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Impact of Nanotechnology on Improving the Performance and Lifespan of Implants

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***Abstract:* -** The application of nanotechnology to enhance the performance and longevity of implants is a captivating and cutting-edge topic in biomedical engineering. This field encompasses a wide range of research and applications that ultimately contribute to improving patients' quality of life. The findings of this study demonstrate that nanotechnology, upon entering the medical realm, has revolutionized the performance of implants. By manipulating materials at the nanoscale, this technology enables the creation of novel surfaces and structures that exhibit enhanced biocompatibility and prolonged implant function. Key advantages include improved biocompatibility, enhanced mechanical properties, reduced risk of inflammation and infection, increased drug delivery efficiency, and the development of biomimetic materials. These advancements have a profound impact on the performance and longevity of implants. Recent strides in nanotechnology offer promising solutions to challenges such as the lack of standardized regulations, biocompatibility and immune response, and the high costs and limited insurance coverage in the medical field. Nanotechnology enables more precise treatments, durable materials, and minimally invasive procedures.

Keywords: Nanotechnology, dentistry, dental materials, implants, nanoparticles, nanocomposites

1-INTRODUCTION

The application of biomaterials, such as metals, composites, and polymers, in medical sciences has expanded significantly in recent years. These materials generally possess a combination of desirable biocompatibility and mechanical-physical properties. Implants, as human-made devices, represent a crucial and promising application of biomaterials for the physical or functional replacement of bodily organs. The external surface of implants, which is in direct contact with living tissue, is constructed from biomaterials and alloys that are resistant to the body's ionic environment (Spector et al., 1978; Gupte, Advani, 1999). Nanotechnology is now widely employed in implants, revolutionizing the field.

Nanotechnology is the manipulation of matter on an atomic, molecular, and supramolecular scale. This involves the creation of materials, devices, and systems with novel properties and functions due to their small size. At the nanoscale, where dimensions range from approximately 1 to 100 nanometers, materials exhibit unique characteristics influenced by quantum mechanical effects. One critical aspect of nanotechnology is the dramatic increase in surface area relative to volume as particle size decreases. This phenomenon significantly enhances the interaction between materials and their environment. In the context of implants, this increased surface area promotes greater interaction with surrounding cells, such as mesenchymal stem cells, which are crucial for bone integration and implant success (Sullivan et al., 2014).

Nanotechnology is one of the important advances in medical science, which has been able to create a huge revolution in this field due to the unique properties of nanometer materials at the molecular and atomic level. This technology provides the possibility of designing and manufacturing materials with new and improved properties that help to increase the efficiency and effectiveness of treatments (Andersen, 2016). Also, the use of nanometer materials in the construction of implants can improve their mechanical and biological properties. which ultimately helps to increase the lifespan and efficiency of implants (Tomisa et al., 2011).

The necessity of utilizing nanotechnology in implants has garnered significant attention due to its numerous advantages in enhancing implant performance and longevity. Traditional implants often face challenges such as incomplete osseointegration, infection risk, and inflammatory responses. Nanotechnology, through the creation of

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nanoscale surfaces and coatings, can facilitate improved tissue integration and reduce infection rates (Tran et al., 2009). Furthermore, nanotechnology enables the fabrication of implants with enhanced biological and mechanical properties, which can contribute to reduced complications and increased implant lifespan. Consequently, as acknowledged by many experts, the application of nanotechnology in implant design and fabrication can not only improve patients' quality of life but also reduce healthcare costs (Kumar et al., 2020).

Given the increasing demand and significance of implants and their constituent materials, this study, after introducing the fundamental principles and concepts of nanotechnology and its applications in implants, will discuss the impact of nanotechnology on implant performance, the types and classification of nanocomposites in implants, and finally, the challenges and future prospects of nanotechnology in implants.

2- Principles and concepts of nanotechnology in implants

2-1- Implant

1-An implant is a medical device inserted into the body to replace, support, or strengthen a damaged part. Dental and orthopedic implants are the most common types. However, as foreign bodies in the body, implants can trigger inflammatory and infectious responses. To mitigate these complications, implant surfaces are often coated with biocompatible materials to enhance compatibility with the body's environment. Despite these advancements, complications such as infection, inflammation, and even structural failure due to poor material quality or manufacturing processes remain significant challenges in implant use (Jin et al., 2012, Hoffmann et al., 1999).

Over the past few years, the impact of nanotechnology on implant field has begun to rise in a significant manner. Especially, nanomaterials with biological-inspired features are motivating the researchers to explore their role in performance improvement of conventional implants. Nowday bioimplants have emerged as a promising solution for neurological disorders, visual impairments, cardiovascular disease, orthopaedic issues, disfigurement, dental disorders, and other conditions (Fig. 1).

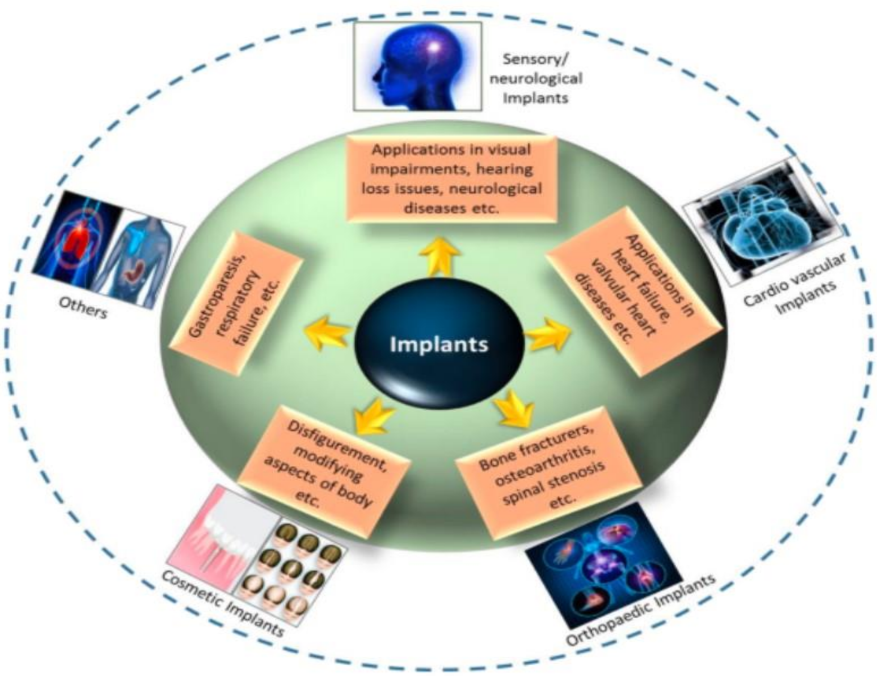

Fig.1. Application-oriented classification of bioimplants into sensory/neurological implants, cardiovascular implants, orthopaedic implants, cosmetic implants, and others(Kumar et al., 2020)

2-2. Nanostructured Surface of Implants:

Nanotechnology has revolutionized the field of medicine by providing new methods to improve the performance and longevity of implants. One of the primary applications of nanotechnology in implants is the nanostructuring of their surfaces to enhance tissue integration and reduce inflammation. This section explores the processes of nanostructuring implant surfaces and their impact on implant performance.

-Processes for Nanostructuring Implant Surfaces:

1. Anodization and UV Radiation: Anodization combined with UV radiation is used to create hydrophilic TiO_2 nanostructured surfaces. This process forms nanotubular structures that can modulate macrophage inflammatory responses and enhance implant performance (Ma et al., 2014).
2. Coating with Ceramic Nanoparticles: Coating implants with ceramic nanoparticles, such as CeO_2 nanoparticles, can impart antibacterial and anti-inflammatory properties. These coatings can reduce bacterial biofilm formation and control inflammation (Li et al., 2019).
3. Creating Nanopatterns: Nanopatterns such as nanoleaves and nanotubes can enhance osteoblast activity. For example, TiO_2 nanotubes with a diameter of 70 nanometers have been shown to reduce inflammatory responses and improve bone integration (Chamberlain et al., 2011).
4. Coating with Polymeric Nanoparticles: Using polymeric nanoparticles such as polycaprolactone and silicon oxide can reduce inflammatory responses and improve tissue integration (Ainslie et al., 2009).

Nanostructuring implant surfaces has brought significant advancements in the field of implantology. By creating nanoscale structures on the implant surface, their surface properties are significantly enhanced, leading to better integration with bone tissue and reduced complications associated with implants. These nanostructured surfaces promote improved bonding between the implant and the bone tissue, thereby reducing inflammation and increasing the overall success rate of implant surgeries.

-Nanostructured Coatings: Nanostructured coatings are nanometer-thin layers applied to the surface of implants. By creating structures at the nanoscale, these coatings significantly enhance the surface properties of implants, playing a crucial role in improving osseointegration and reducing the risk of infection. The mechanism of nanostructured coatings is such that they increase the surface area between the implant and bone, allowing bone cells to adhere and proliferate more easily. They act as scaffolds for bone cell growth, improving the rate and quality of bone formation. Nanostructured surfaces can prevent bacterial adhesion to the implant surface, thereby reducing the risk of infection and decreasing the body's inflammatory response to the implant. Some nanostructured coatings can slowly release bone growth factors, which can enhance the bone healing process (Ercan & Webster, 2010). Various types of nanostructured coatings exist for implants, each with its unique properties. The most important of these coatings include:

1. Nanotubular Titanium Surfaces

Production Method: These surfaces are produced through anodization in dilute hydrofluoric acid at a voltage of 20 volts for 20 minutes.

Features: This method creates uniform nanotubes on the titanium surface.
Effects: Significant increase in adhesion and proliferation of osteoblasts, as well as improved synthesis of intracellular proteins and calcium deposition (Yao et al., 2008).

2. Nanoparticulate Titanium Surfaces

Production Method: These surfaces are produced through anodization at a voltage of 10 volts for 20 minutes.

Features: This method creates heterogeneous nanoparticles on the titanium surface.
Effects: Improved alkaline phosphatase activity and collagen type I synthesis, but with less calcium deposition compared to nanotubular surfaces (Yao et al., 2008).

3. Hydrophilic Nanostructured TiO_2 Surfaces

Production Method: Utilizes anodization and UV radiation to create hydrophilic nanostructured. TiO2 surfaces.

Features: Creates nanotubular structures with varying diameters.
Effects: Nanotubes with a diameter of 70 nanometers showed the best results in reducing macrophage inflammatory response and improving bone integration (Chamberlain et al., 2011).

4. Hydroxyapatite (HA) Coatings

Features and Applications:

Hydroxyapatite (HA), with the chemical formula:

Ca10(PO4)6(OH)2\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2Ca10(PO4)6(OH)2, is a mineral that serves as the main component of bone and teeth. Due to its chemical and structural similarity to bone matrix, HA significantly enhances bone integration.

Advantages:

-High Biocompatibility: This material easily forms bonds with bone tissue.

-Increased Cellular Adhesion: Promotes adhesion and proliferation of osteoblasts (bone-forming cells).

-Applications: It is used as a coating in dental and orthopedic implants. Studies have shown that HA can increase the mechanical strength of implants while also enhancing bone bonding strength. There are various types of hydroxyapatite coatings, including plasma-sprayed coatings, biomimetic coatings, and electrochemical coatings (Habibovic et al., 2004).

5. Diamond-Like Carbon (DLC) Coatings

Features and Applications:

-Diamond-Like Carbon (DLC) is a hard, wear-resistant coating composed of carbon with a structure similar to diamond. These coatings are used in various medical devices due to their unique properties, particularly in joint and dental implants.

Advantages:

-High Hardness and Wear Resistance: Excellent resistance to wear and scratching.

-Biocompatibility: These coatings cause fewer inflammatory reactions and are well-tolerated by body tissues.

Applications: Utilized in joint implants to reduce friction and increase longevity. Also beneficial in dental surgery to reduce wear and extend the lifespan of implants (Ercan & Webster, 2010).

6. Polymeric Coatings

Features and Applications:

Polymers like polylactic acid (PLA) and polycaprolactone (PCL) are used in medical implants due to their biodegradability and biocompatibility. These materials can release drugs and growth factors gradually, facilitating the healing process.

Advantages:

-Biodegradability: Polymers are gradually absorbed by the body, eliminating the need for additional surgeries to remove them.

-Controlled Release of Growth Factors: Engineered to release various growth factors and drugs in a controlled manner (Shah et al., 2013).

-Applications: Particularly used in drug delivery systems and as coatings for dental and orthopedic implants.

7. Composite Coatings

Features and Applications:

Composite Coatings combine different materials, such as TiO2 and HA, to achieve superior properties. These composites are often used to attain optimal characteristics like wear resistance and biocompatibility.

Advantages:

-Combined Properties: Combining TiO2 with HA can enhance both bioactivity and wear resistance.

-Increased Adhesion and Reduced Inflammatory Reactions: These composites improve osteoblast adhesion and reduce inflammation (Webster., 2007).

Applications: Used in the production of advanced dental and orthopedic implants aimed at increasing durability and performance.

3. Nanocomposites and Their Applications in Implants

3.1. Definition and Basic Concepts

Nanocomposites are composite materials composed of nanoparticles or nanofillers dispersed in a matrix material. These composites combine the properties of the matrix material with those of the nanoparticles to create a material with superior performance characteristics. Nanocomposites are hybrid or heterogeneous materials produced by mixing polymers with inorganic solids (such as clays and oxides) at the nanoscale. Their structures are more complex than microcomposites and are strongly influenced by the structure, composition, interfacial interactions, and properties of the individual components. Nanocomposites are usually prepared through in situ growth and polymerization of a biopolymer and an inorganic matrix. Due to the rapid demand for these advanced materials, these nanocomposites are very useful in industries ranging from small to large and very large scales. These environmentally friendly materials, in addition to providing advanced technologies, offer more business opportunities for several industrial sectors such as automotive, construction, electronics and electrical, food packaging, and technology transfer (Sen, 2020).

Nanocomposites can be formed by blending inorganic nanoclusters, fullerenes, clays, metals, oxides, or semiconductors with numerous organic polymers or organic and organometallic compounds, biological molecules, enzymes, and sol-gel derived polymers (Fig 2).

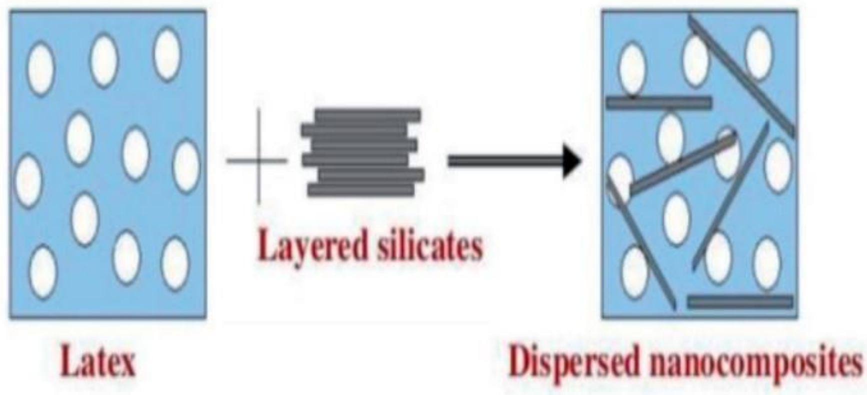

Fig 2.Formation of nanocomposite materials(Sen, 2020)

Nanocomposites, due to their unique properties, which are obtained from the combination of nanoscale components with various matrices, allow for significant improvement in the mechanical, thermal, electrical, and other properties of materials. These materials, by increasing the surface-to-volume ratio of nanoparticles, improve properties such as mechanical strength, hardness, thermal stability, and electrical conductivity. For example, polymer-based nanocomposites containing clay nanoparticles have improved mechanical properties and higher thermal stability compared to pure polymers (Sen, 2020). Therefore, due to the ability to improve mechanical properties, biocompatibility and other required characteristics, nanocomposites have shown great potential and ability to improve the performance of medical implants and various applications, including medical implants, which will be mentioned below:

1. Improved Mechanical Properties

Nanocomposites enhance the mechanical properties of implants, making them more durable and resistant to wear and tear. For instance, incorporating nano-sized NiTi particles into a magnesium alloy has been shown to improve compressive strength and elongation, which are essential for orthopedic applications. The study by Razzaghi et al. (2020) demonstrated that adding 15 wt% of NiTi nanoparticles led to a significant increase in compressive strength by 56% and elongation by 7.6%, compared to the pure magnesium alloy (Razzaghi et al., 2020).

2. Enhanced Biocompatibility

Nanocomposites can significantly improve the biocompatibility of implants, reducing the likelihood of adverse reactions and promoting better integration with body tissues. For example, PEDOT/FHA nanocomposite coatings on Ti-Nb-Zr implants have shown to enhance cell adhesion and proliferation, while also providing excellent surface protection against corrosion and bacterial infections. This makes the implants more suitable for long-term use in orthopedic applications (Madhan Kumar et al., 2019).

3. Antibacterial Properties

Nanocomposites can provide antibacterial properties to implants, reducing the risk of infection post-surgery. For instance, nanocomposites incorporating silver nanoparticles have shown significant antibacterial activity. The study by Pogrebnjak et al. (2019) found that Au-implanted (TiAlSiY)N/CrN nanocomposite coatings exhibited excellent antibacterial effects against both Gram-positive and Gram-negative bacteria, without significant surface contamination (Pogrebnjak et al., 2019).

4. Controlled Drug Delivery

Nanocomposites enable the controlled release of drugs at the implant site, which is beneficial for reducing inflammation and promoting healing. Chitosan/montmorillonite composite nanospheres, for example, have been developed for sustained antibiotic delivery to treat post-implantation bone infections. These nanocomposites provide prolonged release of antibiotics, ensuring effective management of infections while minimizing side effects (Kımna et al., 2019).

3- 2.Types of nanocomposites

Nanocomposite materials can be classified in the following way based on the presence or absence of polymeric material in the composite. The nanocomposites in which the compositions do not contain any polymers or polymer-derived materials are called non-polymer-based nanocomposites (Fig 3). Non-polymer-based nanocomposites are also known as inorganic nanocomposites. They can be further classified into metal-based nanocomposites, ceramic-based nanocomposites, and ceramic-ceramic-based nanocomposites.

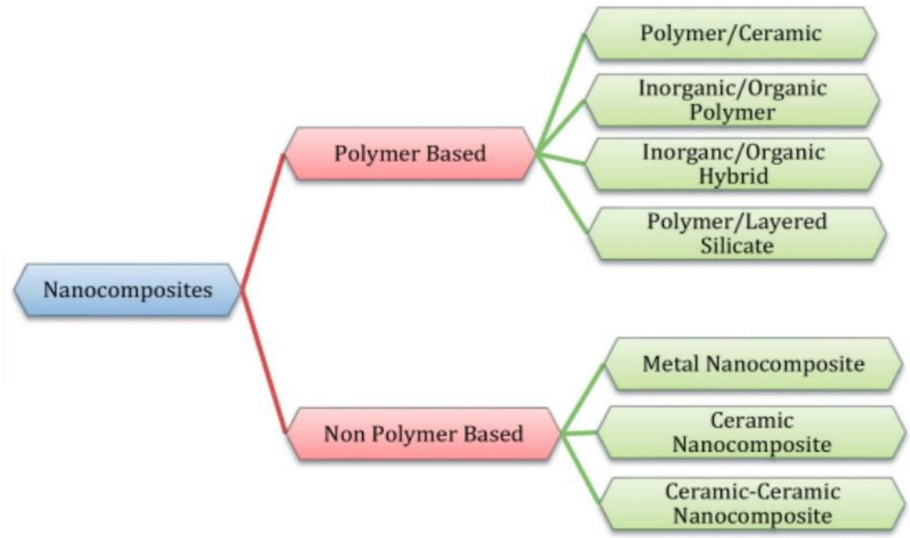

Fig 3. Classification of polymer- and non-polymer-based nanocomposites(Sen., 2020)

3-2-1- Non-Polymer-Based Nanocomposites

-Metal-Based Nanocomposites: Metal-based nanocomposites, especially bimetallic nanoparticles, have been extensively studied due to their enhanced catalytic and optical properties compared to single-metal counterparts. These nanocomposites can exist as alloy structures or core-shell structures, exhibiting novel electronic, optical, catalytic, or photocatalytic properties arising from the synergy between the two metals. They can be characterized by features such as: exceptional ductility, reduced melting points, increased strength and hardness, improved magnetic properties, increased electrical resistivity, and more (Chen, Li., 2011).

-Ceramic Nanocomposites: These composites utilize ceramics as the base material and exhibit excellent thermal and mechanical properties, making them suitable for high-temperature applications. They consist of a ceramic matrix reinforced with nanoparticles, endowing them with unique characteristics. In addition to high-temperature resistance, these composites possess exceptional thermal stability due to their strong crystalline structure and robust chemical bonds. Ceramic nanocomposites are generally very hard and tough, and these properties are further enhanced by the addition of nanoparticles to the ceramic matrix, making them resistant to wear and abrasion. Although ceramics are typically brittle, the addition of nanoparticles can improve their toughness, making them more resistant to cracking and fracture (Suryanarayana & Al-Aqeeli, 2013).

-Ceramic-Ceramic Nanocomposites:These nanocomposites consist of two or more ceramic phases, resulting in enhanced properties such as hardness and thermal resistance (Wang & Hu, 2006).

3-2-2- Polymer Nanocomposites

-Polymer/Ceramic Nanocomposites: These nanocomposites combine polymers with ceramic nanoparticles to enhance mechanical properties, thermal stability, and sometimes electrical conductivity. Consequently, these nanocomposites consist of a soft, flexible polymer matrix and hard, resistant ceramic nanoparticles at the nanoscale.

The addition of ceramic nanoparticles to the polymer matrix results in a three-dimensional network of particles within the matrix. This network enables a more uniform distribution of stresses throughout the material, preventing stress concentration at a single point (Pandey & Rana, 2005).

-Organic/Inorganic Polymer Nanocomposites: These nanocomposites comprise organic polymers with inorganic nanoparticles, improving properties such as flame resistance and mechanical strength. Due to their unique properties, these composites have gained significant attention in various industrial, electronic, medical, and environmental applications. The addition of inorganic nanoparticles like silica, carbon nanoparticles, and metal nanoparticles can enhance the strength, hardness, and creep resistance of organic polymers. In these nanocomposites, inorganic nanoparticles can increase the thermal conductivity of polymers and improve their glass transition temperature and thermal stability. Additionally, metallic and semiconducting nanoparticles can enhance the optical properties of nanocomposites, enabling their use in optoelectronic materials and displays (Masoud et al, 2022).

-Hybrid Organic/Inorganic Nanocomposites: Hybrid organic/inorganic nanocomposites are composite materials formed by combining an organic matrix (such as a polymer) and an inorganic phase (like ceramics, metals, or nanoparticles) at the nanoscale. This unique combination imparts properties to these materials that are not found in either of the individual components. Due to their diverse properties and tunability, hybrid organic/inorganic nanocomposites hold immense potential for applications in various industries, including medicine. With advancements in nanotechnology, the applications of these materials are expected to expand further in the future. Improved mechanical properties, high thermal resistance, and tunable electrical and optical properties are some of the most significant features of these types of composites (Shivalkar et al., 2023).

-Polymer/Layered Silicate Nanocomposites: Polymer/layered silicate nanocomposites are novel materials that have gained significant attention due to their superior properties compared to pure polymers or conventional composites. These nanocomposites exhibit improved physical, mechanical, and thermal properties, which are achieved by dispersing layered silicates at the nanoscale within the polymer matrix. In the following, we will examine various aspects of these nanocomposites:

1-Structure and Preparation Methods: Layered silicates are typically composed of clays such as montmorillonite and hectorite, which are widely used due to their high cation exchange capacity, large surface area, and high surface reactivity. To improve the dispersion of these silicates in the polymer matrix, long-chain alkyl ammonium or phosphonium cations are often used, which modify the surface of the silicates to become organophilic (Ray & Okamoto, 2003).

2- Improved Mechanical and Thermal Properties: Polymer/layered silicate nanocomposites, with low amounts of silicate fillers, enhance mechanical properties such as Young's modulus and tensile strength. Additionally, these materials exhibit improved thermal properties, increasing heat resistance, thermal stability, and flame retardancy (Mittal, 2009).

Various methods exist for preparing polymer/layered silicate nanocomposites, including in-situ polymerization, solution mixing, and melt mixing. Due to their improved mechanical and thermal properties, reduced gas permeability, and flame resistance, polymer/layered silicate nanocomposites are suitable alternatives to traditional composites in many applications. However, challenges such as uniform dispersion of nanoparticles and precise control of the final structure remain (Vermogen et al., 2005).

3-2-3. Uses of polymer nanocomposites

With respect to content expressed, Figure 3 shows the various uses of polymer nanocomposites irrespective of the nature of the field used. Many number of polymer nanocomposites for example, rubber, propylene, styrene butadiene rubber, and ethylene vinyl acetate are used in barrier applications.

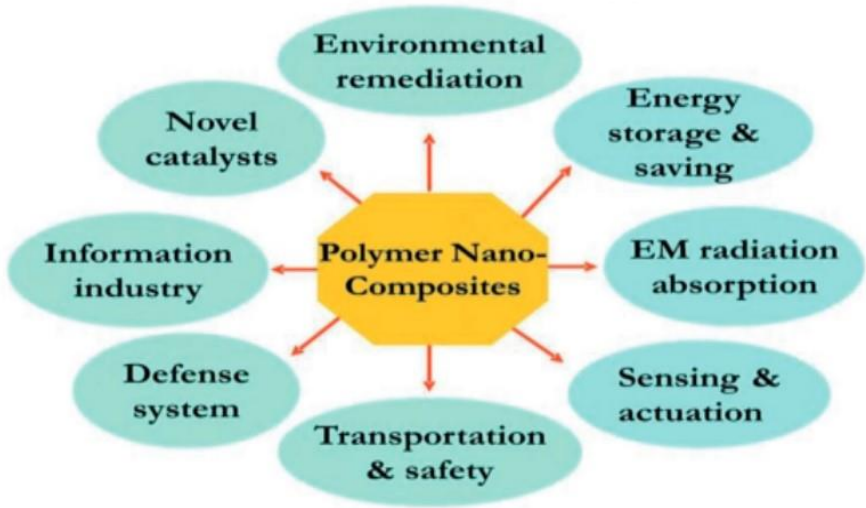

Figure 4.Various uses of polymer nanocomposites(Sen., 2020)

4- The Impact of Nanotechnology on Implant Performance

Nanotechnology has revolutionized the field of medicine, particularly in enhancing implant performance. By manipulating materials at the nanoscale, it enables the creation of novel surfaces and structures that exhibit greater biocompatibility and offer improved long-term implant function. This section delves into the effects of nanotechnology on implant performance and presents supporting scientific evidence:

4-1.Enhanced Biocompatibility and Osseointegration Nanotechnology

By creating nanoscale surface structures on implants, improves the initial interactions between the implant and surrounding tissues. These nanometer-scale surfaces enhance protein adsorption, blood clot formation, and cellular behavior, ultimately facilitating the migration, adhesion, and differentiation of mesenchymal stem cells. Since nanoscale surfaces more closely resemble the extracellular matrix of bone tissue, they increase the surface area for cell attachment, leading to improved osseointegration. Furthermore, the application of bioceramic nanoparticle coatings, such as hydroxyapatite (HA), on implant surfaces enhances biocompatibility by mimicking natural bone tissue (Lavenus et al., 2019).

4-2.Improved Mechanical Properties

Nanotechnology can enhance the mechanical properties of implants by incorporating nanoparticles or nanofillers into polymer, metal, or ceramic matrices. This can improve the strength, hardness, and wear resistance of implants. For instance, adding ceramic nanoparticles to metal matrices like aluminum and magnesium can enhance mechanical properties. These nanocomposites, when produced using appropriate dispersion techniques, can improve strength and creep resistance. Some studies have shown that polymers reinforced with ceramic nanoparticles such as titania and hydroxyapatite can improve mechanical properties including tensile modulus, yield strength, and compressive modulus. Metal-based nanocomposites reinforced with graphene have demonstrated superior mechanical strength and hardness compared to conventional composites. By employing suitable manufacturing processes, these composites can achieve significant improvements in mechanical properties (Webster, 2007).

4-3.Reduced Inflammation and Infection Risk

Nanoscale implant surfaces can mitigate inflammatory responses. Ceramic nanoparticles, such as CeO_2 nanoparticles, possess the ability to reduce inflammation and improve inflammatory responses. These materials can decrease the production of inflammatory cytokines and control inflammation (Li et al., 2019). Additionally, nanoscale implant surfaces can reduce bacterial adhesion and enhance antibacterial activity, thereby lowering the risk of infection. Nanophases of silver and selenium have been particularly effective in this regard, contributing to the prevention of infections (Sullivan et al., 2014).

4-4.Enhanced Drug Delivery via Implants

Nanotechnology can be employed to create intelligent drug delivery systems that release drugs directly from implants. These systems can deliver drugs in a controlled manner and to specific regions of the implant to prevent inflammation and infection (Andersen, 2016). Nanocomposite systems can enable the delivery of multiple drugs from a single implant, providing sustained and controlled drug release. These systems can utilize nanochannels and nanopumps to release drugs continuously at a constant rate, improving treatment efficacy and reducing the need for multiple dosing. Furthermore, nanocomposites can respond to environmental stimuli such as pH, temperature, and electrical signals, enabling smart drug release. For instance, pH-sensitive nanoparticles can release drugs in acidic environments, such as cancerous tissues, enhancing the precision and efficacy of treatment (Liu et al., 2014).

4-5.Production of Biomimetic Materials

Nanomaterials can create surfaces that mimic the natural structures of the body. These characteristics enhance biological activity and improve osseointegration of orthopedic and dental implants. Biomimetic materials, due to their structural similarity to natural tissues, can enhance the bioactivity of implants and accelerate the osseointegration process. For instance, amorphous calcium phosphate nanoscale coatings on titanium and tantalum implants can increase the adhesion and proliferation of osteoblast cells (Kumar et al., 2020). Today, biomimetic coatings are widely used to improve the bioactivity of orthopedic implants. These coatings, including hydroxyapatite and calcium phosphate, can facilitate direct bonding with bone and reduce post-surgical healing time (Koju et al., 2017). Existing scientific research has shown that one of the significant challenges in implants is preventing post-surgical infections. Fortunately, biomimetic materials can also act as antibacterial coatings to reduce the risk of infection. For example, silver nanoparticle coatings on titanium implants can effectively prevent bacterial growth (Liu et al., 2010).

5-Implant Longevity and Nanotechnology

Nanotechnology, as a significant scientific innovation, has had a considerable impact on the lifespan and efficiency of implants, especially medical implants. Implants, which play a crucial role in improving patients' quality of life, face numerous challenges such as corrosion, mechanical fatigue, and bacterial infections. The use of nanomaterials and nanoscale technologies can contribute to improving the mechanical and biological properties of implants, thereby increasing their lifespan. The remarkable advantages of nanotechnology in implants, which lead to increased lifespan, efficiency, and ultimately improved quality of life for patients, will be discussed in the following sections.

5-1.Reducing Failure Rates

The use of nanomaterials in implants can significantly reduce failure rates. Nanocomposites and nanoscale coatings can help improve the mechanical and biological properties of implants. These materials reduce failure rates by enhancing surface interactions with surrounding tissues and increasing biocompatibility. Nanocomposites include nanoparticles or nanofillers dispersed in a matrix material. These materials can enhance the performance of implants by improving their mechanical and biological properties. Nanocomposites can improve characteristics such as biocompatibility and resistance to wear and corrosion (Ramezani & Ripin, 2023).

Improving mechanical resistance, for instance, through the use of nickel-titanium (NiTi) nanoparticles in magnesium alloys, can lead to increased compressive strength and reduced grain size of the materials. These improvements enhance mechanical resistance and reduce the failure rates of implants (Razzaghi et al., 2020).

5-2. Corrosion Protection

Nanocoatings can enhance the corrosion resistance of implants. Nanocomposite coatings and nanoscale oxide layers can prevent metal corrosion and improve resistance to aggressive body environments .Some of these important coatings are as follows:

-Nanocrystalline coatings: Nanocrystalline coatings, such as nanoscale titanium-zinc phosphate coatings, can improve the corrosion resistance of WE43 magnesium alloy implants. These coatings reduce corrosion current density and increase resistance to simulated body environments (Li et al., 2021).

-PMMA-silica nanocomposite coatings: Polymethyl methacrylate-silica (PMMA-silica) nanocomposite coatings can act as a corrosion barrier and bioactive film on Ti6Al4V alloy. These coatings exhibit excellent corrosion resistance and long-term durability in simulated body solutions (Harb et al., 2020).

-Silk nanofiber coatings: Silk nanofiber coatings can increase the corrosion resistance of AZ31 magnesium alloy. These coatings, with nanopatterns created by oxygen plasma, improve antibacterial properties and biocompatibility (Mehrjou et al., 2020).

-Nanoengineered titanium coatings: Nanoengineered titanium coatings, such as titanium oxide nanolayers created by electrochemical anodization (EA), can increase the corrosion resistance and chemical stability of titanium dental implants. These coatings help reduce chemical corrosion and increase the bioactivity of implants (Guo et al., 2023).

-Silica/chitosan nanocomposite coatings: Silica/chitosan (SiO_2/CTS) nanocomposite coatings can improve the corrosion resistance of magnesium alloys. These coatings, by filling the voids in the chitosan coating, increase corrosion resistance in physiological environments (Ma et al., 2021).

5-3. Resistance to Mechanical Fatigue

Nanostructures can improve the mechanical fatigue resistance of implants. For instance, nanocrystalline surface modification can enhance fatigue strength and improve resistance to cyclic loading (Yang et al., 2020). Nanostructures, through various techniques and materials, significantly improve the mechanical fatigue resistance of implants. These advancements ensure longer-term and more reliable performance of medical implants. Some examples are as follows:

-Nanostructured titanium implants: Nanostructured titanium alloys exhibit significantly improved mechanical properties, including increased fatigue resistance. For example, a study showed that titanium with ultra-fine grains (UFG), processed through severe plastic deformation, demonstrated significant improvement in both static and cyclic strength, enabling the miniaturization of dental and surgical implants without compromising performance (Kazarinov et al., 2022).

-Hydrothermally grown TiO_2 nanorods: Coating titanium with TiO_2 nanorods (TNR) can improve both fatigue corrosion resistance and osteogenic properties. This coating enhances the adhesion, differentiation, and mineralization of bone marrow-derived mesenchymal stem cells (BMSCs) while also promoting a favorable immune response. This dual improvement can lead to better osseointegration and longer implant lifespan (Yang et al., 2020).

-**NiTi shape memory alloy nanocomposites:** NiTi-based shape memory alloys (SMAs) with heterogeneous nanohybrid structures exhibit high fatigue resistance and can withstand over 10^8 cycles of reverse phase transformation under significant stress. The combination of crystalline and amorphous phases at the nanoscale strengthens this alloy, improving yield strength and fatigue life (Hua et al., 2021).

-**Graded nanostructured metallic materials:** Materials with graded nanostructures possess superior mechanical properties, particularly in fatigue resistance. These materials suppress stress concentration and damage accumulation under cyclic loading, significantly improving fatigue life (Pan & Lu., 2020).

-**Severe plastic deformation (SPD) techniques:** SPD techniques, such as equal channel angular pressing (ECAP), can refine the grain size of metals like titanium and increase their strength and fatigue resistance. This process results in nanostructured titanium with exceptional mechanical properties, making it suitable for medical implants with improved fatigue performance (Balasubramanian et al., 2021).

5-4. Improved Monitoring and Maintenance

Nanotechnology can contribute to improved monitoring and maintenance of implants. This technology allows researchers to more accurately assess implant performance and take necessary actions quickly in case of any issues. The use of nanoscale smart coatings can lead to self-healing surfaces and antibacterial coatings, reducing the need for frequent repairs (Jaggessar et al., 2017). This technology enhances implant performance through various methods including nanocoatings, nanosensors, and nanogenerators.

Nano-Coatings: Nano-coatings on implants can improve corrosion resistance, reduce infection risk, and increase biocompatibility. These coatings enhance the surface properties of implants, facilitating better integration with body tissues and extending the implant's lifespan (Kumar et al., 2020).

Nanosensors: Nanosensors can monitor the condition of implants and detect problems before they cause serious damage. These sensors measure various parameters such as pressure, temperature, and chemical changes at the implant site, providing real-time data to healthcare providers. This technology is especially useful for monitoring bone healing and detecting potential infections (Sun., 2023).

Nanogenerators: Nanogenerators can provide the necessary power for sensors and other implanted devices. These devices convert mechanical energy into electricity, eliminating the need for external batteries and reducing the need for frequent surgeries to replace them, thereby increasing the implant's lifespan (Yoon & Kim., 2020).

Smart Systems: Smart implant systems utilizing nanotechnology are capable of self-monitoring and self-repair. These implants can detect mechanical and chemical changes and automatically respond, ensuring optimal performance and longevity (Gaobotse et al., 2022).

6. Challenges of Nanotechnology in Implants

While nanotechnology offers immense potential to enhance the performance and longevity of implants, it also presents several challenges and limitations. These include:

-Biocompatibility and Immune Response: The use of nanoparticles and nanomaterials in implants can sometimes trigger inflammatory or toxic reactions within the body, causing damage to living tissues. In some cases, unexpected or severe immune responses can lead to implant rejection or long-term health complications. Thus, developing nanomaterials with improved biocompatibility and designing protective coatings that minimize the body's immune response is crucial. Additionally, conducting rigorous and long-term clinical trials to assess the biological effects of nanomaterials is essential (Zhang et al., 2021). However, the challenge is how to properly mimic living bone tissue. There are three key parameters that significantly contribute to the development of improved orthopaedic implants: surface topography (i.e., nanoscale surface structuring for better optimization of osteoblast functions), surface chemistry (to control chemical surface properties of bioimplants), and wettability (i.e., better cell adhesion on hydrophilic surfaces) (Kumar et al., 2020).

-Controlling and Predicting Nanoparticle Behavior: The behavior of nanoparticles in biological environments can be unpredictable, and their distribution and stability may be inconsistent. For instance, in dentistry, the implant surface modification should cater to the three Is, integration (both osseo- and soft-tissue integration), inflammation and infection, in order to enable early acceptance and long-term survival. While multi-therapeutic nano-engineered implants have been applied, either by combining various drugs or through the inclusion of biopolymers or metal ions/nanoparticles, their effectiveness in compromised patients conditions including advanced age, diabetes or osteoporosis, has not been investigated (Zhang et al., 2021).Therefore, employing advanced technologies such as computational modeling and simulations to predict nanoparticle behavior and designing continuous monitoring systems to track their performance seems essential.

-**Cost and mass production:** The existence of high costs and complexities of nanomaterial production can create limitations in scalability and mass production. Therefore, investing in the research and development of cost-effective production technologies, improving production processes, and using high-scale manufacturing methods to reduce costs is a necessary thing that should be applied to improve the existing conditions in this field. So before commercialization of any new innovation in the biomedical field, there is a need to keep in mind their effects from a value-consciousness point of view. These effects can be classified into: (i) the impact on treatment quality in comparison to the pre-existing treatment options, e.g., reduction of morbidity, increase in implant life, and pain relief; (ii) the effect on value of treatment (relating to quality of treatment); and (iii) the effect on treatment costs in relation to already existing treatment options (Kumar., 2020).

-Safety and Toxicity: Nanoparticles can exhibit toxic properties and have adverse health effects that are not yet fully understood. Consequently, the success of both dental and non-dental implants is increasingly challenged in such patient conditions. Moreover, nanotechnology efforts to enhance soft tissue integration for improved biocompatibility have not been sufficiently investigated (Zhang et al., 2021). Therefore, conducting comprehensive toxicology studies and assessing the long-term effects of nanoparticles on human health and the environment is imperative.

-Standardization and Regulations: A significant challenge lies in the lack of clear standards and specific regulations, which can lead to legal issues and commercial hurdles. The inherent variability in the physical and chemical properties of nanomaterials makes it difficult to establish a standardized legal definition. This poses challenges in developing appropriate regulations for these substances. Furthermore, due to the unique characteristics of nanomaterials, reliable techniques for measuring and quantifying them are limited, complicating monitoring efforts (Lai et al., 2018).

However, efforts to address these issues have been initiated. For instance, the establishment of technical standardization committees has been a step in the right direction. The International Organization for Standardization (ISO) has created a technical committee to develop nanotechnology standards in various areas, including HSE (health, safety, and environment) and product specifications. These standards are expected to play a crucial role in driving nanotechnology development and shaping national and international regulations (Forsberg, 2011). To manage nanomaterial risks, voluntary programs have also been proposed. While these programs have had limited participation to date, they can serve as a defense against legal claims and play a significant role in risk management (Marchant, 2014)."

7-The Future of Nanotechnology in Implants:

Nanotechnology, as one of the most advanced and multifaceted scientific fields, has brought about significant transformations in the realm of medical implants and prostheses. This technology offers numerous capabilities to enhance the quality and efficiency of implants, which can significantly improve patient outcomes. Therefore, this section will explore two primary topics regarding the potential and future research directions of implants:

1.Potential of Nanotechnology in Implants:

-Enhanced Bone-Implant Integration: Studies have shown that nanomaterials, due to their larger surface area relative to their volume, exhibit enhanced interactions with the surrounding cellular environment of implants. This promotes mesenchymal stem cell differentiation and increases implant-bone integration, promising more efficient implant function (Sullivan et al., 2014).

-Reduced Bacterial Adhesion: Research has demonstrated that nanostructured coatings can reduce bacterial adhesion to prostheses, thereby decreasing the incidence of post-surgical infections (Sullivan et al., 2014).

-New Nanotechnology Coatings: The development of controlled nanometer-scale coatings demonstrates the potential to enhance the surface properties of implants and achieve greater success in their osseointegration (Zhang et al., 2021).

-Bioactive Materials and Nanomaterials: Research has shown that nanomaterials can mimic the surface properties of natural tissues, thereby improving cell adhesion and mitigating issues related to corrosion and bacterial adhesion (Kumar et al., 2020).

2. Future Research Directions:

-Advances in Nanomaterials: Extensive research is being conducted in nanotechnology and biomaterials to enhance cell adhesion, proliferation, differentiation, and migration on implant surfaces, coupled with heightened antimicrobial properties. These advancements hold promise for improving future implant performance (Kumar et al., 2020).

-Smart Implants and 3D Structures: Based on current and emerging research trends, the future of nanotechnology appears to involve the development of smart biomaterials, porous structures, and 3D implants that can acquire the desired properties and shapes of stimuli-responsive implants. Digital planning and 3D printing are revolutionizing the way implants are designed and placed. These technologies allow for the creation of precise surgical guides and customized prosthetics, improving the accuracy and predictability of implant procedures (Chen et al., 2023).

-Artificial Intelligence and Machine Learning: Artificial intelligence (AI) and machine learning (ML) are increasingly being applied to dental implantology. AI algorithms can analyze vast amounts of data to identify patterns and predict outcomes, aiding in treatment planning and decision-making. Machine learning models can help customize treatment plans based on individual patient characteristics, potentially improving success rates and patient satisfaction. AI- owered diagnostic tools can also enhance the detection of peri-implant diseases, allowing for earlier and more effective interventions (Tewary et al., 2024).

-Investigation of Ethical, Social, and Legal Issues: Given the existing challenges, the development of nanotechnology-based implants in the future will necessitate addressing ethical, social, and legal concerns. These issues encompass the risks associated with implant use, as well as the need for further clinical trials and research, which must be addressed in collaboration with government and private research institutions (Zhang et al., 2021).

-Nanomedicine Research: Nanotechnology is finding innovative applications in nanomedicine and targeted therapies, which can lead to more accurate disease diagnosis and treatment (Coccia & Finardi, 2012).

8. Discussion and Conclusion:

Nanotechnology, with its unique properties, offers remarkable capabilities for enhancing the quality and performance of medical implants. By providing unprecedented opportunities for the design and fabrication of medical implants, nanotechnology can significantly impact the function and longevity of these implants. Given their importance in human health and well-being, this field warrants increased attention and research. This paper has explored the functionalities, nanostructuring processes for implant surfaces, various nanocomposites, and the impact of emerging nanotechnology applications in implants.

The results of this review demonstrate that nanotechnology, by providing novel and effective methods for improving implant performance and longevity, will play a pivotal role in future advancements in the medical field. The utilization of diverse nanocomposites, including polymeric, metallic, ceramic, and biological materials, can enhance biocompatibility, reduce infections, and increase the mechanical strength of implants. This technology can improve patients' quality of life by enhancing tissue integration, reducing infections, and increasing implant resistance to wear and corrosion. Nanotechnology, upon entering the medical realm, has revolutionized the performance of implants. By manipulating materials at the nanoscale, this technology enables the creation of novel surfaces and structures that exhibit enhanced biocompatibility and prolonged implant function. Key advantages include improved biocompatibility, enhanced mechanical properties, reduced risk of inflammation and infection, increased drug delivery efficiency, and the development of biomimetic materials. These advancements have a profound impact on the performance and longevity of implants.

Despite the highly positive impacts of nanotechnology in enhancing the performance and longevity of implants, several challenges persist in this field. A lack of standardized regulations, concerns about biocompatibility and immune response, and high costs with limited insurance coverage are among the most significant obstacles. Future research in nanotechnology is progressing towards advancements in the production of nanomaterials, the development of artificial intelligence, and the creation of smart implants and 3D structures that can exhibit desirable properties for stimuli-responsive implants, thereby enhancing efficiency and longevity.

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