]
65	Poly (ethylene oxide)	Lead titanate (PT)	Enhance piezoelectric and the pyroelectric properties	[169]
66	Poly (methyl methacrylate)	Iron oxide nanoparticle	Electromagnetic Interference (EMI) Shielding applications	[170]
67	Polypyrrole	MnZn ferrite (MZF)	EMI Shielding Applications	[171]
68	Bacterial Cellulose	copper/zinc nanoparticles	EMI Shielding Applications	[172]
69	Liquid crystalline polymer	Titanium carbide nanoparticles	Good EMI Shielding Effectiveness	[173]
70	Polyurethane	Carbon Nanotubes (CNT's)	Good EMI Shielding Effectiveness	[174]
71	Poly (Lactic Acid) PLA	Carbon Nanotubes (CNT's)	Good EMI Shielding Effectiveness	[175]
72	Poly (trimethylene terephthalate)	Multi-Wall Carbon Nanotubes (MWCNT's)	EMI Shielding Applications	[176]
73	Epoxy	Single-Walled Carbon Nanotubes	EMI Shielding Applications	[177]
74	Epoxy	Graphene	EMI Shielding Applications	[178]
75	Bacterial Cellulose	Metal and Metal Oxides Nanoparticles	EMI Shielding and antibacterial applications	[179]

Table 1 (continued)

Sr	Polymer	Nanomaterials	Applications	Ref#
76	Bacterial Cellulose	Copper and Zinc Oxide	UV-Resistance and Antistatic Applications	[180]

nanoparticles in the relationship to micrometer-sized particles, micro and nano-sized rubber domains, and thermoplastic from the phase separation. They found that fracture toughness of modified thermoset with reactive butadiene-nitrile rubber has significantly improved [186–189].

Coatings applications

Organic and inorganic composites which are based on organic-alkoxylanes and alko oxides are very useful to use in eyeglass lenses hard coating. The addition of nanoparticles in epoxy silane act as an organic and inorganic cross-linking agent that considerably enhances abrasion resistance without affecting transparency. Nanocomposites have also been developed for low surface free energy coatings [87].

The mechanical properties of CNT's are very good therefore it can be used as a reinforcing fiber in high toughness nanocomposites, where lightweight, strength and stiffness are important considerations. The applications of nonlinear optics include protection of optical sensors from the high-intensity laser beam, flat panel displays, electromechanical actuators, light-emitting diodes, field-effect transistors, supercapacitors, and optical limiters.

Nanocomposites offered great improvements over conventional composites in thermal, mechanical, electrical, and barrier properties. Furthermore, it maintains transparency and reduces the flammability of the polymer matrix [190–192].

Industrial applications

Automotive: Used in gas tanks, bumpers, interior, and exterior panels.

Constriction: Used in building sectional and structural panels.

Aerospace: High performance and flame-retardant panels are used in the aerospace industry.

Electrical and electronics: Electrical current boards and electrical components are used in the electronics industries.

Food Packaging: Containers and wrapping films in food packaging [45].

Oils and gas pipelines

Corrosion is the main problem of metal-based products which reduces the lifetime of infrastructure everywhere. There is a need for great attention to the solution to this problem. Normally, corrosion damage and failure are not considered during the designing and construction of pipeline systems because we cannot estimate the corrosion damage due to unexpected changes in the environment. The combined effect of mechanical damage, corrosion, and the environmental assisted damage of material result in unexpected failures. The use of nanocomposites is very important in the manufacturing and structural repair of the damaged pipelines. Kessler et al. pointed out that nanocomposites offer great advantages in pipeline manufacturing and overwrap for the repairing of corroded steel pipelines [193]. The results of different materials corrosion levels are shown in Table 2.

Concerning the cost and performance of nanocomposite reinforced with fibers as an emerging alternative to steel pipelines. Thus, nanocomposites structures purely design in engineering terms, each part provides a specific function and the interaction between functions provides such structure having exceptional characteristic performance.

Pipelines enhanced the collapse and burst pressure rating, significantly increase load carrying capacity, compression strength, and tensile strength as compared to nonmetallic and non-reinforced pipelines. There is

Table 2 Results of corrosion level in polymeric nanomaterials [14]

Polymer Composites	Corrosion Level µ meter	Comments
Polyamide	14	6 kV (AC, 60 Cycles/sec, 48h
Polyamide/LS Nano Material	2.5	Electrode; IEC(b)
Epoxy	110	60 Hz equivalent Time kV(AC)
Epoxy LS Nano Materials	50	720 Cycles/sec
Epoxy/Titanate (15 nm) Nano Material	32	60hrs/120hrs
Epoxy/Silica (40 nm) Nano Material	27	Rod Gap plane electrode
Epoxy/Silica (15 nm) Nano Material	19	

also the possibility to manufacture the pipe with power cables, copper signal wires, and fiber optics installed into the walls of pipes which make us able to embed sensors for smart operating. The sensors can monitor the lifetime performance of the pipe [194, 195].

Some important applications of reinforced composites for gas and oil pipelines are given below,

- Composites having anisotropic characteristics that provide extraordinary collapse and burst pressure rating also increase load carry capability, compressive and tensile strength
- There is no need for welding and joining to long-distance
- Requirements for replacement is dramatically less than metal pipes
- Highly corrosion resistance
- Fulfills the consensus standards for gas and oil pipelines [196]

Automobiles

There are a lot of wear and tear in automobile parts. Nanocomposites are ideal candidates for automobile parts due to their high fracture resistance. Nanocomposites are used to provide strength to the parts where high efficiency is required. Pollution is increasing very rapidly so the automobile manufacturers are working for the development of such technology which can control the same cost-effectively. So polymeric nanocomposites are accepted. Poly nanocomposite has enhanced barriers, heat resistance, impact, and mechanical properties than traditional composites. So, the development of composite having properties like biodegradability, lightweight and recyclability is a challenge. Such composites can be widely used for the manufacturing of automobile body parts. Industries are concerned mainly with the following aspects,

- Aesthetics
- Recyclability
- Reduction of weight
- Performance improvements

Nanotechnology is driving great changes in all such industries at the component, material, and system levels. In the US, the cars contain more nanocomposites like most commonly CNT's in nylon blends which protects against static electricity of fuel systems [197].

According to Buchholz for "step assist" plastic nanocomposites are used widely due to their high scratch resistance, rustproof, lightweight, high strength, and reduction in weight leads to the saving of fuels. Toyota company in 2001 started using nanocomposites in bumpers of cars which make them 60% lighter and two times more scratching and denting resistance.

Nanocomposites show significant improvements in combined electrical, thermal, and mechanical properties. In contaminated environments like industrial and coastal areas, compound insulators are susceptible to surface degradation that causes a breakdown. Micro-fillers are widely used in compound insulation materials. The standard of nanocomposite is investigated through the SEM analysis technique. The results recommend that nanofiller drastically improve the dispersion and enhance the quality of nanocomposite [198].

Air crafts

Over the last decade, researchers make various discoveries during work on nano clays by Toyota Company. Silica nanolayers with high stiffness, high aspect ratio, and large surface area, when dispersed into a polymer matrix, results in significant improvements in polymeric materials properties including photoactive, mechanical, electrical conductivity, barrier properties, controlled drug delivery, resistance to solvent swilling, fire retardancy, ablation performance, and thermal stability. Layer silicate nanocomposites also great applications in tissue engineering, aerospace, automobiles, and food packaging. Epoxy is widely used in coating adhesives, electronics, and composites. It has also been used for aircraft designing. Epoxy has low viscosity, good physical and mechanical performance, and high glass transition temperature.

High-performance composites are used for the manufacturing of fuselage sinks in airplanes. It can also be used as a premier layer for coatings in aircraft which enhances anti-corrosion properties [199–201].

Films

The incorporation of nano-level fillers results in a significant effect on the transparency of films. Nano clays have much better transparency than the conventional filled polymer and reduce haze [202]. A wide range of nanoparticles like ZnO, $TiO_{2,}$ graphene oxide (GO), etc. has been widely used for coating different materials for specific functionality. Cano et al. incorporated TiO_2 nanoparticles into chitosan (CS), developed nanocomposites that can be used as an antibacterial coating and photocatalysis applications [203]. Xu et al. reported chitosan incorporated with graphene oxide films with excellent antibacterial activity against Bacillus subtilis and Aspergillus which can be used as a food packaging, increase strength, and may impart some other functionalities to the surface [204]. Andrade et al. reported that Beta-cyclodextrin (β-CD) coated-Ag NPs reduced more than 99% E. coli as compared to pristine β-CD [205].

Environmental protection

The most damaging environment is considered as a water-laden atmosphere and the polymer materials can encounter it. The ability to absorb less water has a major advantage. By the addition of nano clays, a significant reduction in water absorption is achieved [206, 207]. From the last decade, CNT's and TiO_2 nanocomposites have been widely studied for their photocatalytic reaction with inorganic and organic pollutants in both gas and liquid environment [208]. Yang et al. investigated the incorporation of graphene oxide into polyaniline (PANI) which shows a significant increase in corrosion resistance properties when coated on metals. Hence, such environmentally friendly nanocomposites having strong anti-corrosion properties that can play a significant role in the development of a sustainable environment [209].

Food packaging

The amount of clay incorporated into the polymer and aspect ratio of filler particularly contributes to the overall barrier performance. A high aspect ratio dramatically enhances the gaseous barrier properties. The excellent barrier characteristic has resulted in great interest in the nano clays composite in both rigid and flexible food packaging like processed meat packaging confectionery boil in the bag foods cereals etc. The use of nanocomposites packaging considerably increase shelf life of various type of food [210 - 213].

Fuel tanks

The addition of nano clays into the nanocomposites reduce the transmission of solvents through the polymers such as polyamide. By the addition of nano clays filters into polyamide 6/6–6 results in significantly reduce fuel transmission. Due to such results, considerable interest in these materials is being seen for fuel tanks and automobile components. The reduction of fuel transition reduces the material cost significantly. Some other applications of nanocomposites include.

- Computer chips and thin films capacitors
- Solid polymer electrolyte for batteries
- Fuel tanks
- Automotive engineering parts
- Blades and impellers
- Gas and oxygen barriers [214, 215]

Reducing delamination and cracking in thermoset composites

Fiber-reinforced polymer composites have excellent mechanical properties but there is a problem of delamination due to various mismatches. Polymer composites are widely used in structural applications. Thermoset resins are stronger, stiffer, and more cost-effective than thermoplastic. Thermoset resins are more brittle which can cause cracking and delamination. By adding nanoparticles to both thermoset and thermoplastic the cracking and delamination issues can be controlled effectively. The addition of nanoparticles enhances out of the plane properties of laminate composites and fracture toughness significantly [216, 217].

Anti-ballistic applications of silica nanoparticles composites

Vira et al. investigated the importance of silica nanoparticles in anti-ballistic applications. Multi-axial aramid fabric has been widely used in the manufacturing of body armor composites. Nano-silica particles with nano-metric dimensions result in a high specific surface area. To prevent agglomeration of a nano-silica surface can be changed through a silane coupling agent.

When nano-silica is treated with adhesion promoter silane and added to the matrix, the hybrid composite significantly enhances the shock impact resistance of the bullet. Furthermore, they prepare four samples from aramid fiber and coated them with (AMEO) γ-aminopropyl tri-ethoxy silane/ethanol solution. Tests were conducted to check the bullet resistance of samples. Two samples were impregnated with simple polyvinyl butyral (PVB)/ethanol and the other two with the same solution but with the addition of 30% silica nanoparticles as a reinforcement. Bullet shooting tests were performed for all samples. It was found that the mechanical properties show significant improvement by the introduction of silane-modified silica nanoparticles to the composite of p-aramid / polyvinyl butyral [58, 185, 218].

Biomedical applications

Since last decade, biodegradable polymers fulfill the need for biomedical applications. Polycaprolactone (PCL) is a polyester polymer used in tissue engineering due to its acceptability, comparatively low cost, and convenience for modification. Polylactic acid (PLA) has biological characteristics like degradability, physiochemical conditions, good mechanical durability, and ease to modify, hence it can be used in a severe physical, mechanical and chemical environment without major decays in the features [219]. PLA has a very long decay time therefore it can be used as a replacement of hard tissues where recovery is possible to require in a long time. It can also be used in load-bearing tissue to increase stiffness. Further, it can be used for soft tissue engineering by reducing its molecular weight along with degradation time. Fundamental properties of PLA, its in-situ reinforcement nano/microfibrillar composites which are widely used in health care applications e.g. medical drug delivery system and tissue engineering [55]. PLA is a biodegradable polymer with a lot of importance with suitable characterization for use in biomedical products and food packaging applications [220, 221].

CNT's composites are intensively investigated for several aspects of life, particularly being created for medical applications. CNT's provide strength to metal matrix composites, compound matrix composites, ceramic matrix composites. It also enhances their mechanical properties, cell experiments in vitro, and biocompatibility tests (In-vivo). Composites with adjustable mechanical properties can be used in tissue engineering, transportation of genes, medicines, scaffold, implant, and as a filler in different composites to boost their mechanical properties. CNT's based strengthened composites are not solely applicable as artificial bone implant materials, however, its use in medical applications doubtless rewards opportunities to develop a successive generation of designed biomaterials in the future, like tissue engineering, cell medical aid, drug delivery, and diagnostic device [27, 222]. Magnetic sponges derived from biocompatible and resorbable polymers area units are excellent materials for medical applications [223, 224].

Outdoor insulation applications

The addition of nanometric inorganic compounds improves the properties of polymers and this includes a heap of applications relying upon the inorganic material compound within the polymers. They reviewed compound nanocomposites with carbon nanotubes as fillers and their usage in the electronic industry. Electrical and thermal conductivity values made them ideal candidates to be used in such an area where electrically conducting pads are required [225–227].

Challenges

Agglomeration is one of the main problems while adding nanomaterials in composites. Due to agglomeration, the nanomaterials cannot disperse uniformly which is the main hurdle in the commercialization of nanocomposites. When agglomeration takes place during bulk production then uniform properties are very difficult to achieve.

Conclusion

Researchers made awesome discoveries in the field of nanotechnology in the last two decades. Along with other areas researchers also worked on nanocomposites to enhance their properties. In this study, we focused to collect reputable work on the use of nanomaterials in polymeric composites and their application areas. Different types of nanomaterials and nano clays are used in composites as a filler which enhances ballistic properties and reduces brittleness. Such fillers can also improve chemical/corrosion resistance, enhance mechanical, electrical, optical, EMI shielding, and magnetic properties. It can also improve the stability and functionality of composites. Composites with enhanced properties are widely used in structural, coating, industrial, biomedical, thermoelectric, and photovoltaic applications. Furthermore, it also reduces delamination and makes surfaces hydrophobic and its applications are found in oil and gas pipelines, automobiles, air crafts, environmental protection, food packaging, films, and electronic devices.

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