magnetochemistry

MDPI

Review

Current Application of Magnetic Materials in the Dental Field

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Abstract: Integrating magnetic materials into dentistry has emerged as a promising advance for addressing diverse dental conditions. Magnetic particles comprising a magnetic core encapsulated within a biocompatible coating offer precise manipulation through external magnetic fields, rendering them invaluable in targeted drug delivery, magnetic resonance imaging, hyperthermia therapy, and diagnostic assays. Their tunable properties allow optimization for specific applications, enhancing therapeutic efficacy while minimizing off-target effects. Additionally, pre-adjust magnets showcase exceptional magnetic field strength and energy density. Their utilization in dental implants and orthodontic treatments facilitates tissue engineering and tooth movement, augmenting clinical outcomes and patient comfort. This review synthesizes current research directions and clinical applications of magnetic materials in dentistry, offering insights into their potential to transform dental healthcare and enhance patient well-being.

Keywords: magnetic materials; magnet; magnetic field; dentistry; oral disease; nanoparticles; nanomaterials

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1. Introduction:

In recent years, the application of magnetic materials in dentistry has emerged as a promising avenue for addressing various dental conditions [1–3]. Magnetic materials, characterized by their magnetic responsiveness, biocompatibility, and ability to interact with magnetic fields, offer a versatile platform for diagnostic [4,5] and therapeutic [6,7] interventions in the dentistry field.

Among most magnetic materials, magnetic particles are widely studied in biomedical applications [8–10]. These particles typically consist of a magnetic core, often composed of iron oxide or other magnetic materials, encapsulated within a biocompatible shell. Their magnetic responsiveness enables precise manipulation and control through external magnetic fields, rendering them invaluable tools in targeted drug delivery [11–13], magnetic resonance imaging (MRI) [8,13–15], hyperthermia therapy [10,16], and probing [17,18]. The size, shape, and surface chemistry of magnetic particles can be finely tuned to optimize their performance for specific applications [19–21]. In drug delivery [9,13], for instance, magnetic particles offer the advantage of targeted delivery to desired sites within the body, minimizing off-target effects and enhancing therapeutic efficacy.

In addition to magnetic particles, pre-adjust magnets, especially NdFeB magnets [22], represent today's most powerful permanent magnets. Comprised primarily of neodymium, iron, and boron, these magnets possess exceptionally high magnetic strength and energy density, making them essential components in numerous modern technological applications. NdFeB magnets have two poles, commonly called north and south poles, which exert magnetic field and forces on other magnets or magnetic materials. NdFeB magnets owe their superior magnetic properties to the alignment of their crystal structure during manufacturing, which results in a highly organized arrangement of magnetic domains. Magnetic forces are utilized in dental implants [23–25] and orthodontic treatments [26,27]

to facilitate tissue engineering and tooth movement, offering patients a more efficient and comfortable clinical experience.

In light of these advancements, this review paper aims to provide a comprehensive overview of the current applications (Figure 1) of magnetic materials in the dental field from the research direction (magnetic particles) and clinical direction (magnet/magnetic field). By synthesizing the latest research and reviews in this field, we aim to shed light on the potential of magnetic materials to revolutionize dental healthcare and improve patient outcomes.

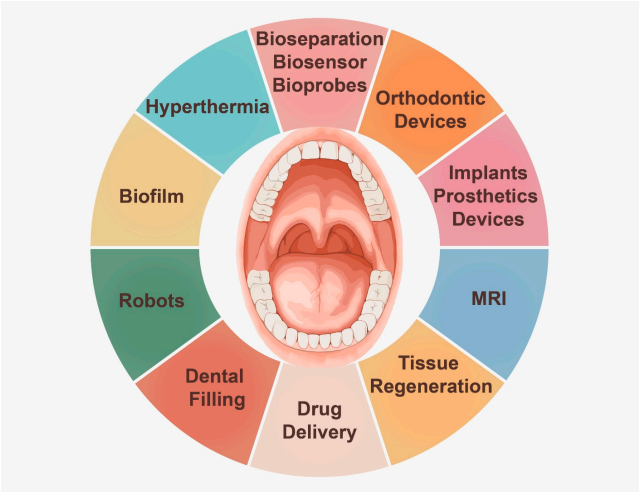

Figure 1. Magnetic materials address application needs in the dental field.

2. Forms of Magnetic Particles in Dental Research

2.1. Magnetite Iron Oxide

Magnetite is the most famous mineral ore used in dental research and belongs to the iron oxide family (Figure 2A), which has the chemical formula Fe_3O_4 [28,29]. Magnetite contains Fe^{2+} and Fe^{3+} ions. With a typical color of black or brownish black, it is the most common magnetic mineral found in metamorphic, sedimentary, and igneous rocks. The strong magnetism of Fe_3O_4 is made possible by magnetite's unique ferromagnetic characteristics, which set it apart from other iron oxides [28]. Magnetite's crystal structure is a polyhedral representation of the inverse spinel. At room temperature, it has four different crystalline polymorphs and a face-centered cubic arrangement in a regular pattern [29].

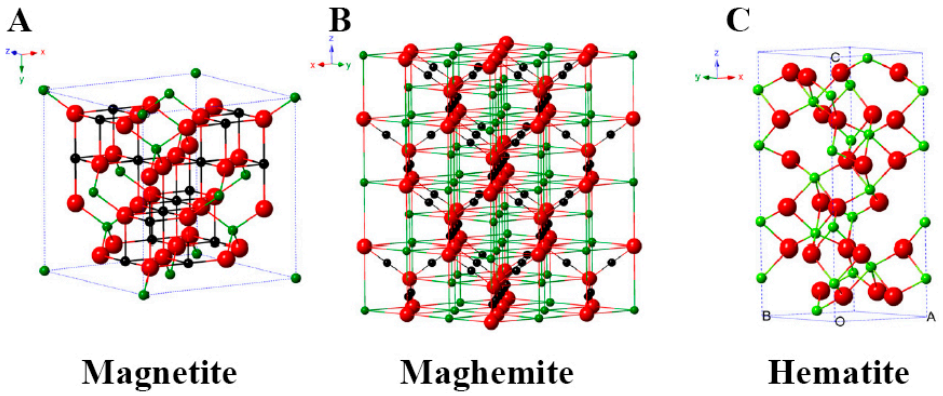

Figure 2. Different crystal structures of magnetic particles. The black, green, and red balls represent Fe^{2+}, Fe^{3+}, and O^{2-}, respectively. (**A**) The magnetite crystal form of magnetic particles. (**B**) The maghemite crystal form of magnetic particles. (**C**) The hematite crystal form of magnetic particles. Reprinted (adapted) with permission from [30]. Copyright 2015 American Chemical Society.

2.2. Maghemite Iron Oxide

Maghemite (γ-Fe_2O_3 nanoparticle, Figure 2B) is comparable to magnetite in that it has a similar crystal structure and electron diffraction patterns [31]. The iron atoms in maghemite are in an Fe^{3+} oxidation state, which are nonetheless ferromagnetic minerals with a similar lattice structure to magnetite. When subjected to an external magnetic field, they exhibit a strong magnetic response and magnetize readily. Maghemite can change into hematite at higher temperatures [32]. Compared to other Fe^{3+} oxides, like hematite, maghemite exhibits a more tremendous magnetism due to its lattice structure [33]. Moreover, its remarkable magnetic characteristics and low health risks have attracted much interest in biomedical uses. Maghemite is becoming an excellent option for creating magnetic nanoparticles for use in biomedicine [34].

2.3. Hematite Iron Oxide

Hematite (α-Fe_2O_3, Figure 2C) is a naturally occurring oxide mineral found in large quantities of rocks and soils [35]. Hematite is weakly ferromagnetic at room temperature [36]. Compared to other oxides, hematite is more accessible to synthesize and notably stable in environmental circumstances. Its crystal structure includes both corundum and rhombohedral forms. Hematite's biodegradability, non-toxicity, low corrosion, and ease of processing have made it a popular choice for various applications, such as gas sensors, environmental treatments, and magnetic storage media [37].

3. Applications of Magnetic Particles

3.1. Drug Delivery

Magnetic particle drug delivery is a technique that uses magnetic particles to transport medications to precise locations within the body [38,39]. Magnetic particles have the potential to enhance medication accumulation in targeted tissues, destroy sick tissues, and initiate drug release, making them valuable in nanotherapy [40]. These particles can be customized to achieve biocompatibility by attaching a variety of bioactive compounds to their magnetic cores, encased in organic polymers or inorganic metals [41]. Utilizing magnetic particles can mitigate the likelihood of specific adverse reactions and decrease the required medication dosage during therapy [42]. In addition, they have the ability to offer image and controlled release functionalities to drug delivery materials [43].

The medication delivery agent is often injected into the bloodstream via a catheter, which places the injection site near the intended target. This method lowers medication dosages, lessens side effects, and improves drug delivery precision [44,45]. Other methods exist as well, such as oral administration. Magnetic particles can be directed to the targeted tissues with the help of an external magnetic field [43]. Furthermore, by functionalizing these magnetic particles with therapeutic chemicals, they can be directed onto particular dental tissues by applying external magnetic fields. With potential uses in root canal therapy and periodontal therapy, this targeted medication delivery system provides a precise and least intrusive way to treat dental illnesses [39].

When paired with chemotherapy medications and an external magnet, superparamagnetic nano-carriers have shown promise in treating superficial oral malignancies by enhancing the anti-tumor effect. Such biocompatible, superparamagnetic, hollow mesoporous nanoparticles with magnetic targeting properties were created by Lin [46] and colleagues. They loaded bleomycin (BLM) into the mesoporous structure of the superparamagnetic nanoparticles by polyacrylic acid (PAA) surface engineering (Figure 3A–C). This drug delivery system allowed the BLM to be substantially released in the focal area while being affected by a magnetic field. Furthermore, the BLM-loaded PAA-functionalized magnetite nanoparticles caused localized apoptosis in tumor cells, exhibiting the ability to target targets in vitro and inhibit tumor growth in vivo. Crucially, this tailored drug delivery method is simple and does not require sophisticated chemistry or materials engineering. It can potentially advance nanotherapeutics for effective treatment of head and neck cancer. Similarly, magnetic Fe_3O_4 nanoparticles modified with polyethyleneimine

(PEI) can also act as delivery vehicles for therapeutic siRNA that targets B-cell lymphoma-2 and Baculoviral IAP repeat-containing 5 to Ca9-22 oral cancer cells. Fe_3O_4 nanoparticles were confirmed to be more effective in delivering siRNAs to Ca9-22 cells than to CAL27 oral cancer cells, suggesting they have a bright future for siRNA delivery applications [47].

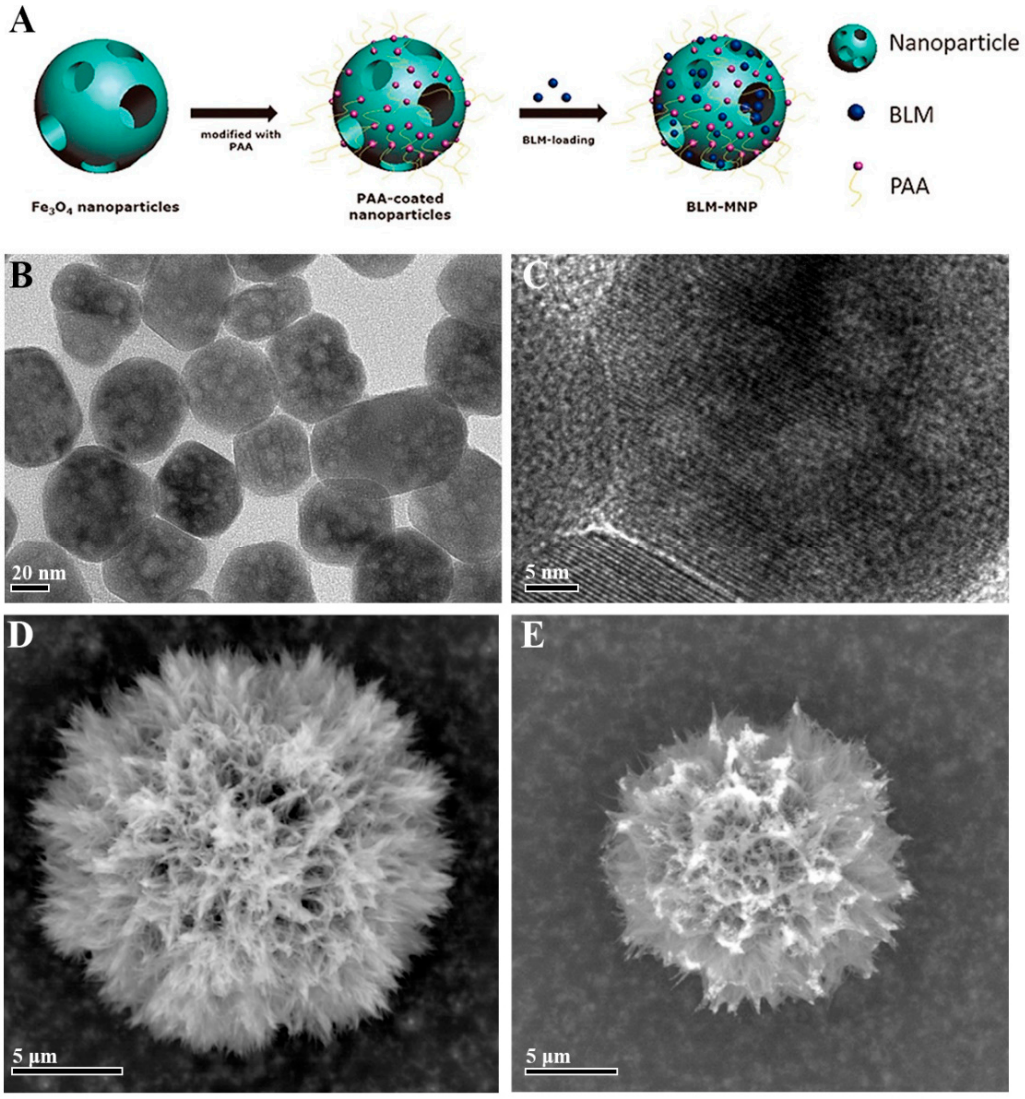

Figure 3. (**A**) The synthesis of the surface-engineering PAA magnetic nanoparticles for BLM delivery. (**B**) TEM image of uncoated Fe_3O_4 nanoparticles. The Fe_3O_4 nanoparticles are spheres shaped with multiple hollow mesoporous structures. (**C**) Amplified images of the regions of interest are boxed in Figure 3B. Image reproduced with permission from [46]. Spherical CHX particles (**D**) and CHX/Fe_3O_4 spheres (**E**). Image reproduced with permission from [48].

In addition to anti-oral cancer medications, amino silane was used to modify the general antiseptic and disinfectant reagent chlorhexidine (CHX) on magnetic nanoparticles [49]. CHX can result in strong antibacterial and antifungal effects against microbial biofilms, potentially making them a good choice for treating oral microflora-related local infections. Moreover, CHX showed limited toxicity towards human osteoblasts and enhanced antibacterial action when salivary proteins are present, reinforcing their prospective use in these applications. By functionalizing CHX particles with iron oxide (Fe_3O_4) nanoparticles, Luo et al. [48] created a unique method to improve medication release within dental resin, which was made possible by an external magnetic field (Figure 3D,E). These hybrid particles were then exposed to different lengths of magnetic field exposure on resin discs, which caused

the particles to aggregate close to the surface and substantially increased the CHX release from the resin discs with magnetic stimulation. This study highlights the possibility of tailored medication delivery to infection sites in therapeutic settings. Thus, the magnetic field responsiveness of Fe_3O_4-functionalized CHX particles offers a promising prospect for targeted medication delivery.

Magnetic particles loaded in biological osteogenic components can further promote osteoblast proliferation, differentiation, and angiogenesis. Patricio [50] prepared hybrid superparamagnetic microspheres explicitly designed for delivering recombinant human bone morphogenetic protein-2 (rhBMP-2) in levels that are useful for therapy (Figure 4A–D). These microspheres have extended-release characteristics. When evaluated using human mesenchymal stem cells, these microspheres showed an exceptional ability to promote bone formation. In addition, the release of rhBMP-2 from the microspheres could be controlled by applying a pulsed electromagnetic field. This unique characteristic highlights the possibility of controlling the biological activity of these small devices from a distance, providing significant opportunities for future use in carefully designed bone regeneration and individualized treatments. Xue et al. [51] developed an innovative magnetic drug-loaded osteoinductive $Fe_3O_4/CaCO_3$ hybrid microspheres (MDHMs), demonstrating exceptional drug delivery capabilities. The MDHMs have a consistent magnetic characteristic, with a saturation magnetization of around 4.41 emu/g and an impressive responsiveness to magnetism. MDHMs are vaterite microsphere structures with a consistent size and shape and possess distinct nanostructures with pores of a specific size, showing potential in bone tissue engineering. The in vitro results indicate that MDHMs possess excellent drug transport capabilities, osteoinductive potential, and magnetic properties, making them highly promising for treating peri-implantitis.

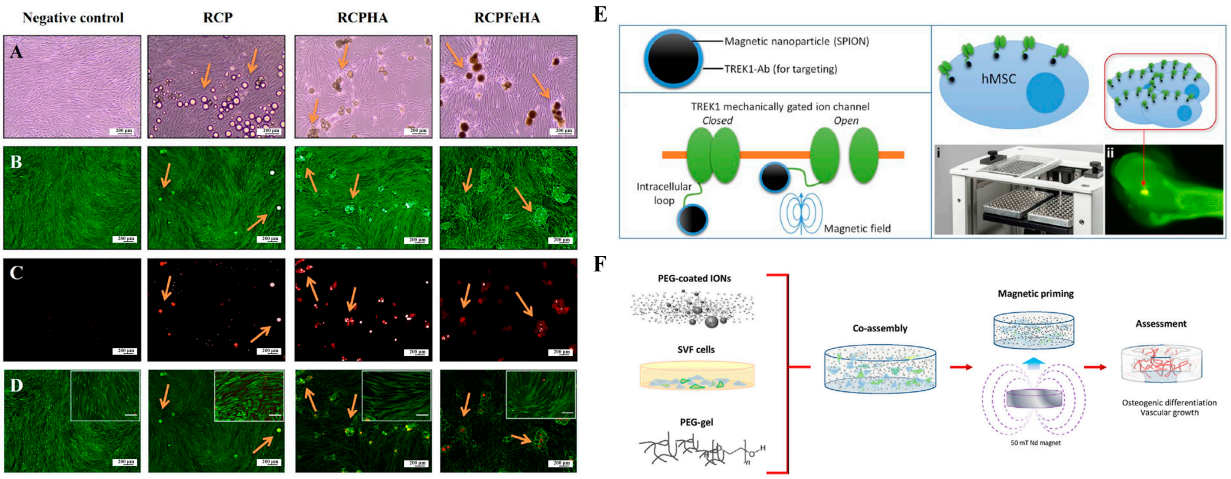

Figure 4. Bright-field images (**A**) and live (**B**), dead (**C**), and merged (**D**) monolayer human mesenchymal stromal cells (hMSCs) in the presence of iron-doped hydroxyapatite microspheres (orange arrows). Image reproduced with permission from [50]. (**E**) A TREK1 ion channel activated by magnetic ion channels. Antibodies that target the TREK1 ion channel's mechanosensitive intracellular loop region were used to functionalize magnetic nanoparticles. An external magnetic field can be used to activate the ion channel because of the nanoparticle's attachment to it. Magnets may be controlled remotely by tagging TREK1 in hMSCs. (**i**) MICA bioreactor moving magnetic array used in this investigation, and (**ii**) remote control of injected hMSCs. Image reproduced with permission from [52]. (**F**) The generation of magnetic hydrogels by the co-assembly of cells, magnetic nanoparticles, and polyethylene glycol (PEG) gels and their stimulation by the application of an external magnetic field. Image reproduced with permission from [53].

Henstock et al. [52] observed that functionalized magnetic nanoparticles were linked to either the mechanically regulated TREK1 K^+ channel or RGD-binding domains of human mesenchymal stem cells (Figure 4E). The combination of mechanical stimulus and

sustained release of BMP-2 proteins from polymer microspheres had a significant additive effect on mineralization. This increased the efficiency of BMP-2 delivery and showed that nanoparticle-mediated mechano-transduction can be used in synergy with pharmacological approaches for orthopedic tissue engineering to optimize bone formation. Thus, those functionalized magnetic nanoparticles can enhance the intracellular cascade impact of exogenous growth factors by providing mechanical stimulation, thereby optimizing their therapeutic potential.

Additionally, live cells and MNPs may be used to intelligently transport and guide cells to specified locations when an external magnetic field is present [53]. A unique three-dimensional magnetic nano-hydrogel was created by mixing stromal vascular fraction cells generated from human adipose tissue with a hydrogel based on polyethylene glycol (PEG) and combined magnetic nanoparticles (Figure 4F). This hydrogel possesses both osteogenic and blood vessel-forming capabilities. The $CD31^+$ endothelial cells in the magnetically actuated gels exhibited a greater concentration, forming elongated capillary-like structures.

3.2. Hyperthermia

Inducing localized hyperthermia is a promising minimally invasive tumor-fighting tactic [54]. Iron oxide nanoparticles are well known for their potential to induce hyperthermia by either Brownian relaxation or Néel relaxation processes. Various parameters can be used to assess their eligibility for cancer treatment [55], including the ability to enter tumor cells efficiently, targeting, and internalizing [56]. Iron oxide nanoparticles are also easy to administer in clinical settings, have little toxicity and biocompatibility over a broad dosage range, and are flexible enough to target particular tumor types or organs that have metastasized [57]. Especially, superparamagnetic iron oxide nanoparticles (SPIONs) are currently being investigated widely in clinical settings as agents for magnetic hyperthermia because of their strong surface reactivity, which enables a broad spectrum of biofunctionalization, and their capacity to create stable suspensions [58]. The nanoparticles' size and the alternating magnetic field frequency affect how much heat can be produced in magnetic hyperthermia with SPIONs [59]. This technique involves applying an alternating magnetic field to tumors to cause cytotoxic hyperthermia using magnetic nanoparticles [60,61].

Altanerova [55] reported the potential of using magnetic nanoparticles enclosed within human mesenchymal stem cell (MSC) exosomes to specifically eliminate tumor cells by inducing hyperthermia through magnetism. They labeled MSCs, modified to express the yeast cytosine deaminase/uracil phosphoribosyl transferase suicide fusion gene (yCD/UPRT), with Venofer, a nanoparticle composed of iron oxide and carbohydrates. Their labeling strategies did not have a detrimental effect on cell proliferation or the ability of MSCs to migrate toward tumors. The MSCs labeled with Venofer generated exosomes containing iron oxide, which were effectively taken up by tumor cells. Combining exosomes derived from Venofer-labeled MSCs that express the yCD/UPRT gene with the prodrug 5-fluorocytosine resulted in a significant and dose-dependent tumor growth inhibition. Furthermore, tumor cells subjected to this approach were effectively eradicated by applying hyperthermia induction employing an external alternating magnetic field.

Kazeli and colleagues [62] created three-dimensional magnetic nanocomposite (Mg_2SiO_4-$CoFe_2O_4$) scaffolds (MS) utilizing the polymer foam replica process. The scaffolds exhibited remarkable hyperthermia capabilities (Figure 5A,B). The nanocomposite (NP) shows a significant increase in temperature, going from 19 °C to 43 °C in under 100 s, with a specific loss of power (SLP) at 450 W/g. Their findings indicate that MS holds excellent potential for bone tissue regeneration and cancer treatment, primarily when used in conjunction with the targeted administration of active medicinal compounds and magnetic hyperthermia.

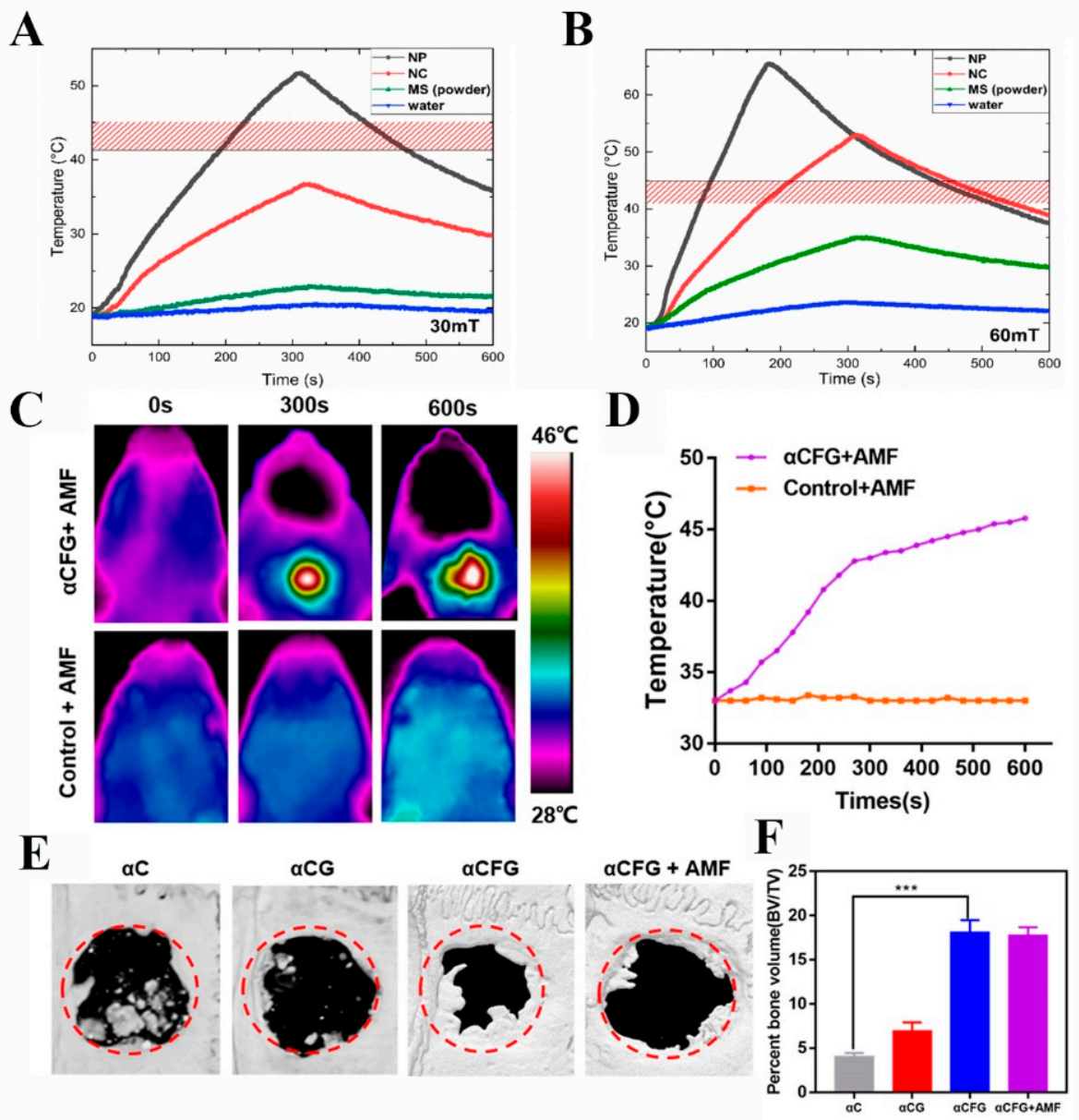

Figure 5. The hyperthermia application of magnetic particles. Hyperthermia curves of NPs ($CoFe_2O_4$ nanoparticles), NCs (Mg_2SiO_4–$CoFe_2O_4$ nanocomposites), and MSs (magnetic scaffolds) at (**A**) 30 mT and (**B**) 60 mT. Image reproduced with permission from [62]. Injectable magnetic bones cement in vivo magnetothermal effects, and osteogenesis is examined in the following ways: thermal images and magnetothermal curves of SD rats' cranial defects at different times under 250 Gs intensities of an alternating magnetic field (**C**,**D**) and micro-CT analysis of the defected area in the cranial bones of SD rats in various groups eight weeks after surgery (*** $p < 0.001$) (**E**,**F**). Reprinted (adapted) with permission from [63]. Copyright 2019 American Chemical Society.

Kawashita [64] has successfully synthesized SiO_2-cored Fe_3O_4 microspheres with dimensions within 20–30 nm. These microspheres are made up of tiny crystals of Fe_3O_4 or γ-Fe_2O_3, which were formed through precipitation from an aqueous solution and then subjected to heat treatment, exhibiting ferrimagnetism, with a saturation magnetization of 53 or 68 emu/g. When disseminated in an agar phantom and exposed to an alternating magnetic field, they exhibited heat generation in vitro.

Magnetic hyperthermia can also enhance the process of osteogenic differentiation. Nevertheless, the specific mechanisms responsible for the osteogenic effects of magnetic hyperthermia are not yet fully understood [65]. According to some studies, hyperthermia

may affect bone metabolism by boosting blood circulation. Others indicate that it promotes the expression of genes associated with bone formation by increasing mitochondrial activity and accelerating the production of bone-related genes [66]. The processes responsible for osteogenic stimulation from magnetic hyperthermia are still being researched. Compared to the photo-responsive technique, magnetothermal therapy utilizing an external alternating magnetic field provides the benefit of enhanced tissue penetration at greater depths. This feature renders it a promising choice for treating profound tissue lesions, such as bone cancers. In addition, magnetic field-responsive therapy provides a non-invasive and highly controllable approach, simultaneously meeting the requirements for procedures such as bone tumor ablation and localized bone regeneration. When magnetic Fe_3O_4 nanoparticles are exposed to an external magnetic field, they can increase temperatures within the range of 42 °C to 45 °C (Figure 5C–F) [63]. The temperature rise can potentially damage or eradicate cancer cells by causing bleeding or blocking blood vessels while minimizing harm to nearby healthy tissues [67,68]. Nevertheless, there is a notable obstacle to augmenting the heating rates of nanostructures composed of iron oxide. This obstacle pertains to attaining therapeutic temperatures for the intended purpose. Employing higher heating rates can serve as an alternative method for enhancing the uniformity of iron oxide-based nanostructures. According to Kumar's study [69], the hyperthermia impact of nanostructures based on SIONPs can be significantly improved by applying a layer of gold. The application of highly low-frequency oscillating magnetic fields is feasible. Although research on magnetic field-induced bone therapy and regeneration is still in its initial phases, the positive results have attracted increasing attention. Future research could concentrate on attaining consistent and uniform magnetic heating and devising techniques to reduce the potential risk of thermal harm to adjacent healthy tissues. These factors may contribute to developing more efficient and secure uses of magnetic treatments for bone repair and regeneration.

3.3. Bone Regeneration

The static magnetic field produced by permanent magnets offers various therapeutic benefits, including not needing a power device and being able to create the magnetic field in the desired direction [70]. As a result, magnetic field stimulation is more appropriate for long-term localized healing [71]. Utilizing magnetic fields in bone regeneration shows excellent potential for improving dental implantology. Researchers plan to enhance bone formation and promote the integration of dental components with surrounding tissues by utilizing magnetic fields on bone grafts or implants. This method has considerable potential to increase the success rates of dental implants and enhance patient outcomes [72].

Previous studies have shown that magnetic fields with a strength of 1 T have the ability to speed up the process of bone fusion and enhance the development of bone-forming cells at a cellular level [73]. It has been shown that the high magnetic fields influence the alignment of cells and bone matrix protein [74]. The performance of moderate magnetic fields generated by permanent magnets in wound healing and osteoconduction has garnered significant attention. The magnetic field of 100 mT was observed to be in advance of the magnetic fields of 200–400 mT and 600 mT. This suggests that researchers have the ability to study magnetic fields with lower levels of strength [70].

De Abreu [75] studied the impact of buried magnetic field stimulation on bone healing in rat calvaria following reconstruction using autogenous bone grafts, synthetic powdered hydroxyapatite, or allogeneic cartilage grafts. Additionally, magnetic implants were inserted into half of the animals. Quantitative histomorphometry assessments of bone healing were conducted at all time points. The analyses revealed statistically significant interactions between the groups and postoperative time. The rats that underwent autogenous bone repair and were exposed to magnetic stimulation exhibited more significant bone fill percentages compared to those without magnetic implants. Furthermore, the results indicated that the former group had superior bone repair quality compared to the latter group after 60 days post-surgery. After a period of 60 days following surgery, the group of

animals treated with autogenous bone grafts and exposed to a magnetic field showed a higher level of bone repair. The animals treated with autogenous bone grafts had the most significant bone repair, followed by those treated with powdered synthetic hydroxyapatite and allogeneic cartilage grafts.

Zhao et al. [76] effectively integrated nano-hydroxyapatite (nHAP) and Fe_3O_4 nanoparticles into the chitosan/collagen (CS/Col) organic matrix (Figure 6A–D). They found a remarkable improvement in cell adhesion, proliferation, and osteogenic differentiation. Unlike electrical materials, the effectiveness of magnetic materials mainly relies on magnetic fields. This combination exhibited higher values in trabecular bones compared to electrical materials. Nevertheless, the absence of a cohesive benchmark for evaluating magnetic materials has hindered the ability to establish a direct relationship between their attributes and performance.

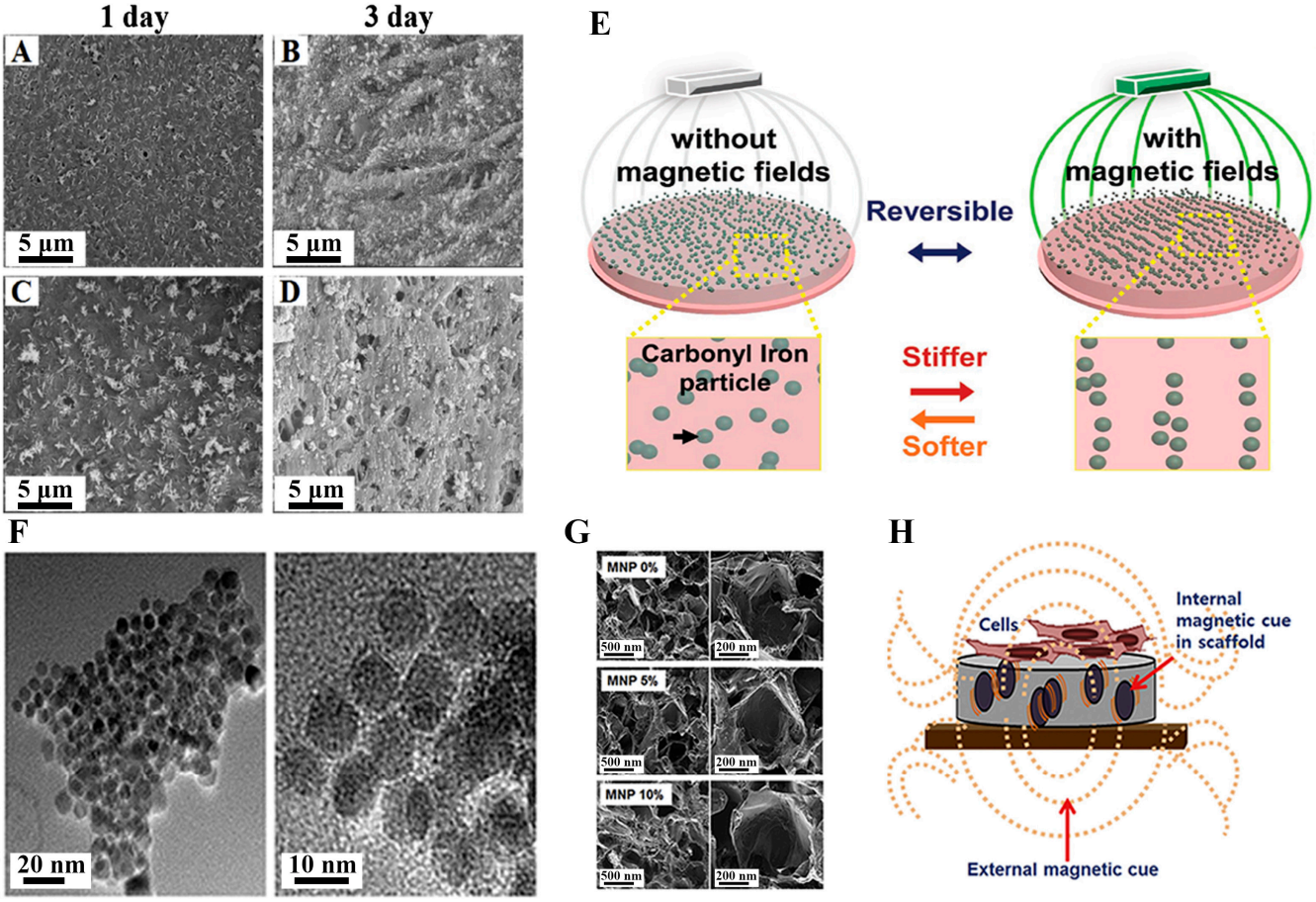

Figure 6. The biomineralization evaluation of chitosan/collagen/nHAP (**A**,**B**) and chitosan/collagen/Fe_3O_4/nHAP (**C**,**D**) scaffolds in simulated body fluid. Image reproduced with permission from [76]. (**E**) Diagram illustrating the magnetoactive hydrogel system created by adding carbonyl iron. Image reproduced with permission from [77]. (**F**) TEM images of MNPs at low and high magnification. (**G**) SEM images of the scaffolds with different MNP contents at low and high magnification. (**H**) Diagram illustrating how the external magnetic field and inside magnetic nanoparticles work together to provide magnetic signals that can affect how cells respond. Image reproduced with permission from [78].

The work of Yang et al. [79] utilized γ-Fe_2O_3 nanoparticles (γ-IONPs) and α-Fe_2O_3 nanoparticles (α-IONPs) to create innovative IONP–calcium phosphate cement (CPC) scaffolds. The addition of IONP into CPC significantly improved the osteogenic development of human dental pulp stem cells (hDPSCs), which have excellent potential for substantially enhancing bone regeneration in dental, craniofacial, and orthopedic applications. A sig-

nificant increase in ALP activity, osteogenic gene expressions, and cells' synthesis of bone matrix minerals was observed compared to control groups. The improved formation of new bone cells was due to the specific surface structure of the IONP-CPC scaffold and the uptake of IONPs released from the scaffold by the cells.

Due to the distinctive 3D network structure, which contains a significant amount of water and possesses functional qualities, hydrogel scaffolds are considered highly promising for bone tissue engineering applications [80], including repairing cartilage injuries, skull defects, and arthritis. These scaffolds have adjustable mechanical strength, good biocompatibility, and impressive bioactivity, making them suitable for use in bone regeneration [81]. Yun [78] and colleagues prepared the combination of an external static magnetic field (SMF) and a magnetic nanocomposite scaffold consisting of polycaprolactone/magnetic nanoparticles that affect osteoblastic functions and bone formation (Figure 6F–H). The SMF enhanced the osteoblastic development of primary mouse calvarium osteoblasts by working with magnetic scaffolds. This magnetic nanocomposite scaffold increased the expression of bone-associated genes and alkaline phosphatase activity, showing in the stimulation of integrin signaling pathways (mitogen-activated protein kinase and nuclear factor-kappa B). In addition, the SMF/magnetic scaffold stimulated the growth of osteoblasts, which in turn enhanced the construction of blood vessels by endothelial cells. When the magnetic scaffolds were inserted into defects in the skulls of mice, the use of an SMF significantly increased the formation of new bone after 6 weeks. Combining an external SMF and magnetism scaffold could be a valuable approach for regenerative bone engineering.

Significant bone defects resulting from aging, trauma, or illness provide a crucial therapeutic issue as they cannot be fully mended. Magnetic materials utilized to stimulate bone regeneration physically have garnered attention due to their promising potential and easy implementation in clinical settings. Hou et al. [82] discovered that osteoblasts' adhesion and proliferation rate significantly enhanced with increasing concentrations of m-nHA (Fe_2O_3 coated with nano-hydroxyapatite). The osteoblasts preferred adhering to and multiplying on the m-nHA/PVA hydrogels compared to the PVA and nHA/PVA hydrogels. However, the γ-Fe_2O_3/PVA hydrogels were shown to be the most suitable for osteoblasts. In addition, when the m-nHA content in the composite hydrogels increased, there was a notable enhancement in the adhesion density and proliferation of the osteoblasts, notably when the level reached approximately 50 wt%.

Fan et al. [83] developed composite nanogels made of chitosan and heparin to encapsulate Fe_3O_4 nanoparticles, achieved by utilizing Watson–Crick base pairing between thymine and adenine to form nucleobase pairs. The magnetic biopolymer nanogels demonstrate rapid magnetic responsiveness, achieved through the encapsulation of superparamagnetic iron oxide nanoparticles. Under the influence of an external magnetic field, the release of BMP2 was carefully regulated.

Abdeen et al. [77] introduced a modifiable magnetic hydrogel structure by incorporating functional carbonyl iron (CI) particles into a polyacrylamide hydrogel (Figure 6E). CI particles can increase the flexibility of a gel when exposed to a strong magnetic field while not impacting the proliferation of cells. Upon the implantation of MSCs into the magnetic hydrogel matrix, their ability to promote angiogenesis and undergo osteogenic differentiation was enhanced. The scientists concluded that magnetic stimuli were crucial in beginning signals for osteogenesis. The performance of hydrogels can be influenced by various characteristics of magnetic particles, including their composition, dimensions, morphology, and crystal structure.

3.4. Skin Regeneration

Drobota and colleagues [84] investigated a simple technique for producing gelatin-based materials containing iron oxide nanoparticles for future skin wound recovery. This magnetic gel is meticulously calibrated to align with the specifications perfectly and with the intended application in direct contact with human or animal skin. The in vitro assay established the absence of toxicity in the samples and antibacterial properties.

Fallahiarezoudar [85] reported a novel blend, including three distinct biocompatible and biodegradable substances for soft tissue applications. Five different ratios of a mixture consisting of poly-l-lactic acid (PLLA) and thermoplastic polyurethane (TPU), with a 1% (w/v) inclusion of maghemite (γ-Fe_2O_3) nanoparticles, were subjected to electrospinning. The resulting materials were then analyzed in terms of their morphology, degradation rate, biological compatibility, and mechanical properties to achieve adjustable properties. PLLA exhibited a mass change of 47.15%, while TPU had a mass change of 6.7%. PLLA was found to have a high tensile strength and a very low elongation at break based on the stress–strain curve, whereas TPU demonstrated considerable elasticity.

3.5. Tooth Structure Regeneration

Farag et al. [86] revealed novel magnetic nanoparticles composed of iron oxide and Mg–phosphate ceramic (nMgP-Fe) for treating bone and pulp–dentin illnesses (Figure 7A–D). The crystal phases that resulted from the nMgP-Fe material's nanoscale size range of 10–40 nm were recognized as farringonite and magnetite. It was shown that nMgP-Fe exhibited superparamagnetic properties, with coercivity and residual magnetization values of 20 Oe and 0.06 emu/g, respectively. Iron ions were released less often in the dissolving test than magnesium and phosphate ions. After cultured with nMgP-Fe particles, DPSCs exhibited a greater rate of cell differentiation into osteoblasts, possessing superparamagnetic characteristics and biocompatibility, rendering them an auspicious material for the regeneration of bone and pulp–dentin.

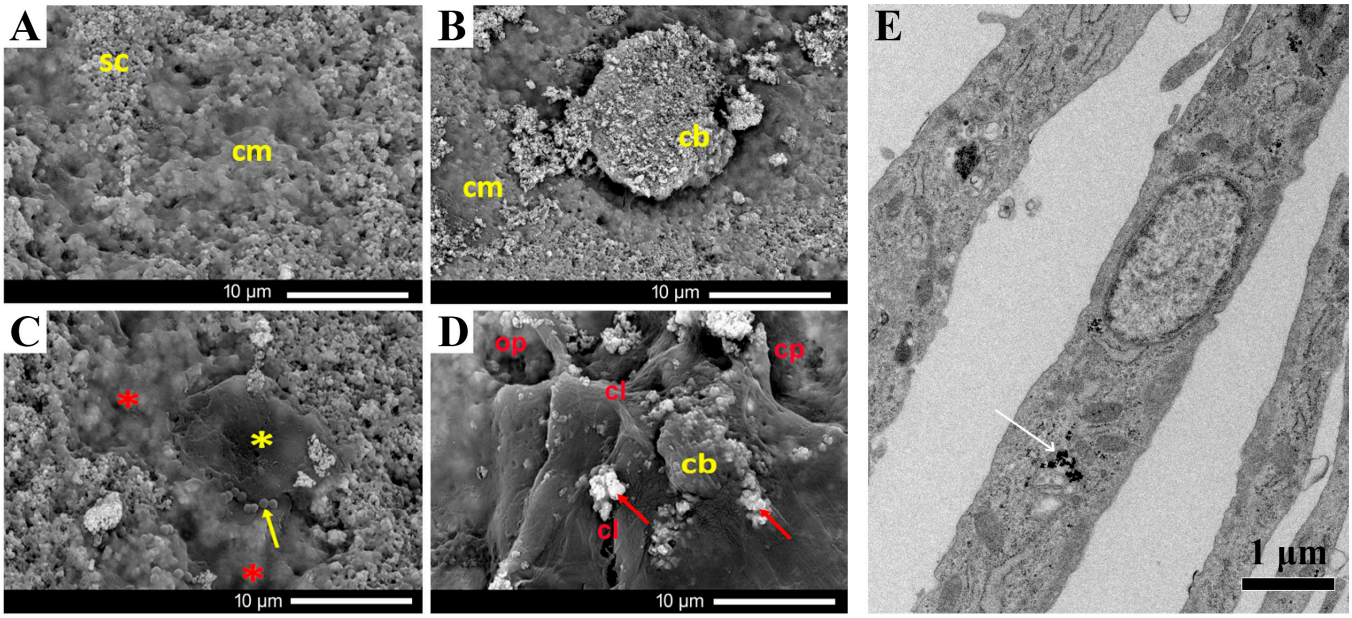

Figure 7. SEM images of DPSCs/nMgP-Fe at 24 h reveal (**A**,**B**) the formation of a collagenous extracellular membrane (cm) on the scaffold (sc), as well as (**C**,**D**) DPSCs with a rounded cell body (cb) devoid of cell processes after 48 h. The morphology of the cell is stellate (yellow asterisk), the substance is matrix-like (red asterisks), the mineral deposits (red arrows), and the cell body has exocytotic outgrowths, collagen fibers (cl), opened and closed pores (op and cp), and a nodular vesicular structure (yellow arrow). Image reproduced with permission from [86]. (**E**) TEM image of odontogenic cells treated with 100 pg magnetite/cell of MNPs (white arrows). Image reproduced with permission from [87].

Koto [87] utilized a magnetic force-based tissue engineering technique to build a composite cell sheet comprising dental epithelial cells (DECs) and dental mesenchymal cells (DMCs). The magnetic nanoparticles (MNPs) were evenly distributed throughout the carbon composite (CC) sheet. The microenvironment in the CC sheet may resemble

that observed during the developmental phase of a tooth bud (Figure 7E). The use of MNPs in the CC sheet has the potential to become a novel and unique technique for the artificial reconstruction of tooth enamel. In the CC sheet, the mRNA expression of markers linked to the basement membrane and enamel differentiation was examined. Collagen IV expression was detected by immunostaining in the region of the CC sheet that separates the DMC and DEC layers. The findings indicated that the connection between epithelial and mesenchymal layers resulted from physically putting the DEC in close proximity to the DMC using magnetic force.

3.6. Magnetic Resonance Imaging (MRI)

The utilization of MRI in powerful magnetic fields has dramatically improved diagnostic imaging, which is a fundamental aspect of general healthcare [88]. This technology can provide high-resolution imaging of dental structures, identifying and assessing problems such as root canal infections, temporomandibular joint abnormalities, and malignancies [88–91].

Mastrogiacomo et al. [92] prepared calcium phosphate-based composites (CPCs) by incorporating a core–shell structured dual contrast agent (csDCA) made of colloidal gold and superparamagnetic iron oxide, fulfilling the imaging and regeneration criteria necessary for pulp capping applications (Figure 8). This csDCA is an MRI contrast agent and a CT contrast agent, providing improved biological performance, excellent handling properties, and good imaging contrast for pulp capping agents. Additionally, a dentinogenic factor, specifically BMP-2, was included. Incisors treated with BMP-2 exhibited enhanced the formation of tertiary dentin and accelerated the breakdown of cement, as evaluated using micro-CT analysis.

For patients who are not ideal candidates for surgery, such as those with advanced head and neck cancer, the image-guided thermal ablation of tumors is becoming a more frequently recognized minimally invasive option for surgery. Superparamagnetic iron oxide with special surface modifications has been utilized to guide the laser ablation of maxillofacial cancer [93] due to the fact that these artificial NPs may be heated selectively for simultaneous imaging and are magnetic resonance-active.

Marites et al. [94] developed a multifunctional material consisting of superparamagnetic iron oxide coated with a gold nanoshell (SPIO@Au NS), which exhibits superparamagnetics. This material possesses both optical and magnetic capabilities. It was then combined with a targeting agent, the C225 monoclonal antibody, which specifically binds to the epidermal growth factor receptor. The in vivo biodistribution study tumors demonstrated the specific targeting of C225-SPIO@Au NS instead of the non-targeting and blocking groups. The targeted destruction of cells using nanoshells through photothermal ablation was observed. In the absence of laser therapy, no cell death occurred. However, among the groups subjected to laser treatment, only the cells treated with C225-SPIO@Au NS showed significant cell killing and optical capabilities. Both in vitro and in vivo studies demonstrated that these nanoshells exhibit magnetic resonance activity and may be selectively heated to enable simultaneous imaging and photothermal ablation therapy.

Magnetic nanoparticles can attach to the stem cell surface, labeling mesenchymal stem cells without a transfection agent [95,96] and influencing the behavior of cells and the single-cell clinical 5 T magnetic resonance detection capacity. Magnetic nanoparticle endocytosis has no effect on the survival, proliferation, destiny, or differentiation of stem cells.

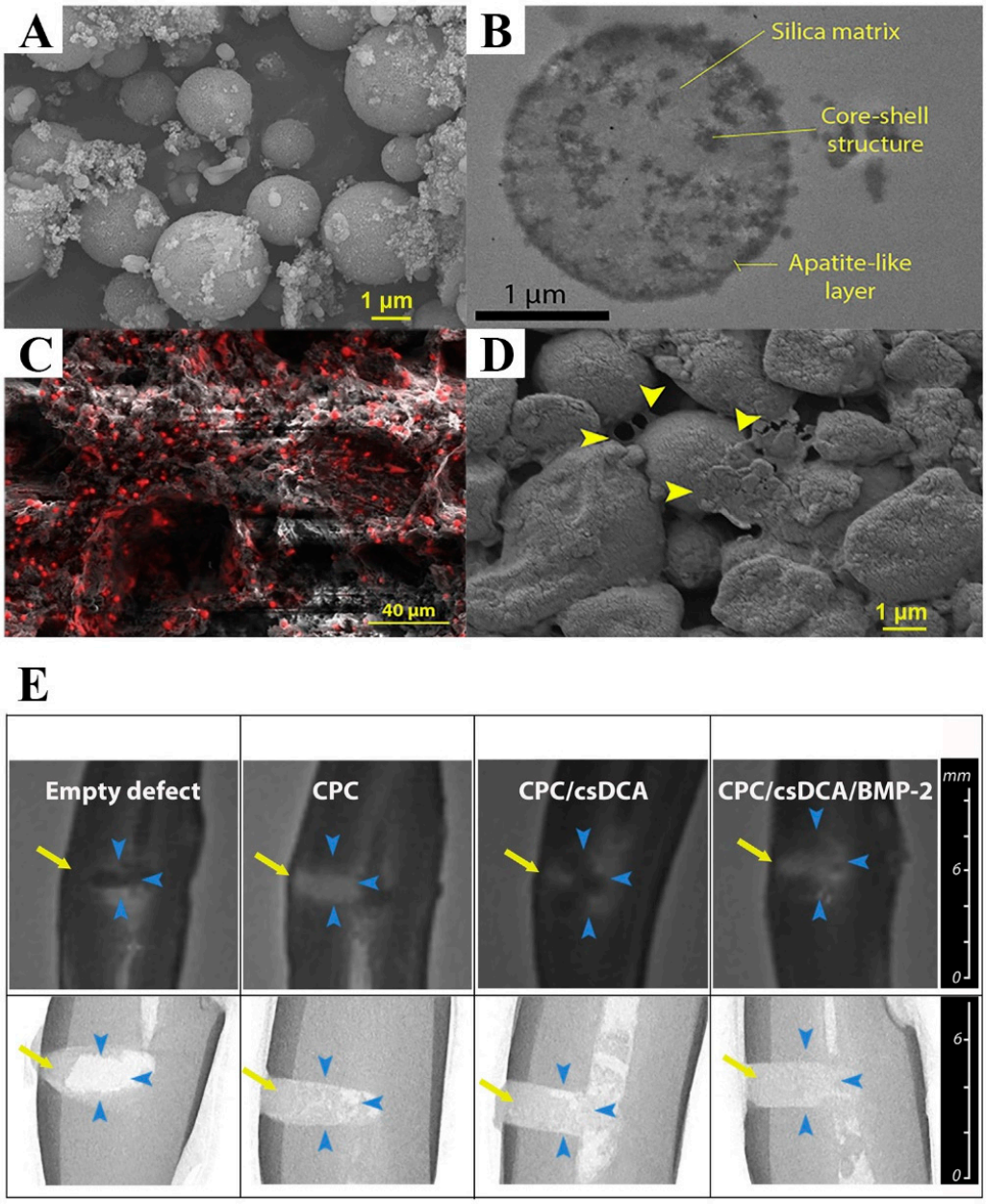

Figure 8. (**A**) SEM and TEM (**B**) images of csDCA particles. (**C**) SEM picture and EDS spatial resolution map overlap. SEM picture of particles of csDCA trapped in the CPC phase (**D**). Junctions between a particle and cement are indicated by yellow arrows. (**E**) Goat incisors following direct pulp capping in vivo. The white area: the room. The cylindrical defect, with or without implanted material, is shown by blue arrows. The glass ionomer filler is represented by the thin layer shown by yellow arrows. Top: MRI acquisitions. Bottom: mCT reconstructions. Image reproduced with permission from [92].

3.7. Bioseparation

Bioseparation plays a crucial role in applying magnetic nanoparticles [97]. Superparamagnetic magnetic nanoparticles are ideal for this approach because of their inherent magnetism, which facilitates the movement of biomaterials using a magnetic field. Essentially, isolating distinct biological entities is frequently utilized in this application within the field of biomedical research [98–100]. This application typically involves separating cells, bacteria, viruses, enzymes, proteins, genes, and in vitro DNA [101]. Compared to traditional separation techniques, magnetic bioseparation has a number of advantages,

including faster localization or retrieval times. The many advantages of magnetic iron oxide-based nanostructures, such as their small size and high surface area, are advantageous to their application. They are also quicker and less expensive than traditional column affinity chromatography. Magnetic nanoparticle-based surface-functionalized nanostructures are commonly employed to enhance bioseparation. These nanostructures may be altered to add functional end groups by adding polymers and surfactants. They have an intermediate efficiency. Li et al. [102] examined the synthesis of carboxymethylated dextran-coated magnetic iron oxide-based nanostructures utilizing the coprecipitation method for the purpose of bioseparation application. The antibodiy-coated particles possess superparamagnetic characteristics, enabling the separation of the antigen from the sample solution.

Adams [103] and colleagues published a study on the use of Fe_3O_4@SiO_2 nanoparticles, modified with gold and poly(vinylpyrrolidone), for bioseparation and sensing. The particles possess a distinct surface morphology consisting of roughened gold nodules. Applying surface coatings inhibits oxidation and facilitates the functionalization of particles, allowing them to target a diverse variety of moieties effectively. The gold layer on the particle surface is both uniform and ultrathin, allowing for a high magnetic saturation comparable to bare magnetite. The presence of gold nodules promotes the formation of localized areas of high intensity that amplify the electromagnetic field surrounding the surface of the particles. This property makes them valuable for sensing applications, such as surface-enhanced Raman spectroscopy. Additionally, the strong magnetic core enables the rapid separation (within approximately 30 s) of target molecules from a solution once they have attached to the particles.

Oral keratinocyte stem cells are essential in tissue homeostasis, wound healing, and neoplasia. However, it is still challenging to identify and characterize them. Notably, fluorescence-activated cell sorting (FACS) and magnetic-activated cell sorting (MACS) have been used to obtain homogenous populations of oral keratinocyte stem cells [104]. The experimental conditions were often established using a mixture of media supplements containing beta-glycerophosphate, ascorbic acid, and dexamethasone in varying doses. Calenic et al. also connected proliferation-related markers, CD71 and Integrin α6β4, onto magnetic beads and separated three different oral keratinocyte stem cell subpopulations, suggesting that a magnetic system may be an essential tool in acquiring oral keratinocyte stem cells for research [105,106].

Yang et al. [107] created a cluster of superparamagnetic nanoparticles that are sensitive to variations in pH. This cluster separates blood extracellular vehicles (EVs) by specifically recognizing transferrin and transferrin receptors.

3.8. Biosensors and Bioprobes

The application of magnetic materials in the development of bioprobes and biosensors offers novel prospects for diagnostic and monitoring applications in dentistry [108]. These state-of-the-art devices have the potential to identify oral problems in their early stages and monitor patients' response to treatment, enabling personalized dental care strategies [109].

Li et al. [110] initially developed composite nanoparticles consisting of carbon dots immobilized on silica (Fe_3O_4@SiO_2@mSiO_2-SiCDs) with dual emission properties (Figure 9A). As the concentration of the nanoparticle solution increases, the distance between the nanoparticles reduces. This leads to a phenomenon called concentration-mediated scattering, which causes a shift towards longer wavelengths in the fluorescence peaks. The precise arrangement of the Fe_3O_4@SiO_2@mSiO_2-SiCDs nanoparticles and the scattering phenomena influenced by concentration are crucial factors in the redshift. Li et al. [111] also developed a fluorescent probe (Figure 9B) that can detect and remove F^- ions from the platform based on the core–shell structure. The minimal detection limit has been reduced to 65 nM while maintaining a wide linear response range of 1 to 25 μM. The ion adsorption capacity can reach a maximum of 21.4 mg/g, significantly reducing the concentration of F^- ions in tap water and effectively preventing dental fluorosis.

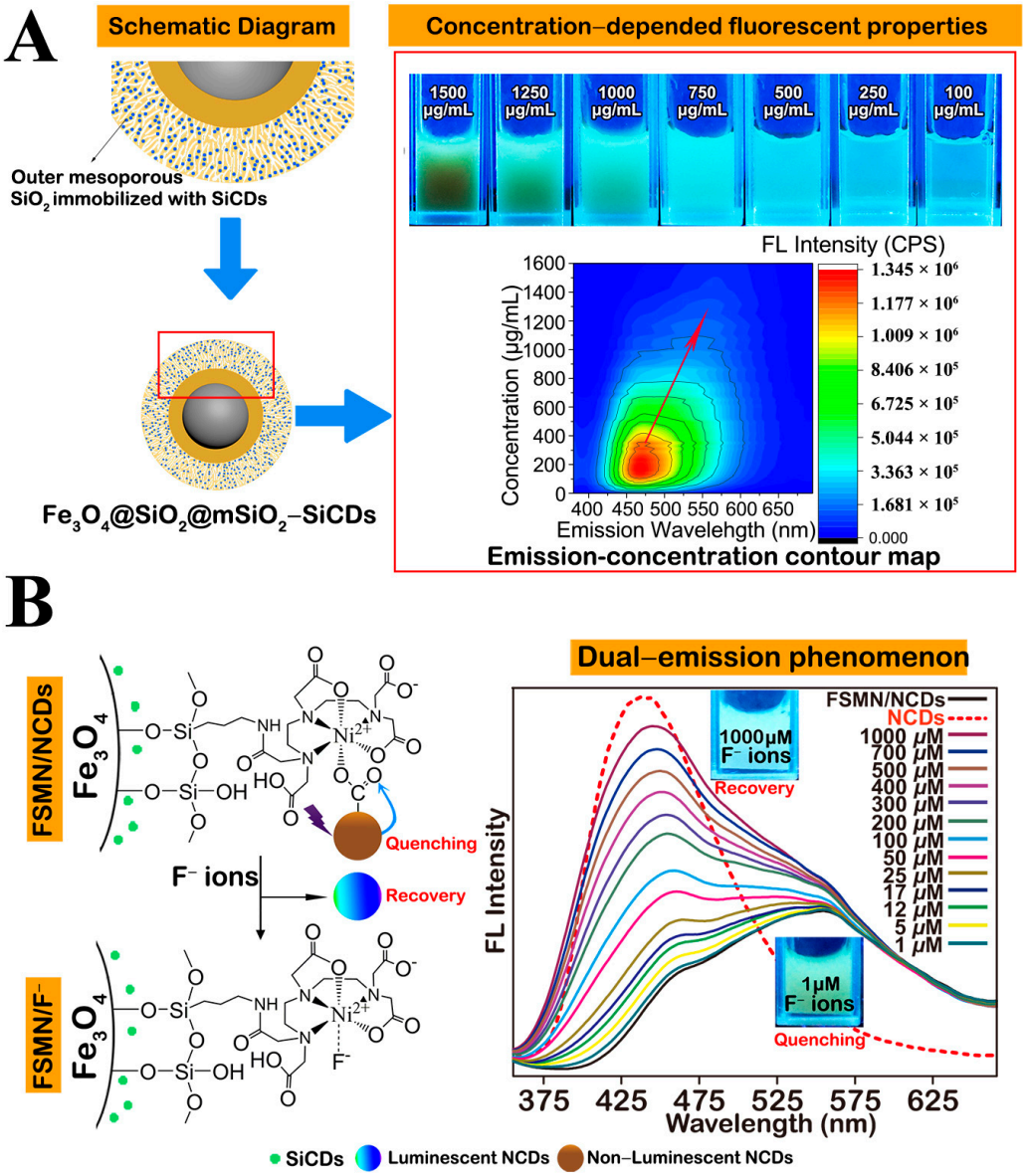

Figure 9. (**A**) Magnetic nanoparticle solution exhibits blue emission at lower concentrations and yellow-green emission at higher concentrations, which would be a kind of probe design strategy. Image reproduced with permission from [110]. (**B**) Fe_3O_4@mSiO_2-SiCDs@DTPA-Ni^{2+}/NCD fluorescent probe for fluoride ion detection and removal. Reprinted (adapted) with permission from [111]. Copyright 2021 American Chemical Society.

3.9. Biofilm

Oral biofilms, composed of microbial communities embedded in a matrix of extracellular polymeric substances, play a pivotal role in developing dental caries, periodontal disease, and other oral infections [1]. These biofilms provide a protective environment for pathogenic bacteria, facilitating their colonization and persistence in the oral cavity.

Both IONPs and free iron ions possess antibacterial capabilities [1]. The unbound Fe^{2+} ion can undergo a reaction with hydrogen peroxide, leading to the formation of a hydroxyl radical and Fe^{3+} ion. The reaction between Fe^{3+} and the superoxide anion radical (O_2^-) further results in the production of molecular oxygen and the restoration of Fe^{2+} as the original catalyst [112,113]. In contrast to free ions, IONPs do not have a substantial detrimental impact on mammalian cells [114]. The antibacterial activities of IONPs are believed to be linked not only to their oxide form but also to their size, shape, and other physicochemical characteristics [115]. This approach presents a novel

strategy for combating oral infections and maintaining oral health. Multiple varieties of iron oxides have been identified. The two most commonly seen minerals are hematite and magnetite [1].

The utilization of IONPs offered a novel strategy for treating drug-resistant illnesses due to their distinct characteristics, such as size, magnetic moment, and surface features (Figure 10A–E). These nanoparticles engaged with free-floating bacteria and bacteria entrenched in a biofilm structure [116,117]. The primary method that nanoparticles use to exert toxicity against pathogens is by their ability to bind to the cell wall and then rupture the membrane. This disruption can occur through direct engagement with the membrane or through the oxidation of macromolecules [118]. Recent results suggest that IONPs are not harmful to mammalian cells since they may engulf and break down nanoparticles by lysosomal fusion [118]. These features enable nanoparticles to preserve normal cell function while simultaneously inhibiting the mechanisms that facilitate pathogen growth and the development of infections. The features of IONPs control their selectivity in enhancing the function of tissue-forming cells while simultaneously limiting the growth and viability of pathogens that cause infections.

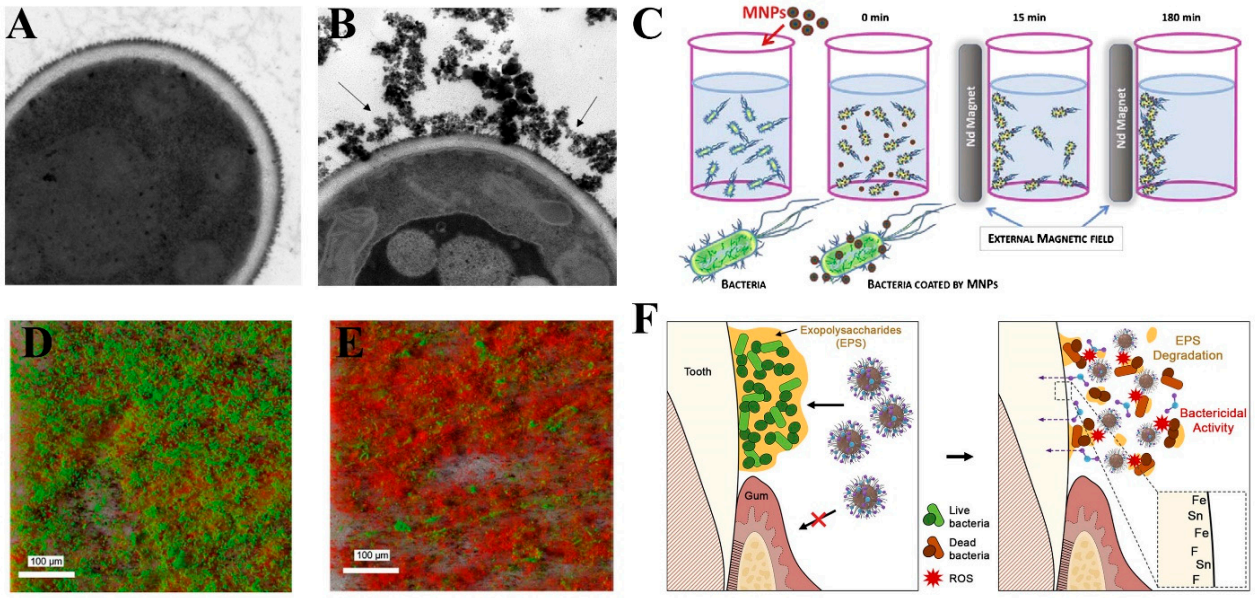

Figure 10. TEM images of C. albicans after 3 h of incubation in the presence of magnetic nanoparticles. Control (**A**) and MNPs (**B**). (**C**) The illustration of the pathogen separation process by magnetic nanoparticles. Image reproduced with permission from [116]. The pathogen separation process by magnetic nanoparticles. Membrane integrity of the PA01 biofilm after hyperthermia using SPIONs. The biofilm was treated with 20 mg/mL (**D**) and 60 mg/mL (**E**) of the SPIOS solution. Image reproduced with permission from [117]. (**F**) Chemical interactions and therapeutic activity of the combined treatment of Fer and SnF_2. The black arrow means the binding of exopolysaccharides or Fer in the oral cavity. Image reproduced with permission from [119].

In preventing and treating oral infections, mainly biofilm-related disorders, magnetic nanoparticle-based dental materials show effective results in bacteria inhibition. Huang et al. [119] found that ferumoxytol (Fer) has demonstrated enhanced efficacy in killing and breaking down caries-causing biofilms, which is achieved through the catalytic activation of hydrogen peroxide after combining it with stannous fluoride (SnF_2) (Figure 10F). The combination of Fer and SnF_2 significantly inhibits the accumulation of biofilms and reduces enamel damage more effectively than using either substance alone. Additionally, it was found that the stability of SnF_2 is augmented when combined with Fer in aqueous solutions, simultaneously boosting the catalytic activity of Fer without the need for any other substances. Significantly, the combination of Fer and SnF_2 demonstrates outstanding

efficacy in managing dental caries in living organisms, even at concentrations four times lower than usual, without causing any adverse effects on the host's tissues or the oral flora. Their findings demonstrate a robust therapeutic synergy by combining approved medicines and utilizing easy SnF_2 stabilization to prevent a widespread oral illness with reduced fluoride exposure.

Baskaran et al. [120] used Fe_3O_4 nanoparticles in the hyperthermia method. By ball milling, they synthesized nanocomposites consisting of Ce-doped hydroxyapatite (HAP) with Fe_3O_4 NPs. The obtained Ce@HAP-Fe_3O_4 nanocomposites exhibit excellent pathogen inhibition towards *E. coli*.

3.10. Robotic Research

Because of their distinctive superstructure assembly and superparamagnetic characteristics, nanoscale iron oxide-based nanostructures are among the most visible metallic nanostructures. They have a lot of promise and are generating a lot of attention in robotics [121,122].

Oh et al. demonstrated that magnetically guided assemblies of IONPs could rearrange and adjust themselves to intricate and restricted surfaces using contactless, adjustable magnetic fields. This technology shows promise in treating biofilms on teeth, the root canal, and oral mucosal surfaces. IONPs can form a structure resembling a bristle [123]. These bristles can change their length and shape at various scales to interact with different surfaces. They can quickly vary their shape, length, and stiffness to withstand and apply strong shear stress. Using automated motion pattern control, these bristles can precisely target complex three-dimensional shapes of human teeth removed from the body to collect biofilm samples with microscale accuracy. At the same time, they mimic the actions of toothbrushing and flossing, providing real-time antibacterial activity to achieve both mechanical and chemical removal of contaminants, as well as the detection of pathogens from multiple kingdoms. Furthermore, by utilizing programmable algorithms, assemblies built from nanozyme-based IONPs achieved accurate spatial targeting of mucosal fungal [124] biofilms (Figure 11A) while minimizing harm to the surrounding host tissue, thus preventing any unintended impacts on non-target areas.

Mayorga-Martinez et al. [125] created magnetic microrobots using halloysite nanotubes as a structural framework and Fe_3O_4 nanoparticles as the magnetic component, enabling magnetic propulsion (Figure 11B). These microrobots were then coated with polyethyleneimine to encapsulate ampicillin and inhibit their disassembly. These microrobots demonstrate the ability to move in multiple ways, individually and in groups. Furthermore, they can transition between tumbling and spinning movements, as well as switch between vortex and ribbon motions while in swarm mode. The vortex motion mode is employed to infiltrate and disturb the extracellular matrix of *S. aureus* biofilm that has colonized on titanium mesh, which enhances the efficacy of antibiotics and decreases the likelihood of implant rejection during bone regeneration.

Meanwhile, swarming magnetic microrobots made of Fe_3O_4 and photoactive materials ($BiVO_4$) enclosed in polyethyleneimine micelles demonstrated the successful removal of dental biofilm on titanium dental implants (Figure 11C). Using a transversal rotating magnetic field, the Fe_3O_4 component propels the solution forward, while the photoactive production of reactive oxygen species in $BiVO_4$ destroys the biofilm colonies. These microrobots, which are both photoactive and magnetically propelled, can effectively eliminate biofilm colonies on titanium implants, showing their potential in the field of precision medicine [126].

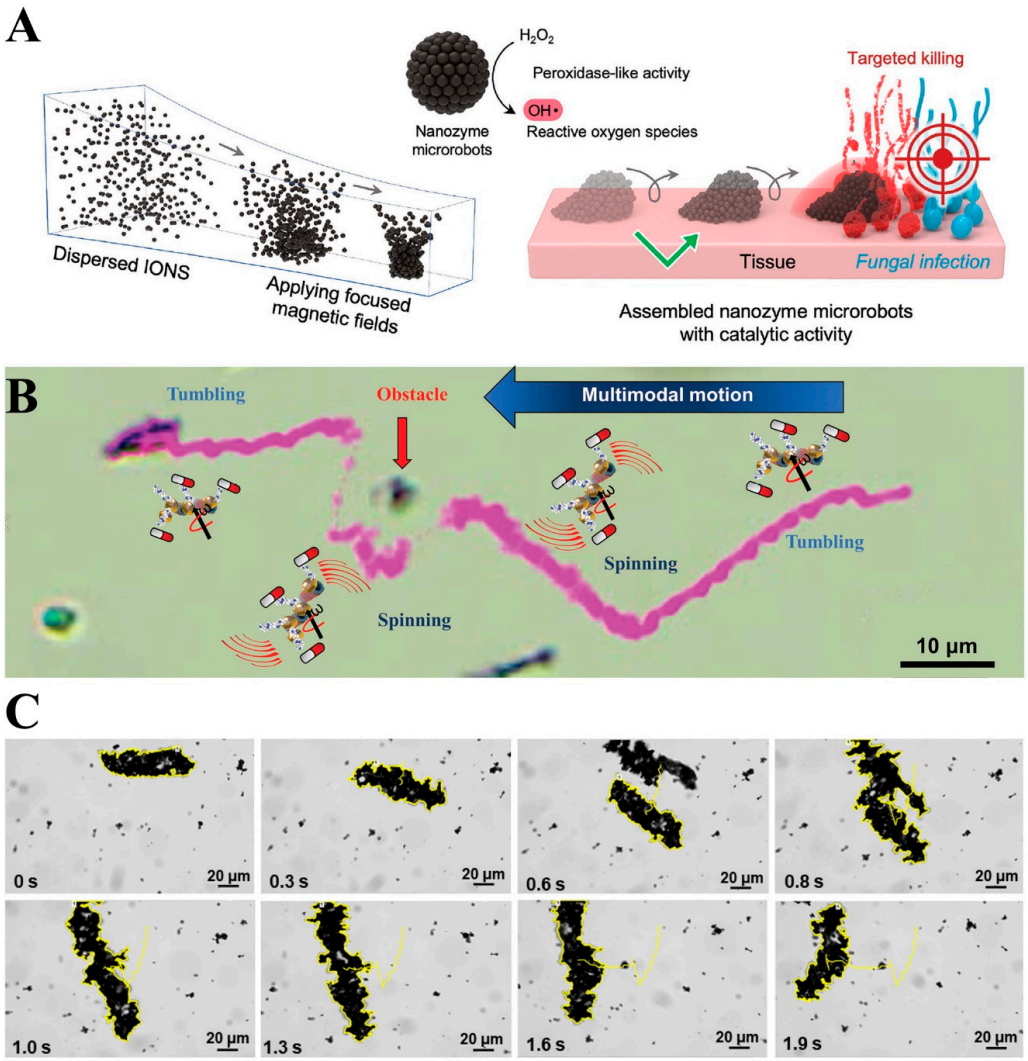

Figure 11. (**A**) Individual nanozymes assembled on-site to form catalytically active superstructures. By manipulating the motion dynamics, shape, and catalytic site of the structured assemblies, nanozyme microrobots specifically designed to target fungal infection may be produced. Image reproduced with permission from [124]. (**B**) Single-phase magnetic Fe_3O_4-HNT/PEI@Amp microrobot moving in three different modes: tumbling, spinning, and tumbling again at 1 Hz. It also exhibits obstacle avoidance. Image reproduced with permission from [125]. (**C**) Time-lapse microscopy pictures showing the lines that trace the Fe_3O_4@PEI/$BiVO_4$ magnetic microrobots swimming in the steering propulsion mode under a transversal rotating magnetic field. Reprinted (adapted) with permission from [126]. Copyright 2022 American Chemical Society.

3.11. Dental Filling

Craciunescu et al. [127] created new magnetic dental composite materials using magnetic nanoparticles. The composites were synthesized utilizing a preparation procedure involving a series of integrated reaction steps performed sequentially, as previously established. It has been demonstrated that each component of dental procedures provides certain advantages. Fe_3O_4 nanoparticles possess biocompatible and non-toxic characteristics, as well as antibacterial capabilities. The inclusion of a SiO_2 layer dramatically enhances the material's mechanical strength. Furthermore, a $Ca(OH)_2$ layer significantly enhances the color of the dental composite material and encourages local calcification. Through the use of magnetic properties, a new technique for treating the tooth surface while exposed to an external magnetic field may be established. Compared to standard methods, this method significantly reduces microfractures and prevents dental cavities beneath filling materials.

4. Potential Toxicity of Magnetic Particles

Ongoing studies and concerns revolve around the possible toxicity of magnetic particles, especially those employed in biomedical applications [128,129]. It is crucial to assess their biocompatibility and safety thoroughly.

One primary aspect of magnetic particle toxicity is its ability to break down in the body, releasing potentially harmful degradation products. Certain nanoparticles can induce adverse effects in plants, cell lines, and animal models [129]. These effects include ulceration, inflammation, reduced growth rate and viability, and neurobehavioral changes [129]. Research has demonstrated that specific categories of magnetic particles, especially those with responsive surfaces or coatings, can produce reactive oxygen species (ROS) when they come into contact with biological surroundings. ROS can induce cellular damage and elicit inflammatory reactions, presenting potential hazards to overall health [130].

The toxicity profile of nanoparticles can be influenced by various physical parameters, including particle size and the surface-to-volume ratio. Smaller particles can cause toxicity issues more quickly because of increased cellular absorption and negative effects [93]. The high surface-to-volume ratio of nanoparticles, which is central to their functionality, also contributes to their reactivity and potential toxicity [131,132].

The chemical composition, coating, and dosage of magnetic particles are also the key factors influencing their biocompatibility and toxicity. Hydrophobic-modified particles, for example, may penetrate cells more easily, potentially causing more significant biological disruption [133]. Recent studies highlight the importance of surface coatings in mitigating toxicity. For example, coating magnetic nanoparticles with biocompatible materials, like polyethylene glycol (PEG) or dextran, can reduce their immunogenicity and enhance their biocompatibility [134,135]. Moreover, functionalizing magnetic nanoparticles with targeting ligands can improve their specificity for certain tissues or cells [136,137] and might have off-target effects.

Organ-specific toxicity is another critical problem, as different tissues and organs may react differently to the presence of magnetic particles [138]. The liver and spleen, which are primary sites for nanoparticle accumulation, are particularly susceptible to potential toxic effects. Ensuring that magnetic particles can be safely disintegrated and excreted from the body is vital to minimizing long-term toxicity risks.

In summary, while magnetic particles offer exciting possibilities for medical applications, their potential toxicity must be carefully evaluated. Comprehensive studies on their interaction with biological systems and degradation behavior, and long-term effects are essential for advancing the safe and effective use of magnetic particles in healthcare. Future research should focus on optimizing particle design, including surface modifications and functionalization strategies, to minimize adverse effects while maximizing therapeutic benefits. Moreover, conducting thorough research on the future implications and possible buildup of magnetic particles within the human body is crucial. Although the body's natural clearance processes may remove magnetic particles employed for short-term applications, there are worries about their long-term persistence and potential accumulation in tissues. This buildup could result in undesirable effects or unforeseen consequences.

5. Magnets in Dental Clinical Practice

5.1. Magnetic Orthodontic Devices

Magnetic orthodontic devices represent a revolutionary approach in orthodontics, offering alternatives to traditional braces and aligners. These innovative devices harness the power of magnets to facilitate tooth movement, providing patients with a more efficient, comfortable, and aesthetically pleasing orthodontic experience. With a growing demand for orthodontic treatments that are less invasive and more patient friendly, magnetic orthodontic devices have emerged as a compelling solution, garnering increasing attention from both practitioners and patients alike [26] (Figure 12A–C).

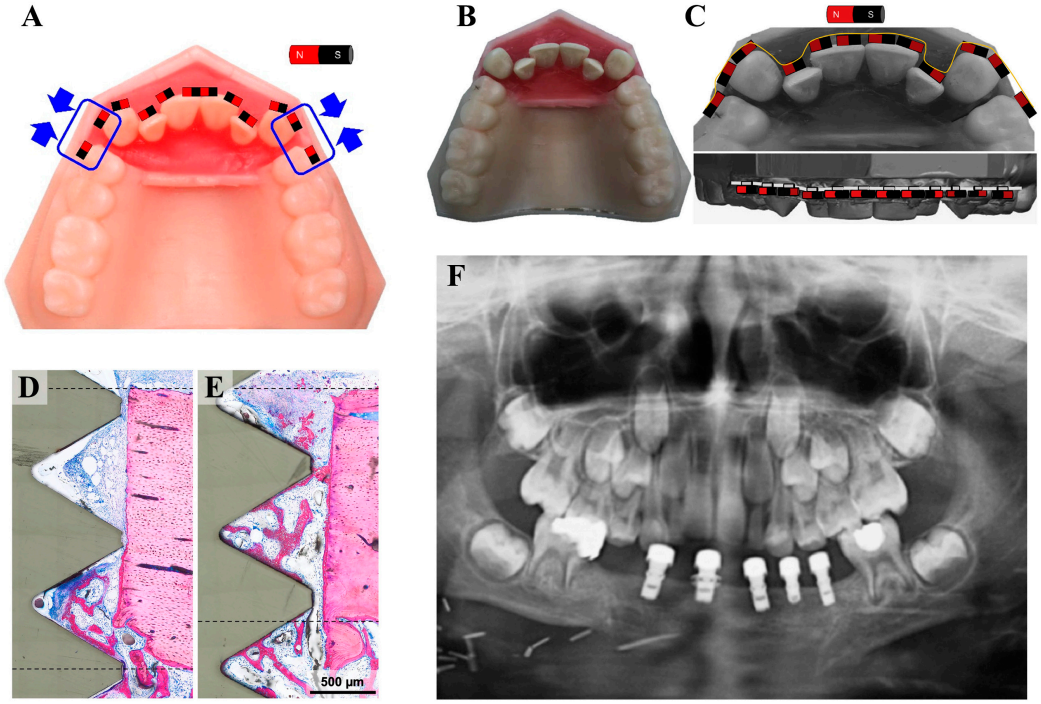

Figure 12. (**A**) Canines can be moved distally by magnetic force. Image reproduced with permission from [139]. Application of attraction (blue arrows) and repulsion force to the moderate crowding case in ex vivo. (**B**) Typodont model of a moderate crowding case, including teeth #6–11. (**C**) Magnets setting for attraction and repulsion force. Image reproduced with permission from [26]. (**D**,**E**) Fifteen days after implant, the cortical compartment in magnetic field implants. Nearly the whole thickness of the cortical bone is covered by new bone that originates in the medullary region, and it continues to grow into the cortical peri-implant bone area. Image reproduced with permission from [24]. (**F**) Twelve months after starting magnetic abutment loading, the postoperative follow-up radiograph shows no pathologic symptoms and no peri-implant bone loss. Image reproduced with permission from [140].

Unlike conventional braces that rely on wires and brackets to apply force to teeth, magnetic orthodontic brackets utilize untouchable magnetism to guide tooth alignment. These fixed magnetic brackets reduced operation times, minimized discomfort, and improved oral hygiene maintenance [139]. In the typodont model, the magnet's placement played a crucial role in generating tipping or physical motion. While tipping forces are produced with lever force with a fulcrum—the level of the paraffin wax in our ex vivo investigation or the level of the alveolar bone in orthodontics—body movement is produced with linear force. When the magnetic force is applied more incisively, the lever force's distance from the fulcrum increases with a larger torque/rotation force ratio for the same power applied. The converse happens when the magnetic force is moved more apically with a decrease in tipping force and an increase in linear force for body movement. Additionally, magnetic orthodontic devices present a discreet option for patients seeking orthodontic correction without the conspicuous appearance of traditional braces [141,142].

Advancements in materials science, engineering, and orthodontic technology have fueled the development of magnetic orthodontic devices [139]. Innovations in magnet design also come to the functional appliance. Han et al. [143] designed a Class III functional appliance to evaluate and compare the cellular morphologic changes and proliferating cell nuclear antigen (PCNA) expression within craniofacial sutures in growing Rhesus monkeys. During Class III treatment, pterygopalatine and zygomaticomaxillary sutures are more active than other craniofacial sutures in craniofacial complex remodeling. The magnetic twin-block appliance effectively promoted suture remodeling by enhancing the activity and proliferation of osteoblasts, osteoclasts, and fibroblasts, especially in the early phase.

Zhao et al. [144] prepared a novel effective magnetic orthopedic appliance (MOA-III) for skeletal class III children. After treatment, the maxilla rotated downward and forward simultaneously. The lingual compensation of the lower incisors was the most notable alteration in the jaw. The jaw moved backward and downward at the same time, although there were no appreciable alterations in the mandible's overall length. The lower lip returned backward, and the upper lip migrated forward for the soft tissue measurement.

Overall, magnetic orthodontic devices hold promise for addressing specific challenges encountered in conventional orthodontic treatments, such as difficult-to-correct malocclusions or relapse cases. Their ability to apply controlled magnetic forces to guide teeth into desired positions offers orthodontists greater flexibility and precision in treatment planning and execution.

5.2. Magnetic Implants and Prosthetics

Magnetic implants and prosthetics represent a groundbreaking advancement in dentistry, offering innovative solutions for patients requiring dental restoration or rehabilitation due to their remarkable biocompatibility and integration capabilities with surrounding tissues. These sophisticated devices also harness the power of magnetic materials to enhance stability, functionality, and patient comfort, revolutionizing the landscape of dental implants and prosthetic treatments.

Neodymium–iron–boron (Nd-Fe-B) and samarium–cobalt (Sm-Co) are the commonly employed magnetic materials that serve as the cornerstone or attachment for these prosthetic devices, providing unparalleled strength, durability, and resistance to corrosion. This enables the creation of dental implants that seamlessly fuse with the jawbone, offering patients a stable and long-lasting foundation for prosthetic restorations [23–25]. In magnetic dental abutments [140] (Figure 12D–F) and magnetically implantable prosthetic devices [145], where magnetic composites are used to generate an adequate magnetic field to promote effect bone healing. Magnetic mucoperiosteal distraction devices [146] have been used in newborns with complete unilateral and bilateral orofacial clefts.

Akin, H., et al. [147] also studied the effectiveness and the corrosion tendency of different magnetic attachment systems in the oral cavity. Compared to the open-field systems, the closed-field systems showed a stronger attractive force. A statistically significant difference in the attractive force was observed between the Nd-Fe-B and Sm-Co magnets. The Hilop system produced the most attractive force, whereas the Steco system produced the lowest force. Together with enhanced technology, the latest generation of Nd-Fe-B closed-field magnets offers adequate denture retention for clinical use.

One of the critical advantages of magnetic implants and prosthetics lies in their ability to facilitate osseointegration, the process by which the implant integrates with the surrounding bone tissue. By promoting osseointegration, magnetic implants ensure optimal stability and functionality, minimizing the risk of implant failure and enhancing patient satisfaction. Siadat et al. [25] evaluate the effects of static magnetic fields (SMFs) on the implants immediately placed in fresh extraction sockets. Radiofrequency analysis (RFA) measurements showed significantly higher stability for implants in the test group than that of the control group after 1 month. In month 2, less crystal bone loss was observed in the test group.

Moreover, magnetic implants and prosthetics offer versatility in addressing diverse clinical scenarios, ranging from single-tooth replacements to full-arch restorations. Their customizable design allows for precise tailoring to each patient's unique anatomical and functional requirements, ensuring optimal aesthetics and functionality.

6. Future Prospects

The application of magnetic materials in dentistry is an evolving field that promises significant advancements in both diagnostic and therapeutic techniques. As the understanding of magnetic materials and their interactions with biological tissues deepens, new

avenues for enhancing dental care are emerging. Here, we explore the potential future directions for the research and application of magnetic materials in dentistry.

6.1. Dental Research Aspects

Future diagnostic research could focus on refining MRI techniques to achieve higher-resolution images of dental structures, aiding in the early detection of dental pathologies such as temporomandibular joint disorders, periodontal diseases, and dental caries. Enhanced MRI protocols specifically tailored for dental applications could provide non-invasive, precise diagnostic capabilities, improving patient outcomes.

Magnetic particles also offer a promising therapeutic platform for targeted drug delivery. Future studies could explore the functionalization of magnetic particles with various therapeutic agents, including antibiotics, anti-inflammatory drugs, and growth factors, to target specific dental tissues. The use of external magnetic fields to direct these nanoparticles precisely to the site of infection or injury could minimize side effects and enhance therapeutic efficacy. Research could also investigate the development of smart drug delivery systems that respond to specific stimuli, such as pH changes or the presence of certain enzymes, to release drugs in a controlled manner.

The field of regenerative dentistry could greatly benefit from the integration of magnetic materials. Magnetic scaffolds, for example, can be engineered to support the growth and differentiation of stem cells into dental tissues. Future research might focus on optimizing these scaffolds for better integration with natural dental structures and enhancing their mechanical properties. Additionally, the use of magnetic fields to stimulate cellular activities and tissue regeneration presents an exciting area for further exploration, potentially leading to breakthroughs in repairing and regenerating damaged dental tissues.

However, the research on magnetic particles in the diagnosis and treatment of oral diseases is still in its early stages, and there is some controversy about their effect and toxicity on cells. Lots of scholars have shown that magnetic particles themselves can promote cell differentiation. For example, FERAHEME® (Ferumoxytol) has received a significant amount of attention due to its FDA-cleared status for use in humans. Some scholars believe that magnetic nanomaterials may cause damage to cells and may stimulate cells to produce reactive oxygen free radicals that damage cell membranes, DNA, and proteins by activating cysteine proteases, causing cell apoptosis. Therefore, further basic research on the mechanism and application of magnetic particles is needed. Strict biosafety assessment is one of the keys to the application of magnetic particles in the treatment of oral diseases.

6.2. Dental Clinical Aspects

In orthodontics, magnetic forces are already used to facilitate tooth movement. Future advancements could lead to the development of more sophisticated magnetic devices that offer greater control and efficiency in orthodontic treatments. Similarly, in prosthodontics and implants, the use of magnetic attachments for dentures and implants could be refined to provide better stability and comfort for patients. Continued interdisciplinary innovation will be key to realizing these advancements and integrating magnetic materials into everyday dental practice.

7. Conclusions

Integrating magnetic materials into dentistry represents a significant advancement with far-reaching implications for diagnosis, treatment, and patient care. By exploring magnetic particles and magnets, this review has underscored the diverse applications and potential benefits of magnetic materials in dental healthcare. Magnetic particles offer precise targeting and delivery of therapeutic agents, facilitating improved treatment outcomes while minimizing adverse effects. Their versatility in drug delivery, imaging, and diagnostic assays holds promise for revolutionizing dental therapeutics and diagnostics. Similarly, magnets' remarkable strength and field density make them invaluable components in

various dental applications, including implants and orthodontic treatments. Their ability to facilitate tissue engineering and tooth movement enhances clinical outcomes and patient experiences. By synthesizing the latest research and clinical insights, this review highlights the transformative potential of magnetic materials in dentistry. Continuing research and innovation in this field will be instrumental in advancing dental healthcare and improving patient outcomes. Embracing the opportunities afforded by magnetic materials promises to usher in a new era of precision dentistry characterized by enhanced efficacy, safety, and patient satisfaction.

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