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Nanocomposites in Engineering: Where We Have Been and Where We Are Going?

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A B S T R A C T

Nanocomposites have attracted significant attention in recent decades due to their outstanding mechanical, thermal, and functional properties, enabling advances in advanced engineering applications. This review presents recent progress in nanocomposite materials for engineering products, with emphasis on fabrication methods, material classes, and applications. Widely used fabrication techniques, including sol-gel processing, chemical vapor deposition, and melt blending, are discussed. Different classes of nanocomposites polymer, metal, ceramic-based, and hybrid systems are comparatively evaluated in terms of strength, durability, thermal performance, and manufacturability. The application of nanocomposites in aerospace, automotive, civil engineering, energy, and biomedical fields is reviewed, and the influence of processing strategies on performance and associated challenges is highlighted. Finally, future research directions toward multifunctional, smart nanocomposites and advanced synthesis approaches are outlined, positioning nanocomposites as promising candidates for next-generation engineered products.

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1. Introduction

Nanocomposites possess superior multifunctional properties including mechanical strength, thermal stability, electrical conductivity, and chemical functionality that make them promising materials across diverse engineering applications [1, 2]. Advances in understanding nanoscale interactions and structure property relationships are enabling precise control over their behavior, facilitating tailored material design. Recent developments in electrical-optical interactions are fostering collaboration among Materials Science, Electrical Engineering, and Analytical Science, potentially leading to significant innovations in energy and electronic technologies using nanocomposites as next-generation materials [3].

Nanocomposite materials combine multiple phases at the nanoscale and have unique mechanical, thermal, electrical and chemical properties. Nanocomposites have been shown to have significant increases in all four of these properties compared to their conventional counterparts [4]. These enhanced properties make nanocomposite materials highly applicable across many disciplines such as Surface Engineering, Biotechnology and Electrical Engineering. Due to the rapid pace of development in the area of nanocomposite materials regarding their design, manufacture and major new applications, a dedicated mini-review summarizing current advances, describing the main barriers to progress and recommending directions for future research is warranted [5].

The continuation of development of biodegradable polymers combined with the use of renewable resources will offer additional avenues for improving the environmental characteristics of nanocomposite materials [6]. The increased use of renewable resources will result in reducing the disposal problems and adverse environmental impacts created by the vast amounts of synthetic polymers currently being produced and used across the globe [7, 8].

Due to the fast development of the industry and new uses of nanocomposite products, it is important to provide a contextual view of the past development, current working characteristics and future direction of nanocomposites. While there are numerous reviews available, summarizing one or more of these aspects, there is a lack of concise mini-reviews that encompass all five aspects (i.e., classification, fabrication methods, applications, challenges, future directions). This review will provide an overview of the past development of nanocomposites, provide details about current applications/limitations, identify new methods for fabricating nanocomposites and provide direction for the future development of nanocomposites. This review will provide researchers/engineers in the field with a detailed roadmap for conducting further research in this area.

2. Historical Development of Nanocomposites

Nanocomposite materials are finished composite materials that include at least one finished component whose size is in the nanometer range [9]. The scientific community developed sufficient interest in the area of what can be termed nanocomposite science due to the limitations associated with standard microcomposite filler material, notably the limited area available for interfacing (thus restricting potential property enhancement). In contrast, the introduction of nanoscale fillers can significantly enhance mechanical, thermal and electrical properties at relatively small amounts of filler content for just about every polymer additive [8].

There was no specific delineation between nanocomposites and their predecessors during the initial phases of development. For instance, very few, if any, polyamide-based composites were engineered to nanomaterial specifications prior to 1976 and function as precursor materials to functionally engineered nanocomposite polymers as they exist today [10, 11].

In 1990, the development of clay/Nylon-6 nanocomposites by Toyota created a major shift in the automotive industry. The extensive property enhancements associated with this nanocomposite technology, when combined with the ability to produce nanocomposites on an industrial scale, initiated increased academia and industry interest in research and applications of nanocomposite materials [12].

Notably, advances continued through a combination of significant milestones in science and technology development, including the discovery of carbon nanotubes in 1991 and the establishment of the United States National Nanotechnology Initiative in 2000. Following these major events, research activities into the microstructural characterization of nanocomposites and associated mechanical and electrical property evaluation have both accelerated [13].

Innovation in the field of nanocomposites will be furthered by recent improvements made to nano-characterization techniques and nano-manufacturing processes that allow the use of innovative filler types, such as graphene or quantum dots [14, 15].

Table 1

History of nanocomposites and their applications in engineering from the 20th century to the present.

Year	Material/System	Application in Engineering	Results	Reference
2000	CNT–Polymer nanocomposite	Structural and electronic applications	Improved mechanical strength Enhanced electrical conductivity	[16]
2004	Graphene-based nanocomposite	Electronics and conductive engineering materials	Graphene isolation Very high electrical conductivity	[12]
2014	Graphene–Alumina nanocomposite	Structural ceramics or wear-resistant components	Small amount of graphene addition (0.25–0.5 vol%) Increased fracture toughness (~75%) Improved wear resistance (10×)	[17]
2016	Metal-based (Al/Al_2O_3 nanocomposite)	Lightweight structural engineering	Ultrasonic cavitation processing Uniform nanoparticle dispersion Increased strength and hardness	[18]

Table 1.
Continued.

Year	Material/System	Application in Engineering	Results	Reference
2021	Hybrid-based (Mesoporous NiCo alloy / rGO nanocomposite)	Electrocatalysts for hydrogen evolution reaction (HER)	Mesoporous NiCo alloy on rGO Low overpotential (115 mV @ 10 mA/cm²) Small Tafel slope (45 mV/dec) High durability in HER	[19]
2022	Polymer-based / Hybrid (Chitosan + GO + CNC; borate-crosslinked)	Smart/food & electronic packaging films	Borate crosslinked hybrid film Higher tensile strength Elongation at break increased 124% Toughness increased 216% Water vapor permeability reduced 50%	[20]
2023	Metal-based hybrid (Mg_3N_2-modified carbon foam / Li metal anode composite)	Energy storage (advanced Li metal batteries)	Ultralight Mg_3N_2-modified carbon foam Suppressed dendrite growth and volume change Nucleation overpotential about 9.3 mV Coulombic efficiency 99.3% Cycling stability 3000 h	[21]
2024	Polymer-based Hybrid (PLA/MXene nanocomposite)	Smart materials (shape-memory engineering)	PLA–MXene composite Balanced strength, flexibility, and conductivity Enhanced shape memory effect Potential use in soft robotics and biomedical devices	[22]
2024	Hybrid-based (Biopolymer-coated Mg-alloy bio-nanocomposite)	Biomedical engineering (bone scaffolds & implants)	Biopolymer-coated Mg alloy scaffold Improved biocompatibility and corrosion resistance Better mechanical stability Controlled degradation and osteoconductivity	[23]
2025	Metal-based (Al–Fe intermetallic nanocomposites from scrap)	Industrial engineering (tribological & thermal applications)	Al–Fe nanocomposites from scrap Eco-friendly and sustainable synthesis High tribo-mechanical performance Good thermal stability for industrial use	[24]

3. Classification of Nanocomposites

Nanocomposites can generally be classified into two categories like Non-Polymeric and Polymer-based. This binary classification may be viewed as an oversimplification because many new nanocomposite materials are hybrids and exhibit both characteristic [25]. In order to offer a more practical approach for producing materials that can be reviewed in a review article, nanocomposites will be organized into a few different categories according to both their matrix material type and their performance characteristics. Non-polymeric Nanocomposites contain Metal/Metal, Metal/Ceramic, and Ceramic/Ceramic systems that are generally used in applications requiring very high mechanical strength, thermal stability, and wear resistance [26].

On the other hand, polymer-based nanocomposites represent the most widely researched and utilized types of nanocomposites [27]. These types of nanocomposites generally consist of polymer/ceramic, inorganic-filled polymers, inorganic-organic hybrids, polymer/layered silicates, polymer/polymer blends, and biocomposites. The main reasons these types of nanocomposites are so attractive are because the mechanical properties are adjustable to meet a specific need, the density is low, they are easy to process and adapt to a variety of engineering applications [7, 28].

3.1. Polymer-based

Polymer-based nanocomposites consist of a polymeric matrix reinforced with nanoscale fillers such as layered silicates, carbon nanotubes, graphene derivatives, or metal nanoparticles. The incorporation of nanofillers at low loading levels enables significant enhancement of mechanical strength, thermal stability, barrier performance, and functional properties without compromising processability [29]. Depending on the geometry and dispersion state of the nanofillers, polymer-based nanocomposites can exhibit intercalated or exfoliated structures, which strongly influence their macroscopic behavior. Owing to their lightweight nature, tunable properties, and compatibility with conventional processing techniques, these systems have attracted considerable attention in engineering applications including automotive components, packaging materials, electronics, and biomedical devices [30].

The variety of fabrication methods that can be used to create nanocomposite materials from polymers with a uniform pattern and performance optimization has been increasing steadily over time [31]. The most common types of synthesis used to create polymer nanocomposites (PNC's) are solution intercalation; in-situ polymerization of intercalated polymers; melt processing using intercalated fillers; and the use of templating techniques (e.g. sol-gel processes) [32]. These techniques allow for effective mixing of the filler into the polymer matrix and contribute to the formation of nanoscale structures that impact the performance of the finished product. Future advances in the techniques used to synthesize and characterize PNC's will further expand the use of polymer nanocomposites across multiple engineering disciplines [33].

3.2. Metal-based

Metal-based nanocomposites, commonly referred to as metal matrix nanocomposites (MMNCs), consist of a metallic or alloy matrix reinforced with nanoscale ceramic, metallic, or carbon-based fillers [34, 35]. The incorporation of nanosized reinforcements enables a synergistic combination of metallic ductility and toughness with enhanced strength, hardness, wear resistance, and thermal stability. Compared to conventional metal matrix composites, MMNCs exhibit superior load transfer efficiency and improved microstructural stability due to the high surface-to-volume ratio of the nanofillers [36]. These characteristics have positioned metal-based nanocomposites as promising materials for demanding engineering applications, particularly in aerospace, automotive, and high-temperature structural components, where lightweight design and enhanced mechanical performance are critical [7, 37].

3.3. Ceramic-based

Ceramic-based nanocomposites are composed of a ceramic matrix reinforced with nanoscale secondary phases, typically ceramic, metallic, or carbon-based nanoparticles [38]. The introduction of nanometric reinforcements significantly enhances the mechanical reliability of ceramics by improving fracture toughness, hardness, wear resistance, and high-temperature stability, which are traditionally limited in monolithic ceramic materials [39]. These improvements arise from nanoscale mechanisms such as crack deflection, grain boundary strengthening, and inhibition of grain growth during sintering. As a result, ceramic-based nanocomposites have emerged as advanced structural and functional materials for demanding engineering applications, including cutting tools, thermal barrier coatings, and components operating under extreme mechanical and thermal conditions [7, 40].

3.4. Hybrid

Hybrid nanocomposites are composed of at least two different types of nanoscale reinforcements incorporated within a single matrix, enabling the simultaneous integration of multiple functionalities within one material system [41, 42]. By combining fillers with distinct physicochemical properties, such as carbon-based nanomaterials, ceramic nanoparticles, metallic nanophases, or emerging two-dimensional materials hybrid nanocomposites can overcome the performance limitations of single-filler systems [43]. The synergistic interactions between different nanofillers allow for the tailoring of mechanical, electrical, thermal, and chemical properties, making these materials particularly attractive for advanced engineering applications. In recent years, hybrid nanocomposites incorporating materials such as graphene derivatives, MXenes, and metal–organic frameworks have gained increasing attention for use in multifunctional structures, sensing platforms, energy storage devices, and biomedical systems, positioning hybrid architectures as a key direction in the future development of nanocomposite engineering [44, 45].

4. Fabrication Techniques

Fabrication techniques play a critical role in determining the final structure, properties, and scalability of nanocomposite materials. Nanocomposite processing encompasses a variety of fabrication methods, including injection moulding and extrusion, depending on the materials that are being processed as well as their applications [46-48]. Common approaches include solution-based processing, in situ polymerization, melt blending, sol–gel synthesis, and vapor deposition techniques, each offering distinct advantages and limitations. Solution and sol–gel methods enable fine control over dispersion and interfacial interactions but are often constrained by solvent use and scalability [49]. In contrast, melt blending and in situ polymerization are widely favored for industrial applications due to their compatibility with existing manufacturing infrastructure and solvent-free processing. Advanced techniques such as chemical vapor deposition further allow precise nanoscale control over coating uniformity and functional layer formation, making them particularly attractive for high-performance and surface-engineered nanocomposite systems. The selection of an appropriate fabrication route therefore depends on balancing property optimization, process complexity, and large-scale manufacturability [17].

4.1. Sol-gel

The sol-gel technique is an established coating method widely used in biomedical devices (see Fig. 1). Sol-gel coatings are well known for their ability to uniformly coat complex geometries and porous surfaces. They also provide a protective layer to reduce corrosion and prevent ions from migrating through the underlying coatings. Sol-gel processing offers advantages over many other coating techniques because of its low-temperature processing. This characteristic of sol-gel coating processes is especially important for biomedical applications, where substrates must not be subject to thermal degradation. The liquid nature of the sol allows the sol to flow deep into any voids and pores on the coated surface, and thus effectively seal those surfaces, as well as enhance interfacial adhesion [50-52].

Calcium phosphate (CaP)-based sol-gel systems have generated a great deal of interest in biomedical research due to their similarity to the inorganic component of bone and their excellent biocompatibility with living tissue [53]. The sol-gel coating process provides a versatile and scalable method for providing functional surfaces with engineered properties, indicating its potential application in advanced biomedical surface engineering [54, 55].

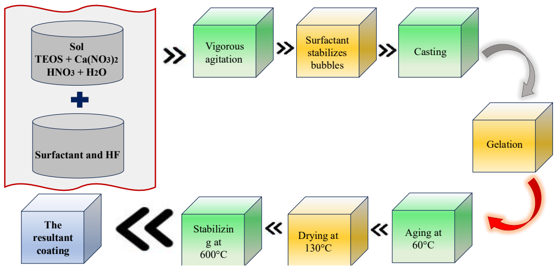

Fig. 1. Illustration of the process for applying a coating via Sol-gel; preparation of the sol and final formation of the solid structure.

4.2. In-situ polymerization

The first technique used to create all forms of polymer-based clay nanocomposites with nylon 6 was the in situ intercalative polymerization approach [56]. The intercalative approach is based on wetting or possibly swelling a layered silicate with an appropriate liquid monomer solution. When the intercalated silicate is suitably polyglycolated (i.e., it is contained within the "intercalated" or "swelled" sheets) to produce a polymer in the interlayer, it is necessary to start polymerization, either through heating or through radiation or through the addition of a physical carrier (or "initiator"). In the latter case, one could either diffuse a suitable initiator into the system or "attach" a suitable organic-mediated initiator or catalyst through methods such as cation exchange to the silicate between the initial swelling step and the formation of an intercalated polymer [57, 58].

4.3. Chemical Vapor Deposition

Chemical Vapor Deposition (CVD) is an established technique for the fabrication of thin films and is especially regarded for its use in engineering applications requiring coating that is both high-quality and durable, as well as providing conformal coverage [59-61]. It has found significant use within the semiconductor industry due to its ability to create dense and uniformly distributed layers and strong interfacial adhesion. CVD provides a key advantage for the production of nanocomposites because it enables precise control of the coating's composition, thickness, and microstructure [62]. This degree of control allows for the deposition of nanocomposite coatings and multifunctional coatings with a specific set of mechanical, chemical, and thermal properties. Therefore, coatings developed through CVD will be well-suited to applications where components are expected to perform under abusive operating conditions such as friction-intensive environments where both wear and corrosion resistance is required [19].

CVD provides a broad spectrum of materials to deposit, generating many different compound types ranging from carbide to nitride, oxynitride, carbon (if it was carbon based like diamond or graphene), and metal and related materials [63]. Additionally, from CVD processes can produce microstructure, with characteristics such as amorphous versus polycrystalline, depending upon process parameters and chemistry of precursor, resulting in the versatility of CVD makes this an attractive technology to create nanocomposites developed for application specific functionality [54]. Manufacturing wise, CVD offers the ability to produce little material waste and has a high compatibility for complicated shapes of substrates. Thus, it has the potential being a viable scalable method for producing advanced nanocomposite coatings for application purposes in areas of mechanical, electronic and energy related engineering [20].

4.4. Melt blending

Melt blending is widely recognized as a robust and industrially viable technique for the fabrication of polymer/clay nanocomposites, exhibiting particularly high efficiency when thermoplastics or elastomers are employed as the matrix materials [64, 65]. Clay is added to the hot liquid polymer during processing with equipment such as Banbury-type mixers or extruders, before being mixed with the appropriate amount of polymer to ensure an even distribution of the two materials. A big benefit of this method is that it is very easy to incorporate into current manufacturing processes such as extrusion and injection molding. Therefore, it provides an excellent means of producing nanocomposites on a large scale while keeping environmental impacts low. Additionally, products from melt blending typically have lower toxicity than those from other methods, while also preserving the chemical structure of both the polymer and clay components. Because of these benefits, there is a growing trend to use melt blending as the primary means of manufacturing nanocomposite materials for performance applications [57, 66].

5. Engineering Applications

The engineering of nanocomposite materials uses the structure-property-application (SPA) relationship to enhance overall mechanical, thermal, electrical and functional performance through the use of nanoscale reinforcement and interfacial interaction [67]. The tailored properties of nanocomposite materials satisfy the demanding performance requirements found throughout many engineering disciplines. Thus, nanocomposite materials have become widely used in many different fields including aerospace, automotive, electronics and biotechnology because of their ability to provide performance efficiency and multifunctionality. Representative engineering applications of nanocomposite materials are presented by functionality in the following subsections, beginning with aerospace applications [8].

5.1. Aerospace

The materials used in aerospace applications are required to provide a combination of properties such as high strength, stiffness, thermal stability, corrosion resistance, and low weight at the same time [68]. Nanocomposites can meet these needs by allowing for control of the microstructure and interfacial properties, resulting in improved performance under severe operating conditions in terms of mechanical and tribological behavior. For example, composites based on the initial system of graphene-reinforced epoxy matrices were shown to improve the strength, increase the temperature at which thermal degradation occurs, and have lower coefficients of friction than unreinforced epoxy. This indicates that these materials can be used in lightweight aircraft structures with increases in the resistance of these structures to fatigue and corrosion [69, 70].

In addition to composites, metals-based nanocomposites have demonstrated many advantages for use as aerospace components subjected to both high-temperature and high-friction loading. One example is that the addition of $MoSi_2$ nanoparticles to aluminum matrices significantly improves wear resistance [71, 72]. This property is critical to the longevity of components that will be in service for long periods of time. In addition, titanium alloy-based nanocomposites containing either graphene oxide or other types of nano powders demonstrate properties such as exceptionally high hardness and thermal stability, two of the primary design characteristics required for structural aerospace materials. Finally, coatings made from nanocomposites (e.g., Al_2O_3 nanoparticle-nickel) have also exhibited improved coated hardware (e.g., turbine blades), as well as resistance to corrosion and grain growth at elevated temperatures, and thus are excellent candidates for turbine blade coatings and other types of protective overlay coatings in aerospace applications [27, 73].

5.2. Automotive

Originally designed for use in aerospace, nanocomposite coatings have since been utilized as high-performance materials in the automotive industry as well. Because the use of nanocomposite coatings has been successful in aerospace, they are now widely accepted in many applications in the automotive industry [74, 75]. Polymer nanocomposite materials (PNC's) are particularly effective because they out-perform standard polymers. Through the use of nanofillers such as nanoclays, polymer nanocomposite materials achieve greater mechanical and thermal properties by enhancing interfacial interactions and restricting the mobility of the polymer chains. Therefore, polymer nanocomposite materials have the potential to be lightweight alternatives to metal in automotive parts, since they overcome the inherent low-strength and low-stiffness limitations associated with conventional polymers [73]. For this reason, PNC materials are used extensively in the automotive industry. An example of this application is the introduction of the first polyolefin-based nanocomposite step-assist component by General Motors in 2002, which contained approximately 3% nanoclay. This material was co-developed with Basell Industries to provide improved stiffness and durability over conventional polyolefin step-assist components (GM, 2009) [76].

5.3. Civil Engineering

Civil engineering materials must endure water damage and challenging conditions for as long as possible. Nanocomposite-useable fiber-reinforced polymers will address this problem. They accomplish this goal by improving both the barrier and mechanical performance of the materials with the incorporation of nanoscale modified inorganic fillers [77, 78]. Organo-modified nanoparticles such as silicate-based fillers have been found to decrease moisture permeability while increasing fire resistance, dimensional stability, and increased levels of mechanical strength. Research using vinyl ester-based fiber-reinforced PNC's indicates that the reinforcement with silicate nanoparticles produces better barrier function, lower rates of chemical degradation, and increased long-term durability than conventional fiber-reinforced polymer systems [79]. The improved performance of PNC's shows that they are a good fit for use in civil infrastructure systems, providing protection against environmental aging and maintaining a high level of mechanical performance over time [80].

5.4. Energy Sector

There is an increasing interest in green nanocomposites because of their potential to provide a balance between environmental sustainability and functional performance in the energy sector [81, 82]. By using biodegradable nanofillers (e.g., chitosan, lignin) in combination with conductive nanomaterials (e.g., graphene, carbon nanotubes, nanoclays) within a green polymer matrix, electrical conductivity, thermal stability and charge transport properties of the resulting composite materials can be enhanced, which is important for energy applications that require effective means to store and manage heat produced from stored charges. Fig. 2 shows various models of green nanocomposites. Green nanocomposites have been evaluated for use in energy storage systems, primarily supercapacitors [83]. Nanofiller-matrix interactions are a critical contributor to increasing energy density, cycling stability, and overall device performance in these devices. The ability to tune the composition of green nanocomposites through selection of the type of nanofiller, concentration of the nanofiller, and processing techniques will help support the development of sustainable forms of energy storage within other energy related applications [84-86].

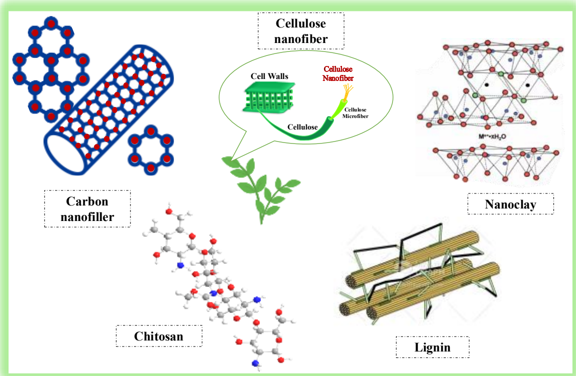

Fig. 2. Types of nanocomposites and green nanofillers.

5.5. Biomedical Applications

Nanocomposites are being used extensively in many aspects of biomedicine, including tissue engineering, repairing bone, oral hygiene, and delivering medications [87]. One issue related to the use of nanocomposites is the rapid removal of nanosized materials from the body after being injected (primarily due to their phagocytosis by reticuloendothelial cells), which can hinder their time of retention in the body, ability to target specific tissues or organs, and ability to adhere to biological tissues [88].

Hydrogels containing nanocomposites offer a viable solution to these challenges through the incorporation of nanoparticles into a biocompatible three-dimensional polymer matrix. Hydrogels provide an appropriate scaffold for growing cells and will enable a sustained release of drugs after being loaded with them [89, 90]. The incorporation of nanoparticles as "nanofillers" in hydrogel matrices also improves the mechanical properties of hydrogels, and can provide the hydrogel matrix with different types of functionality (i.e., increased electrical conductivity, photothermal and magnetothermal properties, as well as the ability to specifically target delivery of an active drug). Therefore, these combined benefits make nanocomposite hydrogels ideally suited to advanced biomedical applications requiring supporting structures and multifunctional capabilities (as shown in Fig. 3) [91, 92].

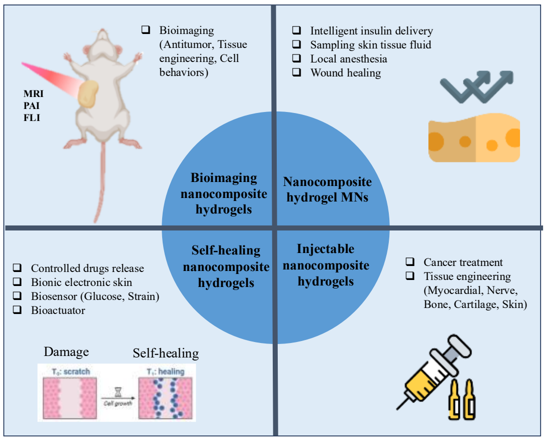

Fig. 3. Hydrogels incorporating nanocomposite materials for the purpose of biomedical application.

6. Challenges

Despite the significant advantages of nanocomposites in enhancing mechanical strength, thermal stability, and multifunctionality, several challenges continue to limit their widespread industrial adoption. Key obstacles include processing complexity, scalability, high cost, and long-term reliability, which necessitate careful evaluation of performance gains versus practical limitations [93]. A major challenge across polymer, ceramic, and metal nanocomposite systems is achieving uniform nanoparticle dispersion and stable interfacial bonding. Inadequate dispersion leads to particle agglomeration, reducing mechanical performance and hindering large-scale manufacturing. Although nanoscale reinforcements can significantly improve stiffness, strength, wear resistance, flame retardancy, and barrier properties, these enhancements often increase processing complexity, cost, or reduce material recyclability [80, 94, 95].

In metal-based nanocomposites, such as aluminum systems, improvements in hardness and load-bearing capacity are frequently accompanied by challenges including nanoparticle agglomeration, increased tool wear, and difficulties in characterizing large-scale components. Similar processing and scalability issues affect advanced applications in biomedicine and environmental engineering, where precise control over functionality, degradation, or material recovery remains difficult [96, 97].

Furthermore, the high cost of advanced nanofillers, such as graphene and high-performance functional materials, represents a significant barrier to commercialization [98]. While lower-cost and more sustainable alternatives exist, they often lack the multifunctional capabilities of newer materials. Consequently, despite their demonstrated potential, challenges related to dispersion control, application-specific performance, and scalable, cost-effective processing continue to restrict the large-scale commercialization of nanocomposite materials [95].

7. Future Directions and Innovations

Ongoing and future work in nanocomposites will continue to address the many unresolved challenges associated with scalability, multifunctionality and long-term durability in a variety of engineering applications. Some of the primary knowledge gaps include finding methods to achieve uniform nanoscale dispersion at large scale, enhancing interfacial stability in extreme in-service conditions and developing fabrication methods that allow for optimization of performance while ensuring efficient manufacturing [99]. While significant research continues to be devoted to polymer-based nanocomposites, new trends will increasingly involve hybrid and ceramic-based nanocomposites, and multifunctional architectures that may incorporate mechanical, electrical and thermal properties into a single material [100]. These advanced materials have the potential to provide high-performance materials for the next generation of aerospace, automotive, electronics, and energy applications. At the same time, these new materials and products will present new challenges related to processing complexity, material compatibility, and cost control.

Sustainability and widespread adoption will continue to drive future development. Encouraging solutions to address these concerns include use of green synthesis routes, recyclable or bio-derived matrices, and low energy processing methods such as solventless melt compounding and controlled in situ fabrication. However, a major obstacle to further adoption and growth of nanocomposite materials is the inability to consistently produce quality and performance materials during scale-up and, therefore, requires more investigation and optimization of processing methods [101]. Piezoelectric and smart composite systems containing multifunctional nanocomposite materials, despite their challenges, have great potential for development in the engineering profession. They incorporate the necessary components to provide actuation, sensing and energy harvesting in addition to the issues of associated with these systems such as cost, integration into existing structures, and compatibility with current building codes/laws/standards still remain to be resolved. As a result, researchers will continue to develop and refine hybrid and multifunctional nanocomposite material designs that will define the next generation of engineering materials and systems used in many industries [95].

8. Conclusion

Nanocomposites can improve mechanical, thermal, and functional characteristics from their unique properties as a matter of scale and the potential to create all types of nanoscale materials. While all three forms of nanocomposite are capable of enhancing material performance (polymer-based, metal-based, and ceramic-based), there are distinct limitations with respect to load-bearing capability, process complexity, and brittleness. Hybrid-based nanocomposite materials provide a potential solution to these limitations; however, the level of success from using hybrid-based nanocomposite materials will be determined by the appropriate selection of the base polymer matrix and nanofiller, the ability to achieve good interfacial compatibility between the matrix and the filler particles, and the processing techniques used during manufacturing. Despite recent developments in scalable manufacture, many challenges remain in the development of uniform dispersions of nanofillers within nanocomposites, improvement in interfacial interactions between polymers and filler materials, and improvements in durability of nanocomposites for long-term applications. Therefore, further research opportunities exist for the development of multifunctional, sustainable, and high-performance nanocomposites through innovative strategies, including green synthesis processes, hybrid architectures, and advanced intelligent materials integration technology to increase the range of applications available for engineers.

Author contributions

Parisa Izadi: Conceptualization, Writing – original draft, Writing – review & editing; **Hoda Khoshavi:** Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare no conflict of interest.

Data availability

No data is available.

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