Journal of
Composites Science

MDPI

Review

An Overview of Enhancing the Performance of Medical Implants with Nanocomposites

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Abstract: Medical implants are essential tools for treating chronic illnesses, restoring physical function, and improving the quality of life for millions of patients worldwide. However, implant failures due to infection, mechanical wear, corrosion, and tissue rejection continue to be a major challenge. Nanocomposites, composed of nanoparticles or nanofillers dispersed in a matrix material, have shown promising results in enhancing implant performance. This paper provides an overview of the current state of research on the use of nanocomposites for medical implants. We discuss the types of nanocomposites being developed, including polymer-, metal-, and ceramic-based materials, and their advantages/disadvantages for medical implant applications. Strategies for improving implant performance using nanocomposites, such as improving biocompatibility and mechanical properties and reducing wear and corrosion, are also examined. Challenges to the widespread use of nanocomposites in medical implants are discussed, such as biocompatibility, toxicity, long-term stability, standardisation, and quality control. Finally, we discuss future directions for research, including the use of advanced fabrication techniques and the development of novel nanocomposite materials. The use of nanocomposites in medical implants has the potential to improve patient outcomes and advance healthcare, but continued research and development will be required to overcome the challenges associated with their use.

Keywords: biocompatibility; mechanical properties; medical implants; nanocomposites; osseointegration; wear resistance

Citation: Ramezani, M.; Ripin, Z.M. An Overview of Enhancing the Performance of Medical Implants with Nanocomposites. *J. Compos. Sci.* **2023**, *7*, 199. https://doi.org/10.3390/jcs7050199

Academic Editors: Siu Hong Dexter Wong and Wang Yi

Received: 18 April 2023
Revised: 7 May 2023
Accepted: 11 May 2023
Published: 15 May 2023

1. Introduction

Medical implants have revolutionised modern healthcare by providing effective and minimally invasive solutions to a wide range of medical conditions [1,2]. They have become essential tools for treating chronic illnesses, restoring physical function, and improving the quality of life for millions of patients worldwide. However, despite their many benefits, medical implants are not without their limitations, and there are numerous challenges associated with their design, fabrication, and use.

One significant challenge facing medical implants is their potential for failure or malfunction, which can lead to complications and adverse health outcomes [3]. Implant failures can result from a variety of factors, including infection, mechanical wear, corrosion, and tissue rejection. These problems can occur even with the most advanced implant materials and designs, leading to the need for implant replacements and additional surgeries.

To address these challenges, researchers have been exploring the potential of nanocomposites to enhance the performance of medical implants [4,5]. Nanocomposites are materials composed of nanoparticles or nanofillers dispersed in a matrix material, such as a polymer or metal [6]. These materials have unique properties that make them well suited for medical implant applications, including high strength, flexibility, and biocompatibility.

The use of nanocomposites in medical implants is still in its early stages, but there has been significant progress in recent years. Researchers have developed a wide range of nanocomposites for different medical implant applications, including orthopaedic implants, cardiovascular stents, and dental implants [7–10]. These materials have demonstrated improved biocompatibility, mechanical strength, and wear resistance, which can help to reduce implant failures and improve patients' experience.

Despite the promise of nanocomposites for medical implant applications, there are still many challenges that must be addressed. One major challenge is ensuring the long-term safety and biocompatibility of these materials, as their small size and high surface area can make them more susceptible to interaction with biological systems [11,12]. Additionally, the development of reliable and cost-effective fabrication methods for these materials is necessary to enable their widespread use in clinical settings.

In this review paper, we will provide an overview of the current state of research on the use of nanocomposites for enhancing the performance of medical implants. We will begin by discussing the types of nanocomposites that are currently being used or developed for medical implant applications, including polymer-, metal-, and ceramic-based materials. We will then examine the various strategies that researchers have employed to enhance implant performance using nanocomposites, including improving biocompatibility and mechanical properties and reducing wear and corrosion. Finally, we will discuss the challenges and future directions for the use of nanocomposites in medical implants, including regulatory approval, long-term safety concerns, and the need for advanced fabrication techniques.

2. Brief Overview of Current Types of Medical Implants

Medical implants are devices or prostheses that are surgically implanted into the human body to replace, augment, or support biological structures [13,14]. Medical implants have become a vital aspect of modern healthcare and are widely used in the treatment of various chronic conditions, physical disabilities, and traumatic injuries. These devices are designed to restore the functions of damaged or missing organs or tissues and enhance the quality of life [15,16]. Below is an overview of the current types of medical implants, their applications, and their limitations.

Orthopaedic implants are used to replace or repair damaged bones and joints. They are commonly used in the treatment of fractures, arthritis, and degenerative joint diseases [17]. These implants include joint replacements, such as hip [18] and knee [19,20] replacements, bone plates [21], screws and pins used to repair fractures [22], and cartilage implants [23] for osteoarthritis patients. Figure 1 shows a patient-specific total knee replacement implant [24] that replaces the damaged or arthritic knee joint. Despite their many benefits, orthopaedic implants can fail due to various factors, including infection, mechanical wear, and implant loosening.

Figure 1. A total knee replacement implant [24].

Cardiovascular implants are devices used to treat cardiovascular diseases, such as coronary artery disease, heart failure, and arrhythmias. These implants include stents [25], pacemakers [26], defibrillators [27], and heart valves [28]. Cardiovascular implants are designed to improve blood flow, regulate heart rhythm, and provide mechanical support to the heart. Figure 2 shows a typical cardiovascular stent [29], an expandable tube used to treat narrowed or blocked arteries in the heart. It is typically used to restore blood flow, alleviate chest pain, and reduce the risk of heart attacks. However, cardiovascular implants can fail due to different reasons, including infection, thrombosis, and mechanical malfunction. Nanocomposite materials have demonstrated significant potential in enhancing the performance of cardiovascular stents, particularly in terms of biocompatibility and haemocompatibility. For example, biodegradable polymeric nanocomposites, such as poly(lactic-co-glycolic acid) (PLGA) reinforced with nanoparticles such as hydroxyapatite or bioactive glass, contribute to enhanced biocompatibility and haemocompatibility. These nanocomposites not only exhibit favourable mechanical properties, but also promote better biocompatibility and bioactivity. As the stent degrades over time, the nanoparticles can release bioactive ions that promote vascular tissue healing and regeneration. This gradual degradation reduces the risk of complications associated with permanent stents, such as late stent thrombosis or in-stent restenosis.

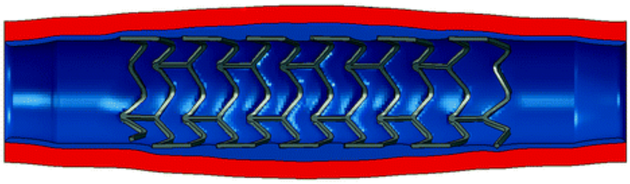

Figure 2. An artery stent fully expanded [29].

Dental implants are used to replace missing teeth. They are typically made of titanium or other biocompatible materials and are surgically implanted into the jawbone [30]. Dental implants provide a long-lasting and stable foundation for dental restorations, such as crowns, bridges, and dentures [31]. These types of implants can fail by infection, implant fracture, and implant loosening. Figure 3 shows four different designs of dental implant connections [31].

Figure 3. Typical dental implant designs [31]. (**a**) SK2 dental implant (S); (**b**) KL dental implant (K); (**c**) ESSENTIAL® dental implant (E); (**d**) VEGA® dental implant (V).

Neurological implants are for the treatment of neurological disorders, such as Parkinson's disease, epilepsy, and chronic pain. These implants include deep brain stimulators [32], vagus nerve stimulators [33], and spinal cord stimulators [34]. Neurological implants are designed to modulate the activity of neural circuits to reduce symptoms and improve the quality of life. The main failure mechanisms for neurological implants are infection, mechanical malfunction, and lead fracture.

Breast implants are used for breast augmentation and reconstruction. They are typically made of silicone or saline-filled silicone shells and are surgically implanted into the breast tissue [35]. Breast implants are designed to improve the appearance of the breasts, restore breast volume after mastectomy, or correct breast asymmetry. Breast implants can fail because of implant rupture, capsular contracture, and infection [36].

Limitations of medical implants: Despite their many benefits, medical implants are not without their limitations. As mentioned above, implant failures can result from a variety of factors, including infection, mechanical wear, corrosion, and tissue rejection. Additionally, medical implants can cause adverse reactions, such as allergic reactions, inflammatory responses, and implant-related infections.

Infection is one of the most significant complications associated with medical implants. When a foreign object is implanted into the body, it creates a potential site for bacterial colonisation and infection. The risk of infection is higher in implants that are exposed to bodily fluids, such as joint replacements, cardiovascular devices, and urinary catheters. Infections can lead to implant loosening, tissue damage, and even sepsis, a life-threatening condition [37].

Implant-related infections, such as biofilm formation and chronic infections, are also significant limitations of medical implants. Biofilms are complex communities of bacteria that can adhere to the implant surface and form a protective barrier against antibiotics and the immune system. Chronic infections can develop when the bacteria are not completely eliminated by antibiotics or the immune system, leading to persistent inflammation and tissue damage [38].

Mechanical wear and corrosion are also significant limitations of medical implants. Over time, the mechanical stresses placed on the implant can cause wear and tear, leading to implant failure [39]. Corrosion can occur when the implant material reacts with the body's fluids and tissues, leading to material degradation and implant failure [40]. In addition, implants that are subjected to cyclic loadings, such as joint replacements and spinal implants, can experience fatigue failure over time [30].

Tissue rejection is another limitation of medical implants. When an implant is introduced into the body, the body's immune system can identify it as a foreign object and mount an immune response. This immune response can lead to inflammation, tissue damage, and implant failure. Tissue rejection can occur with any type of implant, but it is most commonly associated with organ transplants and tissue-engineered implants [41].

3. Types of Nanocomposites for Medical Implants

Nanocomposites, which are composite materials consisting of a matrix and nanoscale filler particles, have emerged as a promising class of materials for medical implants. The common types of nanofillers and their applications are presented in Table 1. In recent years, nanocomposites have been developed with improved mechanical, biological, and antimicrobial properties, making them suitable for a wide range of implant applications.

Polymer-based nanocomposites are the most commonly used type of nanocomposites in medical implant applications. They are made by incorporating nanoscale fillers, such as carbon nanotubes, graphene, and clay nanoparticles, into a polymer matrix. Polymer-based nanocomposites have many advantages, including their excellent biocompatibility, low density, and ease of processing. Additionally, they can be tailored to have specific mechanical and biological properties, making them suitable for a wide range of implant applications [42].

One of the main disadvantages of polymer-based nanocomposites is their relatively low mechanical strength compared to metal- and ceramic-based composites. However, recent advances in nanocomposite technology have resulted in the development of polymer-based nanocomposites with improved mechanical properties. For example, the incorporation of carbon nanotubes into a polymer matrix has been shown to improve the mechanical strength and toughness of the resulting nanocomposite.

Table 1. Common types of nanofillers and their properties.

Nanofiller	Size (Approx.)	Shape	Surface Area (Approx.)	Unique Properties
Carbon Nanotubes	0.4–2 nm (diameter)	Cylindrical	50–1315 m^2/g	High strength, electrical and thermal conductivity, lightweight, chemical stability
Graphene	Less than 1 nm (interlayer)	2D sheets	2630 m^2/g	Exceptional strength, electrical and thermal conductivity, flexible, transparent
Nanoclay	1–100 nm (thickness)	Platelets	50–800 m^2/g	Barrier properties, flame retardancy, dimensional stability, reinforcement
Metal Oxide NPs	1–100 nm	Spherical	Varies	Enhanced mechanical strength, biocompatibility, corrosion resistance, antimicrobial
Hydroxyapatite	20–80 nm	Needle-like	50–100 m^2/g	Biocompatibility, bioactivity, osteoconductivity, promotes bone growth
Silica Nanoparticles	5–100 nm	Spherical	100–400 m^2/g	Biocompatibility, reinforcement, transparency, mechanical strength
Gold Nanoparticles	1–00 nm	Spherical	Varies	Biocompatibility, drug delivery, photothermal therapy, imaging
Silver Nanoparticles	1–100 nm	Spherical	Varies	Antimicrobial, biocompatibility, drug delivery, imaging
Titanium Dioxide NPs	5–100 nm	Spherical/Rods	50–200 m^2/g	Biocompatibility, antimicrobial, photocatalytic activity, UV protection
Zinc Oxide NPs	1–100 nm	Spherical/Rods	Varies	Antimicrobial, biocompatibility, UV protection, drug delivery
Quantum Dots	2–10 nm	Spherical	Varies	Fluorescent properties, imaging, drug delivery, sensing
Polymeric Nanoparticles	10–200 nm	Spherical	Varies	Drug delivery, biocompatibility, customisable properties
Chitosan NPs	1–100 nm	Spherical	Varies	Biocompatibility, drug delivery, antimicrobial, wound healing

Note: NPs stands for nanoparticles. The properties listed in this table are approximate and may vary depending on the specific type, size, and synthesis method of the nanofillers.

Metal-based nanocomposites are another type of nanocomposite that has gained attention for medical implant applications. Metal-based nanocomposites are typically made by incorporating nanoscale particles, such as titanium dioxide or carbon nanotubes, into a metal matrix, such as titanium or stainless steel. These types of nanocomposites have advantages such as high strength, stiffness, and wear resistance.

A primary drawback of metal-based nanocomposites is their potential for toxicity. In some cases, the release of metal ions from the implant can lead to adverse biological reactions and implant failure [43]. Nonetheless, new metal-based nanocomposites with improved biocompatibility have demonstrated potential for reducing the risk of toxicity.

Ceramic-based nanocomposites are another group of nanocomposites that has gained attention for medical implant applications. Ceramic-based nanocomposites are typically made by incorporating nanoscale ceramic particles, such as hydroxyapatite or alumina, into a ceramic matrix, such as zirconia or alumina. Ceramic-based nanocomposites have several advantages, including their excellent biocompatibility, high strength, and wear resistance.

A major disadvantage of ceramic-based nanocomposites is their brittleness, which can limit their use in high-stress implant applications. However, recent progress in ceramic-based nanocomposite technology has led to the creation of novel materials exhibiting enhanced toughness and strength [44,45].

Overall, the advantages and disadvantages of different types of nanocomposites for medical implant applications depend on the specific application and the required properties of the implant. For example, polymer-based nanocomposites may be more suitable for soft tissue implants [42], while metal-based nanocomposites may be more suitable for load-bearing applications such as joint replacements. Ceramic-based nanocomposites may be more suitable for dental implants or bone repair applications.

The manufacturing process for nanocomposite materials varies significantly depending on the type of material being produced. Various methods and techniques have been developed to create these advanced materials, each with its own set of advantages and limitations. For instance, Figure 4 illustrates the manufacturing steps involved in synthesizing an epoxy matrix composite strengthened with nanoparticles. This process begins with the careful selection and preparation of raw materials, which include the base epoxy resin and the chosen nanoparticles. Next, the nanoparticles are dispersed uniformly within the epoxy matrix, typically using methods such as high-shear mixing, ultrasonication, or ball milling. Achieving a homogeneous dispersion of nanoparticles is crucial for optimising the mechanical properties and overall performance of the final composite material.

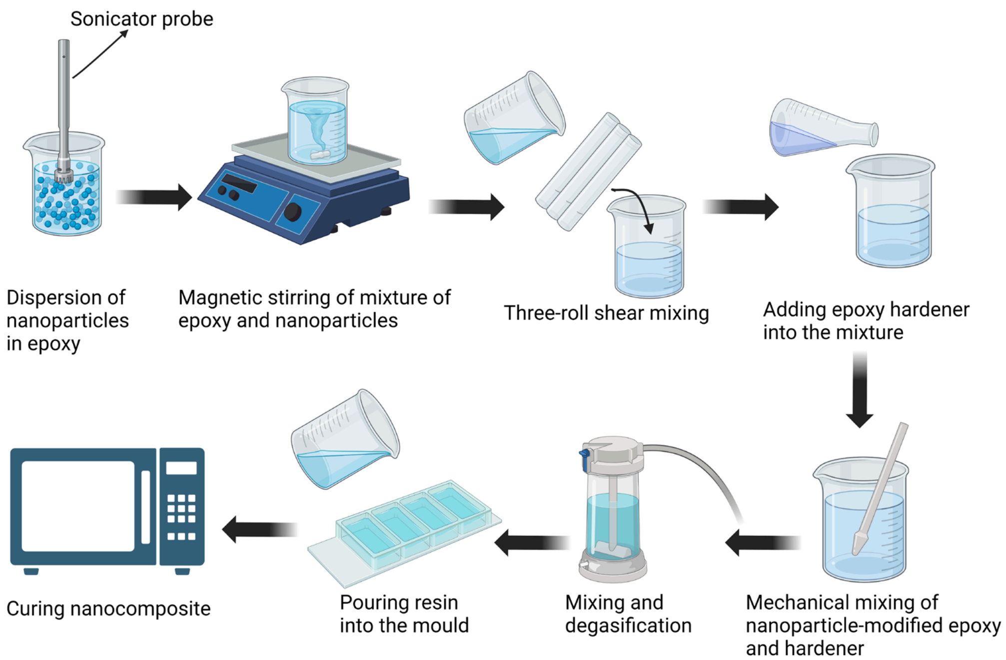

Figure 4. Step-by-step manufacturing process for an epoxy matrix composite strengthened with nanoparticles.

Once the nanoparticles are adequately dispersed, the epoxy resin may be combined with a suitable curing agent, which initiates the cross-linking process, converting the liquid resin into a solid polymer network. The mixture is then poured into a mould or applied onto a substrate, depending on the desired final shape of the composite material. During the curing process, the composite is often subjected to specific temperature and pressure conditions, which can greatly influence the final material properties.

After curing, the solidified nanocomposite material can be removed from the mould or detached from the substrate, followed by any necessary post-processing steps, such as trimming, surface finishing, or heat treatment. The resulting epoxy matrix composite, now reinforced with nanoparticles, exhibits enhanced mechanical properties, such as increased strength, stiffness, and toughness, compared to its non-reinforced counterpart.

It is important to note that the manufacturing process described above is just one example of how nanocomposite materials can be produced. The choice of method and specific steps involved can differ significantly depending on the types of matrix and nanoparticles being used, as well as the desired end-use application of the material. Consequently, ongoing research and development efforts are aimed at further refining and optimising these manufacturing processes to enable the large-scale production of high-performance nanocomposites for a wide range of applications.

In addition to their mechanical properties, nanocomposites can also be tailored to have specific biological properties. For example, the incorporation of nanoparticles with antimicrobial properties, such as silver nanoparticles, into a polymer matrix has been shown to reduce the risk of implant-related infections [46,47]. Similarly, the incorporation of nanoparticles with osteogenic properties, such as hydroxyapatite nanoparticles, into a ceramic matrix has been shown to promote bone growth and integration [48].

One of the main challenges in developing nanocomposites for medical implant applications is ensuring their long-term biocompatibility. While nanocomposites display potential for improving the performance of medical implants, their long-term safety and efficacy in vivo are not yet fully understood. Additionally, the potential for nanoscale filler particles to migrate from the implant into the surrounding tissue and the systemic circulation is a concern that must be addressed.

To address these concerns, researchers are actively investigating the long-term biocompatibility of nanocomposites and developing new strategies for controlling the release of nanoscale filler particles. For example, the use of biodegradable polymers as matrix material can help to reduce the risk of long-term toxicity by promoting the gradual degradation and resorption of the implant over time [49,50].

Examples of Nanocomposites Currently Being Used or Developed for Medical Implants

Nanocomposites are being actively investigated for a variety of medical implant applications. Table 2 lists a few examples of medical implants and devices enhanced with nanocomposites. Some of these examples will be discussed in the following sections.

Polymer-based nanocomposites: One example of a polymer-based nanocomposite that is being used in medical implants is polyetheretherketone (PEEK) reinforced with carbon nanotubes (CNTs) [51,52]. PEEK is a biocompatible polymer that is used in a variety of medical implants, such as spinal cages and dental implants. Adding CNTs to PEEK can improve its mechanical properties, such as strength and stiffness, and enhance its wear resistance. CNTs are known for their excellent mechanical properties, such as high tensile strength and stiffness, and adding them to PEEK can result in a nanocomposite with improved mechanical performance. In addition, CNTs can also impart electrical conductivity to the polymer, which can be useful for some implant applications. Other polymer-based nanocomposites that are being investigated for medical implant applications include polylactic acid (PLA) reinforced with nanoparticles [53,54] and hydroxyapatite nanoparticles dispersed in polyethylene glycol (PEG) [55] for bone tissue engineering.

Metal-based nanocomposites: Metal-based nanocomposites are being investigated for a variety of medical implant applications, including orthopaedic and dental implants. One example is titanium dioxide (TiO_2) nanoparticles dispersed in titanium alloys. TiO_2 can improve the corrosion resistance and biocompatibility of titanium alloys [56], which are commonly used in orthopaedic and dental implants. TiO_2 is also known for its photocatalytic properties, which can be harnessed to develop implant coatings that have antimicrobial properties and can help prevent implant-associated infections [57,58]. Another example is silver nanoparticles dispersed in or coated on stainless steel, which can impart antimicrobial properties to the metal and reduce the risk of implant-associated infections [59]. Silver is a known antimicrobial agent and has been used in various medical devices to prevent infections. By incorporating silver nanoparticles into the stainless steel matrix, the resulting nanocomposite can provide sustained antimicrobial properties without the need for additional coatings or surface treatments.

Table 2. Examples of nanocomposites that can enhance the performance of biomedical devices.

Medical Implant	Nanocomposite Material	Enhancements
Orthopaedic Implants	Carbon nanotube-reinforced polymer	Increased mechanical strength and durability
	Hydroxyapatite/polymer composite	Enhanced bone integration and bioactivity
Dental Implants	Graphene oxide-coated titanium	Improved osseointegration and antimicrobial effect
	Nanoclay-reinforced dental resin	Higher mechanical performance and wear resistance
Cardiovascular Stents	Sirolimus-eluting nanocomposite	Controlled drug release and biocompatibility
	Magnesium-based nanocomposites	Degradable, mechanical strength, biocompatibility
Cochlear Implants	Titania nanotube coating	Enhanced bioactivity and biocompatibility
Soft Tissue Implants	Nanofiber-reinforced hydrogel	Mechanical strength and tissue integration
Bone Cements	Hydroxyapatite/zinc oxide composite	Improved mechanical properties and antimicrobial
Spinal Implants	Carbon nanotube/polyetheretherketone composite	Increased mechanical strength and biocompatibility
Sutures	Silver nanoparticle-coated sutures	Antimicrobial properties and improved tissue healing
Wound Dressings	Chitosan/silver nanoparticle composite	Antimicrobial, biodegradable, and wound healing
Drug Delivery Systems	Polymeric nanoparticles	Targeted drug delivery and controlled release
Nerve Conduits	Chitosan/gold nanoparticle composite	Enhanced electrical conductivity and nerve regeneration
Ocular Implants	Polymeric nanoparticles	Controlled drug release and biocompatibility
Craniofacial Implants	Bioactive glass/polymer composite	Enhanced osteointegration and bioactivity
Tissue Scaffolds	Nanofiber-based scaffolds	Improved cell adhesion, proliferation, and differentiation

Ceramic-based nanocomposites: Ceramic-based nanocomposites are being explored for a range of medical implant applications, such as orthopaedic and dental implants. One example is zirconia (ZrO_2) nanoparticles dispersed in alumina (Al_2O_3) ceramics [60]. ZrO_2 can enhance the mechanical strength, fracture toughness, and wear resistance of alumina ceramics and is also known for its biocompatibility, making it a suitable material for medical applications.

Another example is hydroxyapatite (HA) nanoparticles incorporated into bioactive glass [61,62]. HA is a naturally occurring bioceramic that resembles the mineral component of bone and has excellent biocompatibility and osteoconductive properties. By integrating HA nanoparticles into a bioactive glass matrix, the resulting nanocomposite can promote bone growth and regeneration, making it ideal for bone graft substitutes and dental implant applications.

Moreover, ceramic-based nanocomposites containing silver nanoparticles are being investigated for their antimicrobial properties [63]. By incorporating silver nanoparticles into ceramic matrices, the resulting nanocomposite can provide sustained antimicrobial properties, reducing the risk of implant-associated infections.

In addition to the examples discussed above, there are many other types of nanocomposites that are being explored for medical implant applications, such as graphene-based nanocomposites and hybrid nanocomposites that combine multiple types of nanoparticles. As research in this area continues, it is likely that new nanocomposites with novel properties and applications will be developed. However, it is important to note that the use of nanocomposites in medical implants is still a relatively new field, and there are several challenges that need to be addressed, such as optimising the nanoparticle–matrix interface, ensuring long-term stability and biocompatibility, and developing standardised testing methods to evaluate the safety and performance of these materials. Despite these challenges, the potential benefits of nanocomposites in medical implant applications make them an exciting area of research, and it is likely that they will play an increasingly important role in the development of next-generation medical implants.

4. Strategies for Enhancing Implant Performance with Nanocomposites

In this section, we will explore various strategies for improving the performance of implants using nanocomposites. These strategies are illustrated in Figure 5.

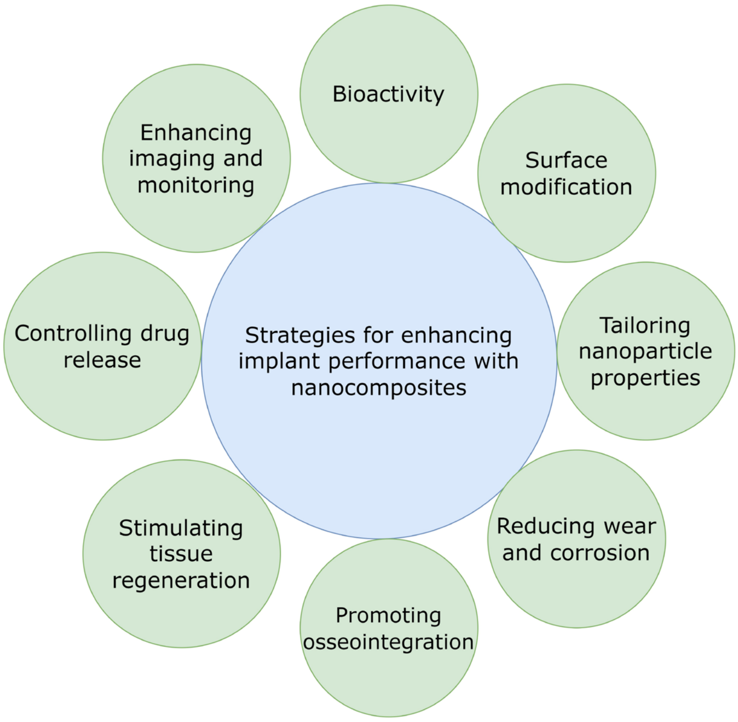

Figure 5. An overview of strategies for enhancing the performance of medical implants with nanocomposites.

4.1. Surface Modification

Surface modification using nanocomposites is a powerful strategy to improve the performance of implants. This approach involves altering the surface properties of the implant material to enhance its biocompatibility, promote osseointegration, or introduce bioactive properties. Surface modification can be achieved through various techniques, including coating, chemical functionalisation, or nanopatterning.

4.1.1. Nanocomposite Coatings

Applying nanocomposite coatings to an implant's surface can improve its mechanical properties, biocompatibility, and corrosion resistance. For example, bioactive glass nanoparticles can be applied to the surface of metallic implants, fostering a favourable environment for bone growth and integration, and decreasing the likelihood of implant loosening [64]. Similarly, copper nanoparticle coatings have the potential to provide antimicrobial properties to implant surfaces, thus reducing the risk of infection [65].

4.1.2. Chemical Functionalisation

Functionalising the implant surface with specific chemical groups or biomolecules can introduce desired properties or bioactivity. This can be achieved through the attachment of nanoparticles with specific functional groups or biomolecules. For instance, tyrosol-functionalised chitosan gold nanoparticles can be used to modify the surface of medical implants, combating fungal infections, enhancing biocompatibility, and promoting cell adhesion [66].

4.1.3. Nanopatterning

Creating nanoscale patterns or textures on the implant surface can significantly influence cellular behaviour, such as adhesion, proliferation, and differentiation. Nanopatterning techniques can be used to introduce nanocomposite materials onto the implant surface, creating a topography that promotes tissue integration. For example, titanium implants with nanopatterned surfaces incorporating hydroxyapatite or bioactive glass nanoparticles have demonstrated improved osseointegration compared to conventional implants [67].

4.2. Tailoring Nanoparticle Properties

The unique properties of nanoparticles can be tailored to optimise their performance within nanocomposite implant materials. By controlling the size, shape, chemical composition, and surface properties of nanoparticles, researchers can create implant materials with enhanced biocompatibility, mechanical strength, and bioactivity. This section will discuss various strategies for tailoring nanoparticle properties and their potential implications for implant performance.

4.2.1. Size and Shape Control

The size and shape of nanoparticles can significantly influence their properties and interactions with biological systems. For example, smaller nanoparticles typically have a higher surface area-to-volume ratio, which can enhance their reactivity and cellular uptake. Researchers can control the size and shape of nanoparticles using various synthesis methods, such as sol–gel, hydrothermal, and precipitation techniques. By tuning these parameters, researchers can optimise nanoparticle properties for specific applications, such as bone regeneration, drug delivery, or imaging [68].

4.2.2. Chemical Composition

The chemical composition of nanoparticles can be tailored to impart desired properties, such as biocompatibility, antimicrobial activity, or bioactivity. For example, silica (SiO_2) nanoparticles display excellent biocompatibility and can promote cell adhesion and proliferation, making them suitable for applications in tissue engineering and regenerative medicine [69,70]. In contrast, zinc oxide (ZnO) nanoparticles possess antimicrobial properties, which can be advantageous in lowering the risk of infection associated with implant materials [71].

4.2.3. Surface Functionalisation

Modifying the surface properties of nanoparticles can significantly impact their interactions with biological systems and their performance within nanocomposite implant materials. Surface functionalisation can involve the attachment of specific chemical groups, biomolecules, or targeting ligands to the nanoparticle surface. For example, functionalising titanium dioxide (TiO_2) nanoparticles with poly-lactic-co-glycolic acid (PLGA) can enhance their stability and biocompatibility when incorporated into orthopaedic and dental implant materials, potentially improving osseointegration and reducing the risk of implant failure [72].

4.2.4. Core–Shell Nanoparticles

Core–shell nanoparticles consist of a core material surrounded by a shell of a different material, providing an additional level of control over the nanoparticle properties. By adjusting the core and shell materials, researchers can create nanoparticles with tuneable optical, magnetic, or electrical properties. For instance, magnetic core–shell nanoparticles can be used to enhance the contrast in magnetic resonance imaging (MRI), while also providing a platform for targeted drug delivery or hyperthermia treatment [73].

4.2.5. Doping and Alloying

Doping refers to the introduction of trace amounts of foreign elements into a nanoparticle's crystal lattice, while alloying involves the formation of a homogeneous mixture of two or more elements. Both doping and alloying can be employed to modulate the properties of nanoparticles, such as electrical conductivity, magnetism, or catalytic activity. For example, doping titanium dioxide nanoparticles with nitrogen can enhance their cytotoxicity properties [74], while alloying copper and silver nanoparticles can generate a material with adjustable electrical conductivity and antimicrobial properties [75].

4.3. Reducing Wear and Corrosion

Wear and corrosion are critical factors affecting the performance and durability of implant materials. Prolonged exposure to the physiological environment and mechanical stresses can cause material degradation and the release of wear debris, which may lead to complications such as inflammation, osteolysis, or implant failure. Nanocomposites offer a promising approach for reducing wear and corrosion in implant materials. In this section, we will explore a range of approaches that employ nanocomposites to reduce wear and corrosion, and the possible impacts these strategies may have on the performance of implants.

4.3.1. Nanoscale Reinforcement

Incorporating nanoparticles into implant materials can significantly enhance their mechanical properties, such as hardness and wear resistance. These nanoparticles can act as reinforcing agents, improving the material's load-bearing capacity and reducing wear under mechanical stress. For example, the addition of carbon nanotubes, graphene, or nanodiamonds to polymeric or metallic implant materials can result in a significant improvement in wear resistance [76].

4.3.2. Protective Nanocomposite Coatings

Nanocomposite coatings can be applied to the surface of implant materials to provide a protective barrier against wear and corrosion. These coatings can be tailored to exhibit excellent adhesion, hardness, and wear resistance, prolonging the service life of the implant. For instance, diamond-like carbon (DLC) coatings can improve the tribological properties and corrosion resistance of metallic implants [77,78].

4.3.3. Corrosion-Resistant Nanoparticles

Incorporating corrosion-resistant nanoparticles into implant materials can improve their overall corrosion resistance. These nanoparticles can alter the material's electrochemical properties, reducing the rate of corrosion in the physiological environment. For example, incorporating noble metal nanoparticles, such as gold or platinum, into implant materials can enhance their corrosion resistance due to the inert nature of these metals [79].

4.3.4. Self-Healing Nanocomposites

Self-healing nanocomposites can be engineered to repair or regenerate their surface upon exposure to wear or damage, minimising the impact of wear and corrosion. These materials can incorporate nanoparticles or nanocapsules that release healing agents, such as polymers or corrosion inhibitors, in response to damage or environmental triggers. For instance, a self-healing hydrogel containing microcapsules loaded with healing agents has been developed for potential use in cartilage repair applications. The microcapsules can release the healing agents in response to mechanical wear or damage, facilitating the recovery of the hydrogel and providing a supportive matrix for cell growth, ultimately enhancing the durability and biocompatibility of the implant [80].

4.3.5. Multi-Functional Nanocomposites

Multi-functional nanocomposites can be designed to address various challenges associated with wear and corrosion, such as bacterial infection, inflammation, or insufficient osseointegration. By incorporating multiple types of nanoparticles, researchers can create implant materials with synergistic properties that enhance wear and corrosion resistance while addressing other clinical needs. For example, a nanocomposite material containing both wear-resistant and antimicrobial nanoparticles can improve implant durability while reducing the risk of infection [81].

4.4. Promoting Osseointegration

Osseointegration is a critical factor for the long-term success of orthopaedic and dental implants, as it ensures a stable and functional connection between the implant and the surrounding bone tissue. Nanocomposites can play a significant role in promoting osseointegration by providing a suitable surface structure, composition, and bioactivity that encourage bone cell adhesion, proliferation, and differentiation. In this section, we will explore various strategies that employ nanocomposites to enhance osseointegration and discuss the potential impact of these approaches on implant performance.

4.4.1. Nanoscale Surface Topography

The surface topography of an implant material plays a crucial role in promoting osseointegration. Research has shown that nanoscale surface roughness can significantly improve bone cell attachment and growth. By incorporating nanoparticles into the implant material or creating nanopatterned surfaces, researchers can develop implant materials with a topography that promotes osseointegration. For instance, titanium implants coated with hydroxyapatite nanoparticles or bioactive glass nanoparticles can encourage bone cell adhesion and growth, leading to improved osseointegration compared to conventional implants [82,83].

4.4.2. Bioactive Nanoparticle Coatings

Coating the implant surface with bioactive nanoparticles can enhance osseointegration by providing a favourable environment for bone cell adhesion and proliferation. For example, graphene oxide nanoparticles exhibit good biocompatibility and osteoconductive properties, making them an effective coating material for orthopaedic and dental implants [84]. In another example, mesoporous bioactive glass nanoparticles have been employed as a coating for titanium implants, which can release bioactive ions that stimulate bone cell activity and promote the formation of new bone tissue, enhancing the overall osseointegration process [85].

4.4.3. Controlled Release of Osteogenic Factors

Nanocomposites can be designed to release osteogenic factors, such as bone morphogenetic proteins (BMPs) or other growth factors, in a controlled manner. These factors can stimulate bone cell proliferation and differentiation, promoting osseointegration at the implant site. For example, incorporating a BMP-loaded hydroxyapatite nanoparticle coating on a titanium dental implant can provide a sustained release of osteogenic factors, enhancing the osseointegration of the implant [86].

4.4.4. Stimuli-Responsive Nanocomposites

Stimuli-responsive nanocomposites can change their properties in response to external stimuli, such as temperature, pH, or light. This dynamic behaviour can be exploited to promote osseointegration by modulating the release of bioactive molecules, adjusting the implant's mechanical properties, or altering the surface topography. For example, thermo-responsive nanocomposite hydrogels can release osteogenic factors in a temperature-dependent manner, providing a controlled stimulus for bone cell activity and osseointegration [87].

4.5. Stimulating Tissue Regeneration

Tissue regeneration is a vital aspect of the healing process and implant integration, as it ensures the restoration of functionality and structural integrity of damaged tissue. Nanocomposites can be employed to stimulate tissue regeneration through various strategies, such as providing a supportive scaffold, releasing bioactive molecules, or modulating cellular responses. In this section, we will examine various approaches that employ nanocomposites to enhance tissue regeneration and discuss the potential implications of these strategies on implant performance.

4.5.1. Nanocomposite Scaffolds

Nanocomposite materials can be used to fabricate porous scaffolds that provide a supportive structure for tissue regeneration. These scaffolds can mimic the native extracellular matrix and facilitate cell adhesion, proliferation, and differentiation. For example, nanocomposite scaffolds containing nanoclay [88] or strontium-doped bioactive glass [89] nanoparticles can promote bone regeneration by providing a suitable environment for bone cell growth and mineralisation.

4.5.2. Controlled Release of Bioactive Molecules

Nanocomposites can be engineered to release bioactive molecules, such as growth factors, cytokines, or small molecule drugs, in a controlled manner. These factors can stimulate cellular responses, such as cell proliferation, migration, and differentiation, promoting tissue regeneration at the implant site. For instance, nanocomposite hydrogels incorporating vascular endothelial growth factor-loaded nanoparticles can promote angiogenesis and accelerate the healing process in damaged tissues [90,91].

4.5.3. Modulation of Cellular Responses

Nanocomposites have the potential to regulate cellular behaviour by altering the implant material's properties, such as surface texture, chemical composition, and mechanical properties. By carefully adjusting these features, researchers can develop implant materials that foster specific cellular responses and tissue restoration. Nanostructured surfaces, for example, can boost cell attachment and growth, while the integration of bioactive nanoparticles can encourage cell specialisation and extracellular matrix synthesis [92].

4.5.4. Adaptive Nanocomposites

Adaptive nanocomposites have the ability to modify their properties in response to external factors, such as temperature, pH, light, or magnetic field. This dynamic behaviour can be harnessed to support tissue regeneration by controlling the release of bioactive molecules, fine-tuning the implant's mechanical properties, or adjusting the surface texture. For instance, pH-sensitive nanocomposite hydrogels can discharge bioactive molecules when there are changes in the local pH, offering a targeted and controlled therapeutic impact [93].

4.6. Controlling Drug Release

Controlling drug release is essential for optimising therapeutic outcomes, minimising side effects, and reducing the risk of complications associated with implantation. Nanocomposites offer a versatile platform for designing implant materials with controlled drug release profiles, tailored to specific clinical needs. In this section, we will discuss different strategies for controlling drug release using nanocomposites.

4.6.1. Nanoparticle-Loaded Implant Materials

Nanoparticles can be used as drug carriers and incorporated into implant materials, providing a controlled and localised drug release. The drug release rate can be tailored by adjusting the nanoparticle properties, such as size, shape, or surface chemistry, and the composition of the nanocomposite matrix. For example, polymeric implants containing drug-loaded mesoporous silica nanoparticles can provide a sustained release of therapeutic agents, minimising the need for repeated drug administration [94].

4.6.2. Layer-by-Layer Nanocomposite Coatings

Layer-by-layer nanocomposite coatings can be applied to implant surfaces to create a multi-layered structure that controls drug release. These coatings can consist of alternating layers of nanoparticles and polymers, providing a tuneable drug release profile by adjusting the number of layers, the type of nanoparticles, and the choice of polymers. For instance, layer-by-layer coatings incorporating drug-loaded nanoparticles and biodegradable polymers can provide a controlled release of therapeutic agents over an extended period [95].

4.6.3. Dynamic Nanocomposites

As mentioned before, dynamic or stimuli-responsive nanocomposites are capable of altering their properties in response to external factors, including electric fields, enzymatic activity, temperature, pH, or light. This adaptable behaviour can be utilised to regulate drug delivery through the manipulation of the implant's swelling, degradation, or permeability. For example, thermo-responsive nanocomposite hydrogels can release drugs in a temperature-dependent manner, providing a controlled and localised therapeutic effect [96].

4.6.4. Magnetic- and Ultrasound-Triggered Drug Release

Nanocomposites containing magnetic- or ultrasound-responsive nanoparticles can be used to control drug release in response to external magnetic or ultrasound fields. These external stimuli can be applied non-invasively and precisely, enabling on-demand drug release and reducing the risk of systemic side effects. For instance, magnetic nanoparticle-loaded implants can release drugs upon the application of a magnetic field [97], while ultrasound-responsive nanocomposites can release drugs in response to focused ultrasound [98].

4.6.5. Hybrid Nanocomposites

Hybrid or multi-functional nanocomposites can be designed to address various challenges associated with drug delivery, such as targeting specific tissues, minimising side effects, or providing a combination of therapies. By incorporating multiple types of nanoparticles or drugs, researchers can create implant materials with synergistic properties that improve therapeutic outcomes. For example, a nanocomposite implant containing both chemotherapy-loaded nanoparticles and magnetic nanoparticles can provide targeted drug delivery and hyperthermia treatment, enhancing the efficacy of cancer therapy [99].

4.7. Enhancing Imaging and Monitoring

Non-invasive imaging and monitoring of implant materials are essential for evaluating implant integration, assessing tissue regeneration, and detecting potential complications, such as infection or implant failure. Nanocomposites offer a promising platform for developing implant materials with enhanced imaging and monitoring capabilities. This section will discuss various strategies for enhancing imaging and monitoring using nanocomposites.

4.7.1. Contrast-Enhancing Nanoparticles

Incorporating contrast-enhancing nanoparticles into implant materials can improve the visibility and detection of implants in various imaging modalities, such as X-ray, computed tomography (CT), or magnetic resonance imaging (MRI). For example, gold nanoparticles can enhance X-ray and CT imaging due to their high atomic number and electron density [100], while iron oxide nanoparticles can improve MRI contrast due to their magnetic properties [101].

4.7.2. Fluorescent and Luminescent Nanoparticles

Fluorescent and luminescent nanoparticles can be incorporated into implant materials for optical imaging and monitoring applications. These nanoparticles can emit light upon excitation, allowing for the visualisation and tracking of implant materials in vivo. For instance, quantum dots or upconversion nanoparticles can be used for fluorescence imaging [102], while persistent luminescent nanoparticles can enable long-lasting luminescence imaging [103].

4.7.3. Multi-Modal Imaging Nanocomposites

Multi-modal imaging nanocomposites can be designed to enhance the detection and monitoring of implant materials across multiple imaging modalities. By incorporating different types of contrast-enhancing nanoparticles, researchers can create implant materials that provide complementary imaging information, improving diagnostic accuracy and enabling a more comprehensive assessment of implant performance. For example, a novel textile scaffold integrated with superparamagnetic iron oxide nanoparticles can concurrently enhance computed tomography and MRI for biomedical implants [104].

4.7.4. Stimuli-Responsive Imaging Nanocomposites

Stimuli-responsive imaging nanocomposites can change their properties in response to external stimuli or changes in the local environment, providing real-time information about the implant's status and the surrounding tissue. For example, pH-sensitive fluorescent nanoparticles can be used to monitor local pH changes, which can be indicative of inflammation or infection, while thermo-responsive nanoparticles can enable temperature mapping and monitoring of implant materials [87,96].

4.7.5. Theranostic Nanocomposites

Theranostic nanocomposites combine diagnostic imaging and therapeutic functionalities in a single implant material, enabling simultaneous monitoring and treatment of various clinical conditions. These materials can provide real-time feedback on the efficacy of a therapeutic intervention, allowing for the optimisation of treatment strategies and improved patient outcomes. For instance, a nanocomposite containing both drug-loaded nanoparticles and contrast-enhancing nanoparticles can enable image-guided drug delivery and monitoring of the therapeutic response [105].

4.8. Bioactivity

Bioactivity refers to the ability of a material to interact with biological systems and elicit specific cellular responses that promote tissue integration, healing, and regeneration. Nanocomposites can be employed to enhance the bioactivity of implant materials, leading to improved performance.

4.8.1. Mimicking Natural Tissue Structures

Nanocomposites can be designed to mimic the structure and composition of natural tissues, creating a more favourable environment for cellular attachment and tissue integration. For instance, integrating tantalum pentoxide nanoparticles into polyetheretherketone implant materials can closely resemble the native bone structure, encouraging bone cell adhesion and proliferation [106].

4.8.2. Bioactive Molecule Incorporation

Nanocomposites can be engineered to incorporate bioactive molecules, such as growth factors, proteins, or peptides, which can stimulate cellular responses and tissue regeneration. These bioactive molecules can be gradually released from the nanocomposite material, providing a localised and controlled stimulus for tissue healing. For example, nanocomposite hydrogels containing vascular endothelial growth factor can promote angiogenesis and accelerate the healing process in damaged tissues [107].

4.8.3. Surface Functionalisation

The surface properties of biomedical implant materials are critical in determining their bioactivity. By functionalising the implant surface with specific chemical groups, biomolecules, or nanoparticles, researchers can create an optimal environment for cell adhesion, proliferation, and differentiation. For instance, the surface modification of implants with bioactive peptides, such as RGD (arginine–glycine–aspartate), or with the addition of nanostructured hydroxyapatite coatings can significantly enhance the biocompatibility of the implants and promote cellular attachment, ultimately improving osseointegration [82,108].

4.8.4. Stimuli-Sensitive Nanocomposites

Stimuli-responsive nanocomposites can be engineered to alter their properties in response to external factors such as light, pH, temperature, magnetic fields, electrical stimulation, or specific chemical agents. These dynamic modifications can be harnessed to regulate the bioactivity of the implant material, facilitating the controlled release of bioactive molecules or fine-tuning the implant's mechanical properties to align with the adjacent tissue. For instance, magnetically responsive nanocomposite hydrogels can be utilised to discharge bioactive molecules under the influence of an external magnetic field, offering a precise and localised therapeutic impact for orthopaedic applications [109].

5. Challenges and Future Directions

In this section, we will discuss the challenges and future directions associated with the application of nanocomposites in enhancing the performance of medical implants. Table 3 lists a summary of current challenges and their potential solutions. By identifying the current obstacles and exploring the potential advancements in nanocomposite technology, we aim to provide a comprehensive outlook on the future of medical implants and their ability to address individual clinical needs while improving patient outcomes.

Table 3. Challenges and potential solutions for the use of nanocomposites in medical implants.

Challenges	Potential Solutions
Biocompatibility and Toxicity	- Investigate and optimise the composition, size, and surface properties of nanofillers
	- Develop coatings or surface treatments to enhance biocompatibility
	- Conduct long-term in vivo studies to assess safety, biocompatibility, and implant lifetime
Long-term Stability	- Investigate the effects of implant geometry, loading, and environmental conditions on stability
	- Optimise nanofiller loading and dispersion to achieve desired mechanical performance
	- Study degradation mechanisms and develop strategies to prevent premature implant failure

Table 3. *Cont.*

Challenges	Potential Solutions
Manufacturing and Scalability	- Develop advanced manufacturing methods such as 3D printing and electrospinning
	- Optimise existing processing techniques to better control nanofiller dispersion and size
	- Investigate scalable and eco-friendly fabrication approaches
Regulatory Approval	- Conduct comprehensive safety and biocompatibility studies
	- Collaborate with regulatory agencies to establish clear guidelines and standards
	- Develop standardised testing protocols for nanocomposite implants
Standardisation and Quality Control	- Establish industry standards for nanocomposite materials and their characterisation
	- Implement robust quality control measures throughout the manufacturing process
	- Develop standardised testing protocols for assessing the performance of nanocomposite implants
Interdisciplinary Collaboration	- Encourage collaborations between researchers, manufacturers, and regulatory agencies
	- Promote interdisciplinary research involving materials science, biology, and engineering
	- Foster partnerships between academia and industry to accelerate the translation of research into clinical applications
Public Perception and Acceptance	- Communicate the benefits and potential risks of nanocomposite implants to the public
	- Engage with patients and healthcare professionals to address concerns and gather feedback
	- Promote transparency and open dialogue between researchers, industry, and the public

5.1. Potential Challenges

Despite the promising potential of nanocomposites in medical implants, several challenges need to be addressed to ensure their successful development and implementation. Some of these challenges include the following.

5.1.1. Biocompatibility and Toxicity

Nanoparticles used in nanocomposites can have different biological properties to their bulk counterparts, potentially leading to concerns about biocompatibility and toxicity. It is crucial to thoroughly evaluate the biocompatibility of nanocomposite materials and any potential toxic effects on cells, tissues, or the immune system to ensure patient safety.

5.1.2. Long-Term Stability

The long-term stability of nanocomposites in the physiological environment is an essential factor to consider. The potential degradation or release of nanoparticles over time can affect the performance of an implant and may lead to adverse effects. Researchers must study the long-term behaviour of nanocomposites under physiological conditions to ensure their stability and durability.

5.1.3. Manufacturing and Scalability

Developing reliable and cost-effective manufacturing methods for nanocomposite materials can be challenging due to the complexity of the fabrication process and the need to maintain the desired properties of nanoparticles. The scalability of these manufacturing methods is crucial for the widespread adoption of nanocomposites in medical implants.

5.1.4. Regulatory Approval

The approval process for medical devices can be lengthy and complex, especially for novel materials such as nanocomposites. Ensuring that nanocomposite materials meet regulatory requirements for safety and efficacy is critical for their successful translation from the laboratory to clinical applications.

5.1.5. Standardisation and Quality Control

Establishing standardised protocols and methods for the synthesis, characterisation, and evaluation of nanocomposite materials is essential for ensuring consistency and reproducibility across studies. Quality control measures must be in place to confirm the desired properties and performance of nanocomposites in medical implants.

5.1.6. Interdisciplinary Collaboration

The development and implementation of nanocomposites in medical implants require collaboration across various disciplines, including materials science, biology, engineering, and clinical practice. Fostering interdisciplinary collaboration can help overcome challenges related to the design, synthesis, and evaluation of nanocomposite materials, as well as their translation to clinical applications.

5.1.7. Public Perception and Acceptance

Public perception and acceptance of nanotechnology and nanocomposite materials play a significant role in their successful implementation in medical implants. Addressing concerns about safety, ethics, and the potential impact on the environment is crucial for gaining public trust and acceptance.

By addressing these challenges, researchers can pave the way for the successful development and implementation of nanocomposites in medical implants.

5.2. Future Directions for Research and Development

As the potential of nanocomposite materials in medical implant applications becomes increasingly evident, research and development in this area will likely focus on addressing current challenges and exploring new possibilities. Some potential future directions include the following.

5.2.1. Developing Novel Nanocomposites

Researchers will likely continue to explore new nanocomposite materials with unique properties, such as enhanced mechanical strength, bioactivity, or drug release capabilities. This could involve investigating novel combinations of nanoparticles and matrices, as well as developing new synthesis and fabrication methods to optimise the performance of these materials.

5.2.2. Enhancing Biocompatibility and Bioactivity

Future research may focus on developing nanocomposite materials with improved biocompatibility and bioactivity to promote better integration with the host tissue, reduce inflammatory responses, and minimise the risk of implant rejection or failure.

5.2.3. Advanced Drug Delivery Systems

The development of nanocomposites for controlled and targeted drug delivery will continue to be an area of interest. Researchers may investigate new approaches to incorporating therapeutic agents into nanocomposite materials or develop stimuli-responsive systems that release drugs in response to specific triggers, such as pH, temperature, or enzymatic activity.

5.2.4. Multi-Functional Implants

The development of multi-functional nanocomposite implants that combine multiple therapeutic modalities, such as drug delivery, electrical stimulation, or photothermal therapy, could be a promising avenue for future research. These multi-functional implants could provide enhanced treatment outcomes by addressing various aspects of the disease or injury simultaneously.

5.2.5. Personalised Implants

Advancements in nanocomposite materials could contribute to the development of personalised implants, tailored to the specific needs of individual patients. This could involve designing implants with patient-specific geometries, mechanical properties, or bioactive coatings based on individual biological or anatomical factors.

5.2.6. In Situ Tissue Regeneration

Future research may explore the use of nanocomposite materials for in situ tissue regeneration, wherein the nanocomposite implant provides a temporary scaffold that promotes tissue regeneration and ultimately degrades, leaving behind healthy, functional tissue.

5.2.7. Advanced Imaging and Monitoring

Developing nanocomposite materials with unique imaging or sensing capabilities could enable more accurate and real-time monitoring of implant performance, tissue regeneration, or disease progression. This could help clinicians make more informed decisions about patient care and detect potential complications early.

5.2.8. Addressing Regulatory and Ethical Challenges

As investigations into nanocomposite materials continue to advance, researchers will need to work closely with regulatory agencies to ensure that these materials meet safety and efficacy requirements. Additionally, addressing ethical concerns related to the use of nanotechnology in medical implants will be crucial for ensuring public trust and acceptance.

Overall, the future of nanocomposites in medical implants is promising, with numerous opportunities for research and development. By exploring these avenues and addressing existing challenges, researchers can contribute to the advancement of nanocomposite materials and expanding treatment options for patients.

6. Conclusions

Nanocomposites have emerged as a promising class of materials with significant potential for enhancing the performance of medical implants. By harnessing the unique properties of nanoparticles and combining them with suitable matrix materials, researchers have been able to develop implants with improved mechanical strength, bioactivity, wear resistance, corrosion resistance, and controlled drug release. These advancements have the potential to greatly impact patient outcomes and expand the range of available treatment options.

This review has highlighted various strategies for enhancing implant performance using nanocomposites, such as tailoring nanoparticle properties, promoting osseointegration, stimulating tissue regeneration, controlling drug release, and enhancing imaging and monitoring.

Despite the numerous advancements in this field, there remain challenges that must be addressed for the successful development and implementation of nanocomposite materials in medical implants. These challenges include ensuring biocompatibility and long-term safety, addressing manufacturing and scalability concerns, navigating regulatory requirements, and fostering interdisciplinary collaboration. Additionally, future research directions in this area should focus on exploring novel nanocomposite materials, developing advanced fabrication techniques, and designing multi-functional and personalised implants.

By addressing these challenges and pursuing future research directions, the field of nanocomposites in medical implants can continue to progress, ultimately contributing to improved patient outcomes and a broader range of treatment options.

Author Contributions: Writing—original draft preparation, M.R.; writing—review and editing, M.R. and Z.M.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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