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Hydrogels-Applications in Dental Medicine: An Updated Review.

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Abstract:

Background: Oral disorders such as caries, pulpitis, periodontitis, peri-implantitis, and oral malignancies often involve microbial infections, inflammation, and tissue damage. Current dental treatments, though advancing, are still limited by the properties of materials used, which may lead to issues such as microleakage, brittleness, and side effects. There is a growing demand for innovative biomaterials to address these challenges in oral and craniofacial therapies.

Aim: This review aims to explore the applications of hydrogels in dental medicine, emphasizing their potential in treating oral disorders, facilitating tissue regeneration, and enhancing drug delivery systems.

Methods: A comprehensive review of literature was conducted to examine the properties, classifications, and functional applications of hydrogels in dental medicine. The chemical mechanisms of hydrogel network formation, including both crosslinked and self-assembled hydrogels, are discussed. The review focuses on their use as antibacterial agents, scaffolds for tissue regeneration, and drug delivery vehicles in various dental treatments.

Results: Hydrogels demonstrate excellent biocompatibility, porosity, and hydrophilicity, making them ideal candidates for dental applications. They are classified based on their chemical formation mechanisms and physical structures. Covalent crosslinking and self-assembly are the primary methods used for creating hydrogel networks. Hydrogels can encapsulate antibacterial agents for treating periodontal diseases, deliver drugs for managing orthodontic movements, and serve as scaffolds in tissue regeneration, showing promising results in tissue repair and drug delivery efficiency.

Conclusion: Hydrogels offer a novel and versatile solution in dental medicine. Their unique properties enable them to overcome the limitations of conventional dental materials, improving treatment outcomes.

Further research into the optimization of hydrogel formulations will expand their potential applications, particularly in tissue engineering and drug delivery.

Key words: Hydrogels, dental medicine, tissue regeneration, drug delivery, periodontal disease, dental biomaterials, antibacterial agents, tissue engineering.

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Introduction:

Oral disorders, such as caries, pulpitis, periodontitis, peri-implantitis, and oral malignancies, generally manifest as microbial infections, localized inflammation, and tissue degeneration. Addressing these oral disorders is essential for preserving excellent oral health as well as general well-being and quality of life [1]. Management of chronic inflammatory disorders such periodontitis, pulp disease, and caries emphasizes the elimination of pathogenic microorganisms, regulation of inflammation, and restoration of the structure and function of compromised tissues. Moreover, addressing the aesthetic and functional requirements of patients is a crucial factor in the restoration of significant maxillofacial bone abnormalities caused by tumor excision, trauma, or deformity [2]. Notwithstanding considerable progress in contemporary dental medicine, the effectiveness of existing treatments is predominantly constrained by the characteristics of the dental materials and biomaterials utilized. Resin composites utilized in dental restorations may experience microleakage over time, resulting in biofilm formation and the onset of secondary caries [3]. Moreover, root canal filling materials used in the treatment of pulp disorders can avert reinfection but do not enhance the brittleness of non-vital teeth [4]. Traditional periodontal treatments, like as scaling and root planning, may lead to adverse consequences, including tooth sensitivity and localized damage. Antibiotic ointments employed in the management of periodontitis may also induce side effects such as photosensitivity and enduring tooth discoloration [5]. Furthermore, bone grafts employed for the restoration of lost periodontal bone and the repair of maxillofacial abnormalities may result in difficulties at the donor site, such as infections and fractures [6]. The administration of anticancer pharmaceuticals has the potential for systemic adverse effects [7]. Thus, there is a substantial demand for the advancement of novel biomaterials to tackle issues in oral and craniofacial therapy and regeneration.

Hydrogels are three-dimensional networks of crosslinked hydrophilic polymers capable of absorbing significant quantities of water while preserving their insoluble structure, thus demonstrating remarkable biocompatibility, porosity, viscoelasticity, and hydrophilicity [8, 9]. Since their inaugural application in biological contexts by Wichterler and Lim in 1960, hydrogels have become extensively utilized across diverse biomedical domains, encompassing drug delivery, tissue engineering scaffolds, encapsulation of cells, proteins, and other biomolecules, biosensors in wearable devices or responsive systems, and as intrinsic antimicrobial materials. In recent years, hydrogels have emerged as promising biomaterials in dentistry, utilized for encapsulating antibacterial agents to combat bacteria in periodontitis, caries, and pulp diseases, functioning as scaffolds for dental tissue regeneration, and serving as drug delivery systems for regulating orthodontic tooth movement.

Classification:

Hydrogels can be classified based on their origins (natural or synthetic), physical structures, crosslinking nature, ionic charges, or preparation methods. However, this review primarily focuses on categorizing hydrogels according to the chemical mechanisms driving network formation and their physical structures, as these are pivotal in determining their functional properties.

Chemical Formation Mechanisms of Hydrogel Networks:

Hydrogels are classified into two main categories based on the chemical processes involved in network formation: those formed via crosslinking and those formed through self-assembly. Crosslinking involves the formation of short bonds between polymer chains, resulting in a polymer network with viscoelastic properties [23]. These crosslinks can be either covalent or non-covalent, each imparting

distinct physical and mechanical characteristics to the hydrogel network. In contrast, self-assembly occurs when molecular units spontaneously organize into ordered structures with varying shapes and sizes [24].

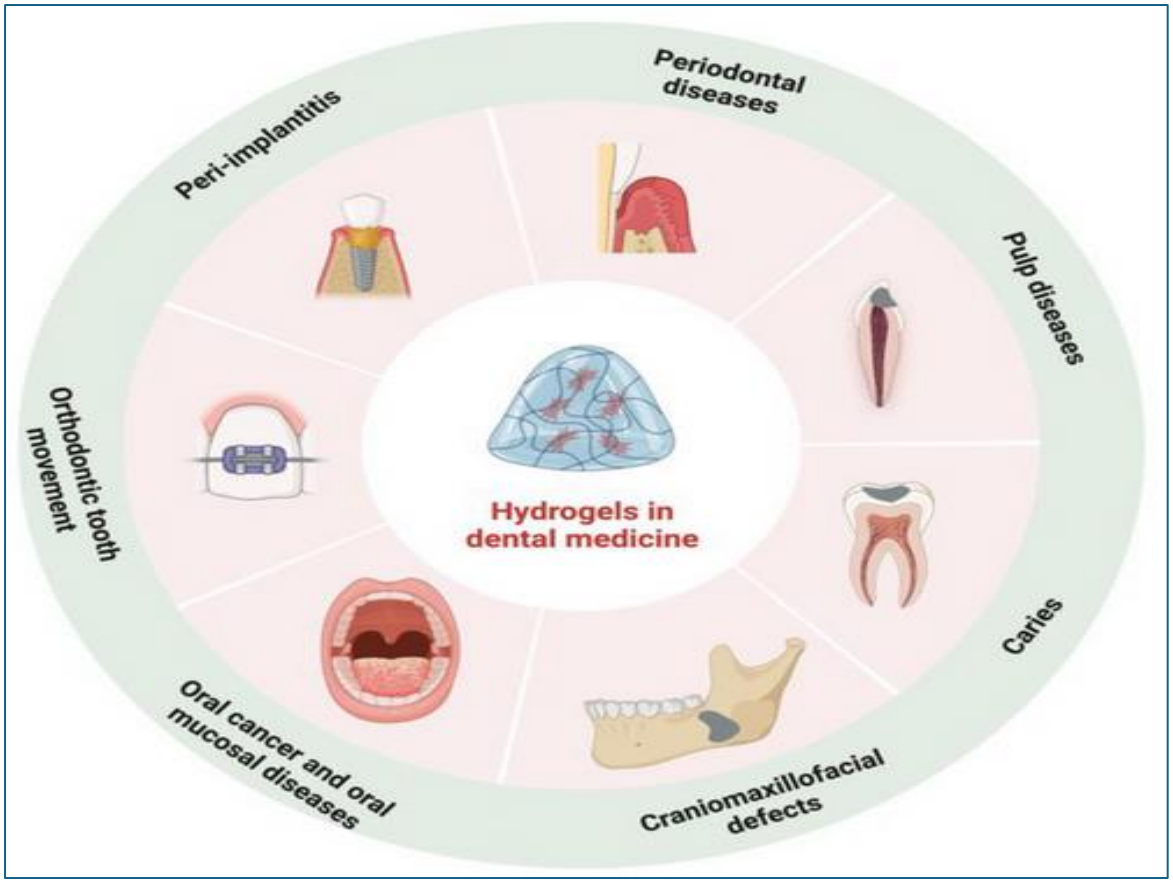

Figure 1: Hydrogels for Dental Applications.

Covalently Crosslinked Hydrogels

Covalent bonds in crosslinked hydrogels can be classified as conventional or dynamic covalent bonds. Covalently crosslinked hydrogels, or chemically crosslinked hydrogels, possess robust and irreversible connections between polymer chains, endowing them with remarkable mechanical strength and durability against degradation [25]. Typical techniques for fabricating such networks encompass photopolymerization, enzymatic crosslinking, oxime crosslinking, Michael-type addition, and Schiff base synthesis [26]. The enduring crosslinks are challenging to decompose, constraining the adaptability of these materials for uses like tissue engineering and cell culture. Furthermore, thorough washing is essential to remove remaining hazardous crosslinking agents [27]. Dynamic covalent interactions constitute a novel category of crosslinks in hydrogels. These hydrogels include dynamic covalent connections, facilitating accelerated breakdown and enhanced remodeling relative to static hydrogels [28]. Dynamic covalent bonds can reversibly dissociate and reconstitute under particular conditions. These bonds can be classified into three primary categories according to the chemical reactions they encompass: exchange reactions (e.g., disulfides, diselenides, and thioesters), reversible addition/condensation reactions (e.g., Diels-Alder reactions involving imines, hydrazones, oximes, and boronic esters), and enzymatic covalent reactions facilitated by enzymes such as monoamine oxidase B, catalase, and urease [29]. These dynamic features provide controlled deterioration, adjustable stiffness, reactivity to environmental stimuli, moldability, and self-healing capabilities, hence broadening their biomedical applications [30].

Noncovalently Crosslinked Hydrogels

Noncovalent or physical hydrogels are constituted by polymer chains interconnected through noncovalent bonds, which encompass electrostatic interactions, hydrophobic interactions, metal-ligand

coordination, hydrogen bonds, and host-guest interactions. These interactions are reversible, enabling hydrogels to experience sol-to-gel transitions in response to variations in temperature, pH, light, stress, enzymes, or other stimuli [31]. A primary benefit of noncovalent hydrogels is their absence of potentially hazardous crosslinking agents, as they are produced without chemical crosslinkers. Moreover, their self-healing characteristics enable them to briefly liquefy under elevated shear stress and thereafter restore their original configuration once the tension diminishes. Nevertheless, the mechanical characteristics of these hydrogels are frequently inadequate owing to the comparatively feeble nature of the noncovalent contacts [27].
Electrostatic interactions between oppositely charged polymers can be utilized to create polyelectrolyte complexes (PECs) [25].

Chitosan, a natural cationic polymer, can create polyelectrolyte complexes with several anionic polyelectrolytes, including alginate, pectin, and chondroitin sulfate, via electrostatic interactions [27]. The characteristics of hydrogels obtained from PECs can be modified by manipulating several parameters, such as charge density, polymer mixing ratios, and solvent conditions. If the net charge of the PEC components is neutral, it may lead to decreased solubility and precipitation [8]. The equilibrium swelling ratio, which governs the solvent content in the hydrogel, is pivotal in influencing the hydrogel's efficacy across many applications [32]. Subtle alterations in solvent composition can induce reversible volume phase transitions, thereby influencing permeability and molecular transport [33]. Synthetic zwitterionic polymers, unlike PECs, may self-assemble into physical hydrogels via intra- and inter-molecular interactions between anionic and cationic blocks, demonstrating exceptional toughness and viscoelasticity [31, 34]. Hydrophobic interactions may arise between the hydrophilic and hydrophobic portions of polymer chains. Pluronic F127, composed of hydrophilic polyethylene oxide (PEO) end groups and a hydrophobic polypropylene oxide (PPO) core, generates a thermoreversible hydrogel in response to temperature variations, as hydrophobic interactions arise between PPO segments after the disruption of hydrogen bonds in PEO [35]. Moreover, hydrophobic interactions may occur between the hydrophobic terminal groups of polymer chains. Voorhaar et al. synthesized a physically crosslinked hydrogel utilizing an ABA-triblock copolymer, featuring hydrophilic N-acryloylmorpholine at the center and hydrophobic isobornyl acrylate at the termini, wherein hydrophobic interactions induced phase separation and the establishment of physical crosslinks among the polymers [36].

Hydrogen bonds, established between a hydrogen atom covalently linked to an electronegative atom and another electronegative atom, can also facilitate hydrogel formation. These bonds may form between diverse functional groups, including amides, carboxylic acids, and hydroxyl groups, or between these groups and electron donors such as pyridine and imidazole [37]. Sharma et al. produced a hydrogel by crosslinking chitosan (a hydrogen donor) with acryloyl phenylalanine (a hydrogen acceptor), yielding a hydrogel with significant self-healing capabilities [38]. Metal-ligand coordination transpires via chelation, wherein metallic ions engage with organic ligands. This Lewis acid-base interaction is more robust than other noncovalent bonds although less potent than covalent ones [39]. Harrington et al. created a mussel-inspired hydrogel utilizing metal coordination between ferric ions and catechol ligands, discovering that the hydrogel's mechanical properties, including stiffness and tensile strength, were markedly affected by the extent of chelation between catecholate and ferric ions [40]. Host-guest interactions denote a specific type of hydrophobic interaction characterized by the engagement between host molecules, which include substantial cavities, and guest molecules that occupy these cavities. Host molecules comprise cucurbiturils, cyclodextrins, crown ethers, and calixarenes, which interact with guest molecules [41-43]. Zhu et al. documented a thermosensitive hydrogel created via orthogonal self-assembly, utilizing poly(N-isopropylacrylamide) as the guest and cyclodextrin as the host. This hydrogel demonstrated rapid self-healing capabilities and the capacity to replicate its self-assembly behavior in reaction to chilling stimuli [44].

Self-Assembled Hydrogels:

Self-assembled hydrogels are a distinct class of physical hydrogels, formed through the spontaneous organization of small molecules into structured assemblies without the need for external agents [45]. These hydrogels are derived from a diverse array of self-assembling molecules, including peptides, recombinant proteins, DNA, synthetic small molecules, and copolymers. Upon immersion in aqueous solutions, these molecules serve as building blocks that self-organize into supramolecular nanostructures. The biocompatibility, targeted delivery capabilities, and biomedical safety of these hydrogels make them suitable for designing smart materials, biomedical agents, and drug delivery systems [46]. The forces that drive the self-assembly process include van der Waals interactions, electrostatic forces, hydrophobic interactions, hydrogen bonds, and π−π stacking [47]. These noncovalent interactions significantly influence the mechanical properties, bioactivity, and morphology of the resulting hydrogels.

DNA molecules are particularly suitable for molecular self-assembly due to their ideal chemical properties [48]. The specificity of Watson–Crick base pairing enables numerous unique DNA strands to form complex 3D nano- or microstructures [49]. In hybrid DNA hydrogels, short DNA sequences are incorporated into polymer backbones, acting as crosslinkers and switchable elements [50]. The secondary structures of these self-assembled DNA molecules are stabilized by multivalent interactions, such as hydrogen bonding, hydrophobic interactions, and π−π stacking, rendering DNA hydrogels stronger than those based on a single supramolecular interaction. Furthermore, the versatility in DNA sequence design allows for the creation of hydrogels with varied responsiveness and functionality [51, 52]. For instance, Cheng et al. developed a DNA-carbon nanotube (CNT) supramolecular hydrogel, which exhibited pH responsiveness and tunable mechanical properties when a cytosine-rich DNA sequence was attached to CNTs through π−π stacking [53].

Peptides are capable of forming various secondary structural motifs, such as α-helices, β-sheets, β-hairpins, and coiled coils. These motifs enable peptides to self-assemble into diverse nanostructures, including fibers, micelles, ribbons, and vesicles [54]. The modularity of self-assembled peptide hydrogels allows for the conjugation of bioactive modules onto the peptide sequence. Yu et al. designed a peptide hydrogel responsive to blood glucose concentrations (BGCs), which releases glucagon in response to elevated glucose levels [55]. Peptide amphiphiles (PAs), a class of peptide derivatives, consist of hydrophilic peptides linked to hydrophobic groups, typically alkyl chains. The hydrophobic tails of PAs promote the aggregation of the hydrophilic segments, resulting in the formation of three-dimensional (3D) networks [56]. These hydrogels are particularly attractive as drug carriers due to their high drug-loading capacities and noncytotoxic properties [57]. For example, Cinar et al. developed a PA nanofibrous hydrogel encapsulating the anticancer drug doxorubicin (DOX), demonstrating a controlled release profile [58]. Additionally, the 3D nanofibrous networks formed by PA self-assembly have been utilized as biomimetic scaffolds for tissue engineering, owing to their high porosity and biocompatibility [59].

Physical Structures of Hydrogel Networks: The physical architecture of hydrogels plays a critical role in determining their properties and functionality. Hydrogels can be classified into monolithic, fibrous, granular, and polymer-particle network structures, based on their network components and the type of linkages formed between the network strands and junctions.

Monolithic Hydrogels:

Monolithic hydrogels represent the most prevalent category, comprising crosslinked polymer networks derived from a singular monomer species [60-62]. These hydrogels have a uniform three-dimensional structure and gel-like characteristics, generally attained with elevated polymer concentrations and crosslinking densities [31]. Li et al. generated a pure hyaluronic acid (HA) hydrogel by a dynamic covalent Schiff base reaction, demonstrating rapid sol-gel transitions, self-healing properties, and pH responsiveness [62]. Feng et al. synthesized a gelatin macromer via host-guest interactions between gelatinous aromatic residues and acrylated β-cyclodextrin (β-CD) monomers. The resultant hydrogels demonstrated improved compressive and tensile strain resistance, as well as fast self-healing following

mechanical failure [63]. The mechanical properties of monolithic hydrogels are determined by the kind of monomer, network mesh size, and crosslinking density. For instance, ionically crosslinked alginate hydrogels exhibit enhanced mechanical strength with elevated ion concentrations or the incorporation of divalent ions that possess greater affinity for alginate crosslinking. Moreover, augmenting the alginate weight percentage from 1% to 3% improves the compression and shear modulus values [64]. Comparable tendencies have been noted for polyethylene glycol (PEG) and polyvinyl alcohol (PVA) hydrogels, wherein augmenting their respective weight fractions enhances mechanical characteristics [65, 66].

Cryogels, a distinct category of monolithic hydrogels, are produced through the cryogelation of suitable monomers or polymeric precursors at temperatures beneath the solvent's freezing point. The frozen solvent crystals serve as porogens, enabling the creation of macroporous cryogels devoid of cytotoxicity [67]. Cryogels exhibit significant porosity alongside osmotic stability and mechanical strength, rendering them suitable for biological and biomedical applications [68]. Diverse modifications of cryogel systems have been established, encompassing the conjugation of various ligands to their surfaces, the grafting of polymer chains onto cryogel surfaces, and the formation of interpenetrating networks of several polymers for customized functionality [69]. Plieva et al. generated stable macroporous PVA cryogels using a crosslinking reaction with glutaraldehyde under acidic circumstances at subzero temperatures. Jain et al. created a polyacrylonitrile (PAN)-gelatin interpenetrating cryogel network, exhibiting considerable swelling, mechanical stability, and biocompatibility conducive to cell proliferation within the scaffold [70].

Fibrous Hydrogels:

In the majority of natural tissues, cellular interactions occur with the native three-dimensional extracellular matrix (ECM), a highly intricate and hierarchical fibrous structure that provides cells with necessary molecular interactions, biofunctional activity, and mechanical support [71]. In contrast to monolithic hydrogels, fibrous hydrogels are constructed through supramolecular assembly, resulting in a fibrous architecture that replicates the mechanical properties of the ECM, including its strain-stiffening behavior [72]. These hydrogels exhibit several crucial characteristics: (i) cytocompatibility, allowing for cell encapsulation without the need for potentially toxic crosslinkers, (ii) high porosity and superior mechanical responsiveness, and (iii) modularity, which enables the integration of biochemical signals, such as cell-adhesive motifs [73]. Lian et al. designed an innovative bio-interface for enzyme-based electrochemical biosensing and cell monitoring applications using a self-assembled nanofibrous hydrogel synthesized from fluorenylmethyloxycarbonyl diphenylalanine [74]. The properties of fibrous hydrogels are contingent on the crosslinking between their fibers and the supramolecular interactions of their molecular constituents [31].

Collagen, owing to its fibrillar architecture, is a highly attractive material for fibrous hydrogels in biomedical applications. As the most abundant protein in mammalian tissues, collagen constitutes the primary component of natural ECMs. There are at least 19 collagen types, with type I being the most commonly utilized in tissue engineering due to its ease of extraction [75]. The fundamental structure of collagen consists of three polypeptide chains that intertwine to form a triple helix, held together by both hydrogen and covalent bonds, which then aggregate to form stable fibers [76]. Collagen can be degraded by metalloproteases, particularly collagenase and serine proteases, permitting cellular regulation of this process in engineered tissues. The mechanical properties of collagen can be enhanced by the incorporation of chemical crosslinkers (e.g., glutaraldehyde, carbodiimide) or physical treatments such as UV irradiation and heating [77].

Electrospun hydrogel nanofibers are fabricated using the electrospinning technique, which involves the continuous formation of fibers from polymer solutions or melts subjected to a high voltage [78]. This technique applies a voltage to a polymer solution at the tip of a capillary tube, which is drawn into a thin jet towards an oppositely charged collector. As the solvent evaporates, fibers with diameters smaller than the jet are formed [79]. By manipulating processing parameters such as applied voltage, temperature, solution conductivity, and viscosity, the properties of the resultant fibers—including diameter, morphology, and porosity—can be regulated [80]. Electrospinning has been employed to create a variety of

fibrous hydrogels, such as submicron porous hydrogels composed of polyacrylic acid and PVA. These fibrous hydrogel scaffolds typically feature interconnected interfiber pores, which promote cell-cell interaction and migration [81]. However, the electrospinning technique faces several limitations, including poor control over porosity and pore size, relatively weak mechanical properties, and an inability to produce diverse three-dimensional hydrogel shapes [82].

Granular Hydrogels

Granular hydrogels, known as microgels, are composed of densely packed hydrogel-based microparticles (MPs) [83]. In contrast to colloidal hydrogels, granular hydrogels demonstrate viscoelasticity at the macroscale owing to their compact structure and micron-sized interstitial gaps, which create an interconnected, porous network that facilitates cell migration and proliferation [84]. The characteristics of granular hydrogels can be adjusted by modifying their microstructure, including the dimensions, size distribution, and packing density of the microgels [85]. These hydrogels are attracting interest as adaptable options for regenerative medicine and various biomedical applications, leveraging their distinctive physical properties—such as shear-thinning, self-assembly, and self-healing—resulting from their dynamic architectures. Under tension, particle-jammed prepared microgels can exhibit liquid-like behavior, occupying voids, and subsequently transform into solid-like materials upon the removal of stress. The shear-thinning properties of granular hydrogels enable their direct use as bulk materials post-injection, eliminating the necessity for gelation. The modular nature of granular hydrogels enables the integration of diverse microparticles to address distinct biological processes or confer certain bioactivities. Moreover, granular hydrogels possess self-healing capabilities, characterized by the disruption and subsequent reformation of physical or chemical connections among microgels, hence improving their stability in active tissues [83, 85, 86]. Mealy et al. created crosslinked hyaluronic acid (HA)-based granular hydrogels employing interparticle host-guest interactions to target rapidly moving tissues, including heart muscle [86]. Chitosan-based granular hydrogels are widely utilized as injectable tissue scaffolds and medication delivery systems [87].

Polymer-Particle Hydrogels

Polymer-particle hydrogels are produced by crosslinking or integrating particles into polymeric networks. Particle-crosslinked hydrogels establish networks by multivalent and dynamic interactions, such as electrostatic, hydrophobic, and coordination interactions, between polymers and nanoparticles [88-90]. The mechanical properties of these hydrogels are significantly affected by three primary factors: (i) the interaction between nanoparticles and polymers, (ii) the size of the nanoparticles in relation to the polymer's persistence length, and (iii) the density of crosslinking [88]. Polymer-particle hydrogels can be designed to demonstrate adjustable mechanical characteristics, tissue adhesion, biocompatibility, biodegradability, and non-immunogenicity [91-93]. Moreover, they can be altered to incorporate sites for the conjugation of bioactive signaling molecules [89], including the establishment of physical barriers to inhibit postoperative adhesion [94]. These hydrogels have reduced cargo release rates owing to their diminished mesh size relative to other hydrogel varieties, including monolithic, fibrous, and granular hydrogels. Polymer-particle hydrogels serve as cell transport vehicles, enhancing cell viability due to their high mechanical strength, which safeguards cells during injection [91]. Appel et al. synthesized polymer-particle hydrogels using hydrophobically modified hydroxypropylmethyl cellulose (HPMC-Cx) and nanoparticles made of poly(ethylene glycol)-block-poly(lactic acid) (PEG-b-PLA), which served as injectable drug carriers. The dynamic network was formed by physical interactions between HPMC-Cx and PEG-b-PLA nanoparticles [89].

Integrating nanoparticles into polymeric hydrogel matrices as fillers is an alternative approach for fabricating particle-polymer hydrogels. In this context, the particles do not directly serve as crosslinks contributing to the mechanical strength of the networks, but instead augment the mechanical properties of the composite material [31]. Nonetheless, particle aggregation inside the polymer matrix can pose considerable problems, potentially resulting in defective networks and structural failure [95]. Consequently, attaining homogeneous particle dispersion within the matrix is essential for the fabrication

of resilient hydrogels. Yanagioka et al. [96] effectively enclosed a colloidal crystalline array within a polymer matrix to achieve uniform particle distribution. An further efficient technique entails dispersing particles into hydrogel precursor solutions before gelation occurs [97]. The integration of particles with varied cargos facilitates the development of multifunctional hydrogels for use in antibacterial therapy and tissue regeneration [98]. Recent investigations have integrated diverse nanoparticles (NPs) into hydrogel networks, encompassing metallic NPs [99], carbon nanotube/graphene NPs [100, 101], polymeric NPs [102], and magnetic NPs [103]. Ag-NPs have been incorporated into hydrogels composed of polyacrylic acid (PAA), methyl methacrylate, and PVA, in conjunction with antimicrobial peptides (AMPs) [98, 104], showcasing considerable promise as functional antimicrobial coatings. Homenick et al. developed a collagen nanoparticle hydrogel using poly(ethyleneimine)-grafted single-walled carbon nanotubes, markedly improving the hydrogel's Young's modulus even at minimal crosslink densities [100]. Zhong et al. augmented collagen's biological stability through the physical incorporation of polyamidoamine dendritic nanoparticles, resulting in enhanced mechanical characteristics and facilitating the proliferation of human conjunctival fibroblasts [102]. Kim et al. synthesized a $CoFe_2O_4$/poly(organophosphazene) nanoparticle hydrogel, whereby $CoFe_2O_4$ nanoparticles were affixed to the hydrogel matrix via hydrophobic interactions with the hydrophobic L-isoleucine ethyl ester moiety on the polymer. This magnetic nanoparticle hydrogel exhibited remarkable thermosensitivity, injectability, and reversible sol-gel phase transitions [103].

Interpenetrating Network Hydrogels

Interpenetrating polymer networks (IPNs) are a class of hydrogels consisting of at least two polymer networks that are molecularly intertwined without covalent bonding. Semi-IPNs are formed when a linear polymer infiltrates a cross-linked network, while full IPNs involve cross-linking both components. The primary advantage of IPNs lies in the formation of dense hydrogel matrices, which exhibit enhanced mechanical properties, efficient drug loading, and regulated physical characteristics [105]. Commonly used polymers for IPN hydrogels include both natural polymers and their derivatives, such as polysaccharides and proteins, as well as synthetic hydrophilic polymers. IPNs can be composed solely of synthetic hydrophilic polymers or a blend of natural proteins and synthetic polymers [106]. For instance, Munoz-Pinto et al. enhanced the mechanical properties of collagen hydrogels by developing collagen-IPN hydrogels, where collagen was infused with poly(ethylene glycol) diacrylate (PEGDA) and cross-linked under UV light. This collagen-PEGDA IPN exhibited a tensile modulus that aligns with the biomechanical properties of vascular tissue (40–900 kPa) [107]. Double network (DN) hydrogels, a subset of IPN hydrogels, have garnered significant attention due to their exceptional mechanical strength and high water retention capacity. DN hydrogels consist of two asymmetric networks: a hard, brittle polymer as the first network and a soft, ductile polymer as the second. Zhang et al. synthesized a biodegradable hybrid DN hydrogel by integrating a methacrylated gelatin (GelMA) network into a nanocomposite hydrogel comprising methacrylated chitosan (CSMA) and polyhedral oligomeric silsesquioxane (POSS) via a two-step photo-crosslinking process. This hybrid hydrogel exhibited a tensile fracture strain of 131.1 kPa, surpassing the tensile strengths of GelMA and nanocomposite hydrogels by more than 11 and 4 times, respectively. These findings highlight the synergistic effect of the two interconnected networks in enhancing the hydrogel's ability to withstand significant external forces [108].

Conclusion:

Hydrogels have gained significant attention in the field of dental medicine due to their unique properties, such as biocompatibility, high water retention capacity, and versatility in modifying their mechanical and chemical characteristics. These properties allow hydrogels to address some of the key challenges in oral healthcare, particularly in the treatment of microbial infections, inflammation, and tissue degeneration. As an emerging biomaterial, hydrogels are increasingly applied in dental practices, offering novel solutions to longstanding issues associated with conventional dental materials. One of the primary applications of hydrogels in dentistry is their use as antibacterial agents. Hydrogels can encapsulate antibacterial drugs or compounds that target pathogenic microorganisms responsible for periodontal diseases, caries, and pulpitis. This ability to deliver antibiotics locally within the oral cavity minimizes

systemic side effects while enhancing the effectiveness of treatment. Moreover, hydrogels serve as scaffolds for tissue regeneration in periodontal therapy and maxillofacial reconstruction. By promoting cell adhesion and tissue growth, hydrogels can aid in the restoration of damaged tissues, providing a biocompatible environment that supports the healing process. Additionally, hydrogels play an essential role in controlled drug delivery systems for orthodontics. These systems can be used to regulate tooth movement by gradually releasing bioactive compounds, offering more precise and effective treatment outcomes. Furthermore, the self-assembly capabilities of hydrogels make them promising candidates for developing advanced biomaterials for oral tissue engineering. Despite their potential, challenges remain in optimizing the mechanical properties of hydrogels, particularly for applications requiring high durability and strength. Research is ongoing to improve their stability, biodegradability, and responsiveness to environmental stimuli. As hydrogels continue to evolve, they hold great promise for transforming dental treatments, enhancing patient care, and addressing complex oral health issues. The ongoing exploration of dynamic covalent bonds and self-assembled networks will likely lead to more adaptive and responsive hydrogel-based solutions in the future.

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الخلفية: تشمل اضطرابات الفم مثل التسوس، التهاب اللب، التهاب اللثة، التهاب المحيط الزرعي، والأورام الخبيثة الفموية غالبًا التهابات ميكروبية، والتهابًا، وتلفًا في الأنسجة. على الرغم من التقدم في العلاجات السنية الحالية، إلا أنها ما تزال محدودة بخصائص المواد المستخدمة، مما قد يؤدي إلى مشكلات مثل التسرب الميكروي، والهشاشة، والتأثيرات الجانبية. هناك طلب متزايد على المواد الحيوية المبتكرة لمعالجة هذه التحديات في العلاجات الفموية والجمجميّة.

الهدف: تهدف هذه المراجعة إلى استكشاف تطبيقات الجيل المائي في طب الأسنان، مع التركيز على إمكانياتها في علاج اضطرابات الفم، وتسهيل تجديد الأنسجة، وتعزيز أنظمة توصيل الأدوية.

الطرق: تم إجراء مراجعة شاملة للأدبيات لفحص خصائص الجيل المائي وتصنيفاته وتطبيقاته الوظيفية في طب الأسنان. يتم مناقشة الآليات الكيميائية لتكوين شبكة الجيل المائي، بما في ذلك الجيل المائي المتشابك وهيدروجيل التجميع الذاتي. تركز المراجعة على استخداماتها كعوامل مضادة للبكتيريا، ومواد داعمة لتجديد الأنسجة، ووسائل لتوصيل الأدوية في العلاجات السنية المختلفة.

النتائج: يظهر الجيل المائي توافقًا حيويًا ممتازًا، ومسامية، ومحبة للماء، مما يجعله مرشحًا مثاليًا للتطبيقات السنية. يتم تصنيفه بناءً على آليات تكوينه الكيميائية والهياكله الفيزيائية. يُستخدم التوصيل المشترك والتجميع الذاتي كطرق أساسية لإنشاء شبكات الجيل المائي. يمكن للهيدروجيل احتواء عوامل مضادة للبكتيريا لعلاج أمراض اللثة، وتوصيل الأدوية لإدارة الحركات التقويمية، والعمل كدعامات في تجديد الأنسجة، مما يظهر نتائج واعدة في إصلاح الأنسجة وكفاءة توصيل الأدوية .

الخاتمة: يقدم الجيل المائي حلاً مبتكرًا ومتعدد الاستخدامات في طب الأسنان. تمكن خصائصه الفريدة من تجاوز قيود المواد السنية التقليدية، مما يحسن نتائج العلاج. ستؤدي المزيد من الأبحاث حول تحسين تركيبات الجيل المائي إلى توسيع تطبيقاتها المحتملة، لا سيما في هندسة الأنسجة وتوصيل الأدوية.

الكلمات الرئيسية: الجيل المائي، طب الأسنان، تجديد الأنسجة، توصيل الأدوية، أمراض اللثة، المواد الحيوية السنية، العوامل المضادة للبكتيريا، هندسة الأنسجة.