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Application of Hydrogels in Tissue Engineering and Future Development Trends

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Abstract:
This study investigates the application of hydrogels in tissue engineering, emphasizing their significance and potential within the field. Initially, the basic properties and classifications of hydrogels are described to establish a theoretical foundation for subsequent discussions. The current applications of hydrogels in the repair and regeneration of various tissues, including bones, skin, and nerves, are analyzed in detail. This analysis highlights the challenges and technological bottlenecks faced by existing applications, such as insufficient mechanical properties and difficulties in controlling degradation rates. Furthermore, the research explores future development trends of hydrogels in tissue engineering, focusing on the integration of smart materials, nanotechnology, and environmentally responsive properties in advanced applications. The study concludes with an industrial analysis of the current state of hydrogel tissue engineering, outlining challenges for clinical translation. Overall, this study offers a comprehensive overview of hydrogels' applications in tissue engineering, providing valuable insights into the field's future development and significant theoretical and practical implications for promoting the application and clinical translation of hydrogels in tissue engineering.

Keywords: Hydrogel; tissue engineering; smart materials; clinical translation.

1. Introduction

In recent years, hydrogels have demonstrated significant potential in the field of tissue engineering, owing to their excellent biocompatibility, tunable mechanical properties, and three-dimensional network structure that closely resembles the extracellular matrix. Research indicates that hydrogels can serve not only as scaffold materials for tissue repair and regeneration but also as carriers for active substances, such as drugs and extracellular vesicles, thereby facilitating precise treatment and functional recovery. For instance, silk-gelatin-based hydrogels are extensively utilized in soft tissue repair and regenerative medicine, attributed to their rich bioactivity and favorable physicochemical properties. In addition, chitosan-based self-healing hydrogels possess the capability to autonomously repair cracks and extend their service life through a reversible dissociation-reconstruction mechanism involving dynamic chemical bonding, presenting a novel solution for medical wound dressings and tissue engineering scaffolds. Furthermore, fibrin-based hydrogels exhibit considerable advantages in the repair of oral and maxillofacial defects, as their flexibility and plasticity allow them to bind with various growth factors, thereby promoting the regeneration of bone tissue, nerves, and muscles. Collectively, these studies underscore the adaptability and versatility of hydrogels in the repair of complex anatomical structures.

Despite the remarkable progress of hydrogels in tissue engineering, several challenges remain. On one hand, the mechanical properties and stability of hydrogels require further optimization to meet the restorative needs of various tissue types. On the other hand, complex preparation processes and long-term safety concerns hinder their clinical dissemination. For instance, oral and maxillofacial tissue engineering imposes stringent demands on the material properties and manufacturing techniques of hydrogels, which current research has yet to fully address. Additionally, the application of hydrogels in specific diseases, such as disc degeneration, is limited primarily due to the dependency of repair efficacy on the functionality of the carried substances, as well as the difficulty in managing the complex inflammatory environment. To tackle these challenges, future research should concentrate on developing intelligent, environmentally friendly, and safe hydrogel materials while integrating nanotechnology to enhance their performance and applicability.

This paper will explain the fundamental properties and classification of hydrogels, followed by a detailed discussion of their applications in bone, skin, nerve, and other tissues. The current technical bottlenecks of hydrogels will be analyzed, and improvement strategies will be proposed to address the challenges of insufficient mechanical strength, degradation rate, and bioactivity when hydrogels are applied in practice. Finally, the future development trends of hydrogels will be introduced, highlighting their close connection with cutting-edge fields such as smart materials, nanotechnology, and environmental responsiveness.

2. Basic Properties and Classification of Hydrogel

2.1 . Definition and Composition of Hydrogel

Hydrogels are a class of hydrophilic polymers characterized by a three-dimensional network structure that enables them to absorb significant amounts of water without dissolving. The primary components of hydrogels are the polymer skeleton and water, which are derived from either natural or synthetic polymers. These polymers can be formed through physical or chemical crosslinking processes, with examples including collagen, gelatin, hyaluronic acid, chitosan, alginate, and agar, all of which are classified as natural polymers. The water contained in hydrogels exists in several forms: bound water, free water, and semibound water. The interplay of these different forms of water imparts unique physicochemical and biological properties to hydrogels. The high water content, combined with the three-dimensional network structure, allows hydrogels to exhibit mechanical properties and biocompatibility akin to those of human soft tissue, making them ideal biomaterials for applications in tissue engineering.

2.2 . Basic Properties of Hydrogels

Hydrogel has high water content and excellent hydration ability, it can absorb a large amount of water and retain it for a long time without dissolving itself, this property makes hydrogel compatible with biological tissues, because its internal water content is similar to that of human tissues, and the structure of hydrogel is made up of crosslinked macromolecular chains, which build up a stable three-dimensional network with the help of chemical or physical forces, so it has unique mechanical properties and response characteristics.

Hydrogels have a porous structure that facilitates cell migration, nutrient diffusion, and waste elimination, and are biocompatible. Most hydrogel materials are non-toxic and non-invasive to biological tissues, and do not trigger significant immune or inflammatory responses, and many can be designed to be degradable, so that they can be degraded and absorbed by the body gradually without secondary surgical removal after completion of the tissue repair function.

Environmental stimuli (temperature, pH, ionic strength, light, etc.) allow responsive hydrogels to respond predictably to take on the characteristics of a smart material, and hydrogels can be easily functionalised and modified with biologically active substances or drugs on demand for targeted therapy or controlled release, making them promising scaffolding materials in the field of tissue engineering.

2.3 . Classification of Hydrogels

Hydrogels can be classified according to various criteria, including source, structural properties, cross-linking mode, and stimulus responsiveness. Based on the source, hydrogels are categorized into three types: natural hydrogels, synthetic hydrogels, and composite hydrogels. Natural hydrogels are primarily composed of natural polymers

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such as gelatin, hyaluronic acid, chitin, collagen, and alginate. These materials exhibit good biocompatibility and can be degraded, although they generally possess poorer mechanical properties. In contrast, synthetic hydrogels, such as polyacrylic acid, polyvinyl alcohol (PVA), and polyethylene glycol (PEG), offer controlled physicochemical and mechanical properties but exhibit low bioactivity. Composite hydrogels integrate the advantages of both natural and synthetic materials, leveraging their synergies to optimize performance. Regarding the cross-linking method, hydrogels can be classified into two categories: physically cross-linked hydrogels and chemically cross-linked hydrogels. Physically cross-linked hydrogels rely on the formation of non-covalent bonds, such as hydrogen bonding and van der Waals forces, which confer good reversibility but limited stability. Conversely, chemically cross-linked hydrogels establish a stable network structure through covalent bonding, resulting in strong mechanical properties but limited degradation. In recent years, dynamic covalent bonded hydrogels have emerged, offering unique advantages in tissue engineering. These can be further divided into temperature-sensitive, pH-sensitive, light-sensitive, ion-sensitive, and other intelligent hydrogels, based on their responsiveness to stimuli. The dynamic covalent bonded hydrogels developed recently possess both stability and reversibility, making them particularly advantageous for applications in tissue engineering. Moreover, hydrogels can be categorized into various types based on their responsiveness to stimuli, including temperature-sensitive, pH-sensitive, light-sensitive, ion-sensitive, and other smart hydrogels. These materials can respond to alterations in the external environment and play a crucial role in precise drug delivery and tissue repair.

3. Current Applications of Hydrogels in Tissue Engineering

3.1 . Application of Hydrogel in Bone Tissue Engineering

Repairing bone defects is one of the core tasks in skeletal tissue engineering, and hydrogel, as an ideal scaffolding material, shows a broad application prospect in the field of bone tissue repair. In recent years, hydrogels have made remarkable progress in the field of bone tissue engineering due to their unique physicochemical properties and highly modifiable nature.

In bone tissue engineering, commonly used hydrogels mainly include natural polysaccharide hydrogels (e.g., chitosan, hyaluronic acid, alginate, etc.) and synthetic polymer hydrogels (e.g., PEG, PVA, etc.). However, these hydrogels have certain limitations in terms of mechanical properties and bioactivity, so they usually need to be modified to meet practical application requirements. Common modification methods include mineralisation, nanocomposite, and biomimetic design. Studies have shown that the incorporation of inorganic components (e.g., nanohydroxyapatite, β-tricalcium phosphate) into hydrogels not only significantly improves their mechanical strength but also enhances osteoconductivity, which is crucial for promoting bone regeneration. In addition, with the development of 3D printing technology, personalised bone repair scaffolds based on hydrogels are gradually gaining attention. For example, the preparation of hydrogel scaffolds with complex structures using 3D printing technology enables precise control of porosity and internal network structure, which can further optimise cell distribution and nutrient transport efficiency [1].

For clinical applications, injectable hydrogels are favoured for their ability to fill irregular bone defects with ease. These hydrogels can be injected directly into the target area through a minimally invasive procedure and subsequently cured in situ in the body to form a stable scaffold structure. To further enhance bone regeneration, researchers often load growth factors (e.g., BMP-2, VEGF, etc.) into the hydrogel to achieve a slow release of the growth factors [2]. Experimental results show that functionalized hydrogels containing bioactive factors are about 30% more successful than conventional materials in repairing complex bone defects, a significant advantage due to their ability to promote the regeneration and integration of bone tissues by loading specific growth factors or cell signaling molecules. In the experiment, the researchers implanted the functionalized hydrogels into an animal model simulating complex bone defects and evaluated the repair effect through micro-CT scanning and histological analysis, and found that the hydrogels not only effectively guided the generation of new bone but also significantly reduced the occurrence of inflammatory reactions [3]. However, despite their superior performance, the high cost and lack of stability still limit their large-scale clinical dissemination, especially the need to introduce high-purity biologically active factors and complex chemical modification steps in the preparation process, which further increases the difficulty and economic burden of production [4]; at the same time, the long-term degradation behaviour in vivo and the maintenance of mechanical properties still need to be optimised. In addition, as an emerging material, self-repairing hydrogels are beginning to show unique advantages, such as certain self-repairing hydrogels designed based on dynamic covalent bonding or non-covalent interactions are able to automatically restore their structural integrity after damage, thus prolonging their service life and enhancing therapeutic efficacy. This property is particularly important for the repair of bone tissue that is subjected to dynamic loads over time, as bone tissue is constantly subjected to external forces such as pressure and tension during daily activities, and conventional materials often suffer from fatigue that leads to performance degradation or even failure. To verify this property, the researchers conducted cyclic compression tests on a self-repairing hydrogel containing borate bonds, and the results showed that the material still maintains high mechanical strength and elastic modulus after undergoing multiple damage-repair cycles, proving its reliability in dynamic environments [5]. At the same time, such materials can be combined with nanotechnology to enhance their mechanical properties and functionality, for example, by incorporating hydroxyapatite nanoparticles to mimic the compositional make-up of the natural bone matrix, thus further improving their biocompatibility and osteogenic capacity [6].

It is worth noting that compared with traditional hydrogels, nanohydrogels have a higher specific surface area and superior drug loading capacity, which can deliver multiple bioactive molecules at the same time and thus synergistically promote the bone regeneration process. At the same time, some research teams are trying to combine preclinical research data and registered product information to explore the feasible path for hydrogels to move from the lab to the market. For example, a bone repair product based on chitosan-hydroxyapatite composite hydrogel has entered phase II clinical trials, with preliminary results showing that its safety and efficacy are better than existing commercial products. By combining the biocompatibility of chitosan with the excellent mechanical and osteoinductive properties of hydroxyapatite, the composite hydrogel forms a unique three-dimensional porous structure, which not only promotes cell adhesion, proliferation, and differentiation but also gradually degrades in the in vivo environment and releases ionic components conducive to bone tissue regeneration. In animal models, the hydrogel was shown to significantly accelerate the healing process of bone defects, and no significant immune rejection or toxicity was observed. In addition, the researchers further optimised the cross-linking density and the preparation process of the hydrogel to ensure that its mechanical strength could meet the needs of different bone tissue repairs, while maintaining good injectability and conformability. These research results lay a solid foundation for the development of more efficient and personalised bone repair materials in the future, and demonstrate the great potential of hydrogels in the field of tissue engineering [7].

3.2 . Application of Hydrogel in Skin Tissue Engineering

The largest organ in the human body is skin, and it has important research value in the field of tissue engineering. Hydrogel has unique properties and many advantages, which make it an ideal material for skin tissue engineering. Hydrogel can provide an ideal moist environment to promote cell migration and proliferation when repairing skin trauma, and can also effectively absorb wound secretion to keep wounds clean. In recent years, more than one kind of natural and synthetic hydrogel has been widely used in skin tissue engineering. In recent years, a variety of natural and synthetic hydrogels have been widely used in skin tissue engineering.

In terms of skin repair, composite hydrogels are particularly prominent. Incorporating biological factors such as epidermal growth factor (EGF) and basic fibroblast growth factor (bFGF) into the hydrogel system significantly enhances the healing of skin wounds, a finding that has been validated in several studies. For example, in a clinical trial on patients with diabetic foot ulcers, hydrogel dressings containing EGF demonstrated higher healing rates than conventional dressings, and the mechanism of action is that these biofactors can promote cell proliferation and angiogenesis, thereby accelerating the tissue repair process [8]. In addition, smart-responsive hydrogels show unique advantages in chronic wound treatment due to their sensitivity to environmental changes such as pH, temperature, or enzyme concentration. A study has shown that a hydrogel based on a temperature-sensitive polymer successfully achieved precise delivery of antibiotics in an infected wound model, effectively inhibiting the growth of drug-resistant strains. More importantly, hydrogel scaffolds incorporating stem cell technology have become a research hotspot in recent years, which can not only provide a three-dimensional support structure for cells but also reduce scar formation and promote functional skin regeneration by regulating the direction of stem cell differentiation.

3.3 . Application of Hydrogel in Neural Tissue Engineering

Nervous system damage often leads to serious dysfunction, and the nerve tissue itself has limited repair ability, so neural tissue engineering has always been the focus of the medical field is difficult to overcome, and the extracellular matrix properties of hydrogel are similar to those of the nerve tissue, which has a unique advantage in the neural tissue engineering, in the past few years, the researchers have successfully developed a number of hydrogel-based neural repair scaffolds, which can create three-dimensional growth environments for the neural cells and promote axonal extension, allowing neurons to establish connections. These scaffolds can create a three-dimensional growth environment for nerve cells and promote axonal extension and neuronal connectivity.

For central nervous system repair, hydrogels composed of hyaluronic acid and collagen are biocompatible and effec-

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tive in supporting neural stem cell survival and differentiation, and conductive hydrogels have recently become a hot research topic, integrating conductive materials such as graphene and carbon nanotubes, which can provide electrical stimulation to aid nerve regeneration. For peripheral nerve damage repair, injectable chitosan-gelatin hydrogels have been shown to promote nerve sheath cell migration and axonal regeneration as well as provide a good support structure for broken nerve connections. It should be noted that the recent development of functionalized hydrogels containing nerve growth factors and cell adhesion sequences has led to a further increase in the efficiency of nerve repair and significant functional recovery in preclinical animal models.

4. Challenges in Current Applications

4.1 . Insufficient Mechanical Properties

4.1.1 Matching mechanical properties with biological tissues

In the application of tissue engineering, one of the main challenges of hydrogel is that its mechanical properties do not match with natural tissues, because different tissues of human body, such as bone tissue, cartilage tissue, myocardial tissue and so on, have specific mechanical properties, for example, the modulus of elasticity of bone tissue is10-20 GPa and the compressive strength is 100-200 MPa, the compression modulus of cartilage tissue is 0.5-1 MPa and the friction characteristics are very good, and the extensibility and elasticity of myocardial tissue are good. Friction characteristics are very good, myocardial tissue stretch and elasticity are good, while the mechanical strength of traditional hydrogel is generally low and easy to crack, high water content of hydrogel is even more so, its tensile strength is generally less than 0.5MPa and compression modulus is less than 0.1MPa, it is simply not able to meet the needs of load-bearing organisations.

In 2021, Kaihuai Zhan et al. showed that about 73% of the hydrogel materials used in clinical practice have mismatched mechanical properties, which severely limits their application in weight-bearing tissues such as bone, cartilage, and tendon, and hydrogels are often unstable in dynamic physiological environments. The mechanical properties of hydrogels are often unstable in dynamic physiological environments, they are prone to fatigue failure under cyclic loading, they may slowly lose strength after long-term implantation, and the structural integrity of hydrogel scaffolds may be compromised due to the gap between the mechanical properties and the biological tissues with the possibility of aberrant cellular behaviours and failure of tissue reconstruction, which is a key impediment to the clinical translation of hydrogels [9].

4.1.2 Methods to improve the mechanical properties of hydrogels

Hydrogel mechanical properties are insufficient, for this problem researchers developed a variety of effective strategies, including dual network hydrogel technology to build two kinds of crosslinked network structure, one is to provide strength of the rigid network, the other is to provide toughness of the flexible network, so that the compressive strength of the hydrogel was successfully increased to6-8MPa, 2023Li Zhong et al. showed that the tensile strength of the new dual-network hydrogel can reach 2.5 MPa, which is a significant advantage over the traditional single-network hydrogel [10].

Nanocomposite enhancement strategies that introduce fillers such as nanofibres, nanoparticles or nanosheets into hydrogel matrices can dramatically improve their mechanical properties, with studies showing that the addition of5% carbon nanotubes or graphene oxides can increase the elastic modulus of a hydrogel by more than 300%, and bio-mineralisation methods and multilayer composite structural designs have been widely applied, with the 2022 developed mineralised gelatin/polyacrylamide composite hydrogels reach a modulus of elasticity of 3.2 MPa, which is close to natural cartilage tissue.

The development of stimulus-responsive mechanically enhanced hydrogels has become the latest research trend, such as photocross linked, heat-sensitive orpH-responsive hydrogels, which can achieve in situ mechanical property modulation in specific environments, and the recent development of photoresponsive hydrogels that increase cross-link density after UV irradiation and increase compressive strength by up to 250%, thus bringing a convenient and useful means of modulation for clinical applications. These methods have resulted in significant improvements in the mechanical properties of hydrogels and have led to a wider range of applications in the field of tissue engineering.

4.2 . Biocompatibility and Degradability Issues

4.2.1 Factors affecting biocompatibility

When hydrogels are used in tissue engineering, the key issue of biocompatibility comes first and has a direct impact on whether the material can be used safely in the human body. A variety of factors can affect biocompatibility, among which the chemical composition, physical structure, and interaction with host tissues are the main aspects. Studies have shown that approximately25-30% of synthetic polymer-based hydrogels have varying degrees of cytotoxicity, while natural polymer-based hydrogels such as collagen and hyaluronic acid are more biocompatible, but antigenicity cannot be completely removed.

In terms of physical structural factors, the porosity, pore size distribution, and surface properties of hydrogels significantly affect cell attachment, migration, and proliferation. Studies have shown that hydrogels with pore sizes between 100–300 μm exhibit optimal biocompatibility with most cell types, whereas pore sizes smaller than 50 μm significantly inhibit cell migration. Additionally, the metabolites released during hydrogel degradation are key factors influencing their biocompatibility.

4.2.2 Degradation rate control

Controlling the degradation rate is another critical challenge in the application of hydrogels for tissue engineering. An ideal scaffold should degrade at a rate that matches the regeneration speed of the target tissue—providing adequate mechanical support while gradually breaking down as new tissue forms. However, achieving precise control over hydrogel degradation is technically difficult due to the complexity of the in vivo microenvironment. The actual degradation behavior of hydrogels is hard to predict, and the regeneration rates vary significantly across different tissue types. Therefore, the degradation profile of hydrogels needs to be highly personalized to suit specific clinical applications.

Recent studies have shown that approximately55% of hydrogel scaffolds have a mismatch in degradation rate during in vivo application, causing the scaffolds to either disappear prematurely or remain for a long period of time, and clinical statistics in 2021 show that mismatch in degradation rate is the second most important factor leading to the failure of tissue-engineered products (second only to insufficient mechanical properties), in response to this problem researchers have developed. To address this problem, researchers have developed several degradation modulation strategies, such as mixing materials with different degradation rates, introducing bonds that can be broken down by enzymes, and designing mechanisms that degrade in response to stimulation [11].

5. Future Development Trends

5.1 . Application of Smart Materials

5.1.1 Responsive hydrogels

An important branch of smart biomaterials is responsive hydrogels, which can respond specifically to external environmental stimuli such as temperature, pH, enzymes, light, electricity, magnetic fields and other environmental stimuli to achieve dynamic control of material properties, and has become a hot research topic with great potential in the field of tissue engineering in the past few years.

N-isopropylacrylamide is a temperature-responsive hydrogel that gels in situ at body temperature to facilitate the loading and delivery of cells and bioactive molecules. pH-responsive hydrogels can be used to target the release of drugs or cytokines in different physiological environments such as acidic stomach and alkaline intestinal tract to enhance therapeutic efficacy, and light-responsive hydrogels can be used to achieve tissue regeneration with the aid of light-controlled cross-linking. The light-responsive hydrogel can control the degree of cross-linking with the help of light to achieve the precise spatial positioning of tissue regeneration, etc. The near-infrared light-responsive hydrogel system can precisely regulate the process of bone tissue formation in vivo, the enzyme-responsive hydrogel can mimic the dynamic remodeling of extracellular matrix to bring the tissue repair to a microenvironment closer to the natural one, and the design of the multiple-responsive hydrogel system opens up a new way of thinking for the precise repair of complex tissues.

5.1.2 Self-repairing hydrogels

There is an advanced class of biomaterials called self-repairing hydrogels, which are capable of restoring structural integrity and functionality after being damaged by external forces, thus greatly enhancing the applicability and durability of hydrogels in tissue engineering.

Reversible bonding (such as dynamic covalent bonding, supramolecular interactions, etc.) is the main way to realize the repair function of self-repairing hydrogels, among which the self-repairing hydrogels based on dynamic covalent bonding such as borate bonding, imine bonding, disulfide bonding, etc., have the characteristics of good repair efficiency and high mechanical strength, whereas those based on non-covalent interactions such as hydrogen bonding, subject-object interactions, electrostatic interactions, etc., have faster repair speeds. The speed of repair is faster, and recent studies tend to build multiple cross-linking networks, such as Sydney Song et al.2023 developed a dual-network self-repairing hydrogel that combines dynamic covalent bonding and supramolecular interactions, which has excellent mechanical properties (compressive strength of more than 3 MPa) and restores more than 85% of the original strength in 5 minutes after the damage, which provides strong support for long-term implantation into tissues, and also provides strong support for long-term implantation into tissue. This provides strong support for long-term tissue implantation. Moreover, the self-repairing hydrogel is stable and degrades in a controlled manner in a long-term implantation environment, which provides a new solution for sustained tissue regeneration [12].

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5.2 . Integration of Nanotechnology

5.2.1 Nanocomposite hydrogel

Nanocomposite hydrogel is a cutting-edge research direction, the introduction of nanomaterials into the hydrogel matrix can effectively overcome the limitations of the traditional hydrogel in terms of mechanical properties, electrical conductivity and bioactivity, etc. Over the years, a variety of nanomaterials, such as carbon nanotubes, graphene, nanocarbon, nano-metal oxides and other nanomaterials, have been successfully introduced into hydrogel systems, resulting in the formation of a nanocomposite hydrogel with unique properties.

Nanocomposite hydrogels are especially prominent in mechanical enhancement, the introduction of carbon nanotubes or graphene nanofillers, compressive strength and modulus of elasticity of the hydrogel will be significantly improved, and studies have shown that the addition of 0.5% graphene oxide can make the mechanical strength of the hydrogel to enhance the mechanical strength of the hydrogel by 300%, and nanocomposite hydrogels have good electrical conductivity and thermal conductivity, constructing tissue engineering scaffolds with electrical stimulation or thermal conductivity may be feasible.It may be feasible to construct tissue engineering scaffolds with electrical stimulation response or thermal conductivity. In terms of bioactivity, the introduction of bioceramic materials such as nanohydroxyapatite and nano-silica, the biocompatibility and osteoconductivity of the hydrogel will be better, and it can lead to the proliferation and differentiation of cells.

5.2.2 Nano drug carriers

In the field of tissue engineering, hydrogels have been revolutionized with the use of nanomedicine carrier systems, which can accurately control the kinetics of drug release and targeted delivery capabilities, thereby improving therapeutic efficiency.

There are two main forms of hydrogel nano drug carriers, one is to embed such nanoparticles as liposomes, polymer nanoparticles and gold nanoparticles in the hydrogel network to form a composite delivery system, and the other is to make the hydrogel itself into a nanosized nanogel, which have a number of advantages, can protect the bioactive factors from degradation and prolong the half-life of the factors, and can achieve a slow release and pulsed release of the drugs. These systems have a number of advantages that protect the bioactive factors from degradation and extend their half-life, allow for slow and pulsed release of the drug, and can cross biological barriers and deliver the drug to the target tissues with precision. Studies have shown that the effective duration of action of growth factors in nano-hydrogel carriers can be extended by a factor of 3 to 5 and allow for much more efficient tissue regeneration, especially in nerve and myocardial tissue engineering, where the reparative facilitation of nano-hydrogel containing NGFs or VGFs is obvious.

6. Conclusion

Hydrogels show great potential in the field of tissue engineering due to their excellent biocompatibility, tunable mechanical properties, and three-dimensional network structure. This study comprehensively explores its applications and future trends. In terms of current applications, hydrogels have been useful in bone, skin and neural tissue engineering. In bone tissue repair, a variety of modified hydrogels, self-repairing hydrogels and nano-hydrogels have their own advantages, but high cost and lack of stability limit their clinical promotion; in skin repair, composite, smart-responsive, and combined with stem cell technology have significant effects; in nerve repair, hydrogels with different compositions and functionalization can promote nerve regeneration. However, hydrogel applications still face challenges. Mechanical properties, mismatch with biological tissues and instability in dynamic environment, affecting its clinical transformation; biocompatibility, chemical composition, physical structure and other factors will trigger immune reactions; degradation, the complexity of the in vivo microenvironment, the degradation rate are difficult to accurately control. In the future, hydrogel research will develop towards multifunctionalization, intelligence and precision. It includes smart material application and nanotechnology fusion. By elaborating on the current applications and future development trends of hydrogels in tissue engineering, this article aims to encourage increased investment from relevant enterprises and to promote stronger collaboration between research institutions and hospitals. Such efforts are essential to translate the promising potential of hydrogels in biomedical and related fields into tangible scientific achievements that can ultimately benefit patients.

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