



# Magnetic Field-Enabled Piezocatalysis: Mechanisms, Materials, and Emerging Biomedical Applications

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Received: December 16, 2025 / Revised: January 23, 2026 / Accepted: January 27, 2026 / Published online: January 31, 2026

**Abstract:** Magnetic field-enabled piezocatalytic therapy represents an emerging frontier in non-invasive biomedical treatments, integrating the principles of magnetostriction, piezoelectricity, and magnetoelectric coupling to remotely drive reactive oxygen species (ROS) generation for therapeutic applications. In this Perspective, we first elucidate the fundamental mechanisms underlying magnetostrictive deformation, piezoelectric polarization, and strain-mediated magnetoelectric coupling, highlighting how mechanical energy derived from magnetic fields can be efficiently converted into localized electric potentials and catalytic activity. We then examine the design and function of magnetostrictive-piezoelectric composite materials, emphasizing core-shell architectures, interface engineering, and nanostructuring strategies that enhance ROS production. Recent advancements in magnetic field-enabled piezocatalytic tumor inhibition, along with comparisons to conventional ultrasound-activated approaches, are discussed. Finally, we outline critical challenges and future directions from the perspectives of material optimization, biocompatibility, mechanistic elucidation, and in vivo evaluation, aiming to guide the rational development of next-generation remotely controllable piezocatalytic therapeutics. This Perspective paper presents a conceptual framework for the design and implementation of magnetic field-enabled piezocatalysis, establishing a connection between materials science and biomedical innovation.

**Keywords:** Magnetostrictive Effect; Piezoelectric Effect; Piezocatalytic Therapy

<https://doi.org/10.64509/jim.11.66>

## 1 Introduction

Despite significant advancements in the field of medical science, nanodiagnosis and treatment technology, cancer remains a major global cause of mortality, underscoring its status as one of the leading contributors to worldwide deaths. The existing typical treatment methods, including surgery, radiation, chemotherapy, immunotherapy, as well as hormone and targeted cell transplantation therapies, still face considerable challenges in terms of efficacy and side effects. For example, surgical treatment is invasive and may carry risks of infection or bleeding, which shows serious limitation for the spread cancer cells [1]. Radiation and chemotherapy therapies invariably result in damage to normal tissues and other undesirable side effects, such as nausea, fatigue, immune system suppression [2, 3].

In this context, targeted therapy has garnered significant attention due to its limited adverse impact on normal tissues. However, the identification of specific molecular markers that respond to cancer cells is imperative, as it renders targeted therapy unsuitable for all types of cancers, and the development of drug resistance in cancer cells towards targeted therapies further hinders its efficacy [4, 5]. The administration of immunotherapy may give rise to immune system-related adverse effects, and there exist substantial interindividual variations in the efficacy of this therapeutic approach [6]. The complex procedure of stem cell transplantation treatment necessitates not only a suitable stem cell donor but also entails potential risks such as transplant rejection and graft-versus-host disease. Therefore, there is an urgent need to develop a robust high-efficient tumor treatment strategy for addressing

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\* Academic Editor: Zhou Li

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the limitations of the abovementioned traditional treatment methods.

In this context, some non-invasive therapeutic modalities emerged and aroused intensive attention. For example, optical therapies (e.g., photodynamic therapy) are effective for tumors located in superficial layers (typically  $< 1$  cm) because of the strong scattering and absorption of light by biological tissues. Ultrasound-activated piezocatalytic treatment provides enhanced penetration for cancer therapy [7]. Although promising, it experiences intrinsic attenuation ( $\sim 1 \text{ dB cm}^{-1} \text{ MHz}^{-1}$ ) and severe reflection at interfaces with high acoustic impedance mismatch (e.g., bone or air cavities), restricting its reach to shallow or unobstructed regions [8].

In stark contrast, magnetic field-enabled piezocatalysis surmounts these physical barriers. Given that biological tissues are fundamentally non-magnetic and transparent to low-frequency magnetic fields, this approach permits a virtually unrestricted penetration depth (exceeding 10 cm) with minimal energy attenuation. This inherent physical advantage renders magnetic field-enabled strategies a distinctive solution for treating deep-seated pathologies (such as those located in the brain or liver) that are inaccessible to both light and ultrasound, while causing reduced mechanical damage to normal tissues. Based on these advantages, a magnetic field-enabled piezocatalytic therapy strategy has been proposed based on magnetostrictive-piezoelectric composite materials through the coupling among the piezoelectric effect, the magnetostrictive effect, and the piezocatalytic process. These materials demonstrate great potential in efficient cancer treatment. Despite its promise, the currently reported magnetostrictive-piezoelectric composite materials are limited, presenting challenges for guiding the development and application of efficient magnetic field-enabled piezocatalytic therapy for cancer treatment.

Therefore, this paper systematically examines the mechanism of magnetic field-enabled piezocatalytic treatment and its potential applications in the biomedical field, aiming to provide theoretical guidance for the development of efficient magnetostrictive-piezoelectric composite materials. Specifically, this paper elaborates on the mechanisms of the magnetostrictive effect, piezoelectric effect, magnetoelectric effect, and piezoelectric catalysis. The fascinating applications of magnetic field-enabled piezocatalysis in cancer therapy have been scrutinized, followed by a summary and outlook for further promoting the development and practical applications of magnetic field-enabled piezocatalytic therapy strategy.

## 2 Multiphysics Mechanisms Underpinning Magnetic Field-Enabled Piezocatalysis

Magnetically activated piezocatalysis relies on a cascade of coupled physical processes, including magnetic, mechanical, and electrical ones. Understanding these interactions at the material and interface levels is essential for designing efficient therapeutic systems capable of operating within deep biological tissues under safe magnetic-field conditions. This section

outlines the fundamental mechanisms that enable this multiphysics activation pathway, beginning with magnetostriction, followed by piezoelectric polarization, and culminating in magnetoelectric coupling. Collectively, these mechanisms establish the theoretical foundation for the biomedical applications discussed in the subsequent sections.

### 2.1 Magnetostriction: Remote Mechanical Actuation via Magnetic Stimulation

Magnetostriction provides a fundamental physical pathway to convert magnetic stimuli into mechanical deformation, forming the first step of magneto-mechano-electrical cascade by enabling non-contact mechanical deformation driven by external magnetic fields. At the microscopic level, magnetostrictive materials contain numerous domains whose magnetic moments are randomly oriented in the absence of a field (Figure 1(a)) [9]. When a magnetic field is applied, these moments progressively rotate toward the field direction, establishing an ordered magnetic state coupled with lattice deformation. Depending on the intrinsic magnetoelastic anisotropy, the material may elongate or contract along the field direction, and the magnitude of strain is typically determined by the saturation magnetostriction coefficient. As a result, magnetic energy is transformed into mechanical displacement in a controllable and deep-penetrating manner [10]. Importantly, significant magnetostrictive deformation can be generated under low-intensity alternating magnetic fields at biologically safe frequencies, uniquely positioning magnetostriction as a remote actuation mechanism for biomedical catalysis.

Advances in magnetostrictive materials have substantially broadened their applicability in biomedical catalysis. Soft magnetic alloys, such as FeGa and FeCo, are characterized by high magnetoelastic sensitivity and low magnetic losses, enabling efficient actuation under weak alternating magnetic fields [11]. In contrast, giant magnetostrictive rare-earth intermetallics (e.g., TbDyFe) exhibit exceptionally large saturation magnetostriction coefficients, highlighting their strong potential for high-efficiency magnetomechanical activation in cancer therapy. Despite their outstanding magnetostrictive performance, the clinical translation of these materials remains constrained by biosafety concerns, particularly cytotoxicity and long-term accumulation arising from the possible release of heavy metal ions.

Encouragingly, recent studies have demonstrated that such risks can be effectively alleviated through rational surface engineering strategies. Encapsulating magnetic cores within inert and biocompatible shells, such as silica, polyethylene glycol, or polydopamine, can physically isolate the active components from the biological environment, thereby suppressing ion leakage and improving *in vivo* compatibility. Beyond surface modification, the synthesis route itself plays a critical role in determining the biosafety and functional performance of magnetostrictive materials. For example, Pascual-González et al. recently reported a mechanochemically assisted synthesis of Co-based spinel compounds [12]. This solvent-free and environmentally benign approach avoids the introduction of toxic organic residues commonly associated with conventional wet-chemical methods, while simultaneously affording materials with high crystallinity

and tunable magnetic properties. The resulting structural robustness and optimized magnetomechanical response suggest that effective actuation can be achieved at reduced material dosages, thereby further enhancing the safety profile and translational potential of magnetostrictive therapeutics.

## 2.2 Magnetoelectric Effect: Bridging Magnetic Actuation and Piezoelectric Polarization

The piezoelectric effect arises in non-centrosymmetric crystalline materials, enabling the direct conversion of mechanical deformation into electrical polarization. As illustrated in Figure 1(b), when an external mechanical stress is applied, microscopic displacement of positive and negative charge centers occurs within the crystal lattice, leading to macroscopic polarization. This generates surface-bound charges and establishes an electric potential along the direction of applied stress. Notably, the surface charge density is directly proportional to the magnitude of the mechanical stimulus, providing a controllable and predictable means of generating local electric fields [13]. The piezoelectric effect is not only fundamental for traditional technological applications, but also serves as the key mechanism for piezocatalysis in biomedical contexts.

Piezoelectric materials can be broadly categorized into inorganic, organic, and organic-inorganic composite systems. Inorganic piezoelectrics, such as BaTiO<sub>3</sub>, PZT, and ZnO, exhibit high electromechanical coupling coefficients, low electrical resistivity, and excellent acoustic impedance matching, making them highly effective in energy conversion and precision sensing applications. Organic piezoelectric materials, including polyvinylidene fluoride (PVDF) and its copolymers [14], are characterized by intrinsic flexibility, low density, high piezoelectric voltage constants, and facile integration into flexible or wearable devices, enabling efficient energy harvesting in soft or dynamic environments [15]. Organic-inorganic composites combine the advantages of both classes, achieving enhanced electrochemical performance, optoelectronic properties, thermal stability, corrosion resistance, and mechanical durability, thus offering a versatile platform for multifunctional applications [16].

## 2.3 Piezocatalytic Therapy: Mechanism and Biomedical Applications

The magnetoelectric (ME) effect describes the intrinsic coupling between magnetic and electric orders in certain materials, whereby a change in magnetic field induces electrical polarization, or conversely, an applied electric field modifies magnetization. This phenomenon embodies a fundamental energy transduction pathway, enabling the interconversion of magnetic, mechanical, and electrical energy [17]. Among these phenomena, strain-mediated magnetoelectric coupling in magnetostrictive-piezoelectric composites has attracted considerable attention attributed to its potential for efficient, non-contact energy conversion.

In typical composite systems, a core-shell architecture is employed to maximize interfacial coupling. As depicted in Figure 1(c), when a magnetostrictive core is embedded within a piezoelectric shell (M@P composite), the application of an external magnetic field induces expansion or

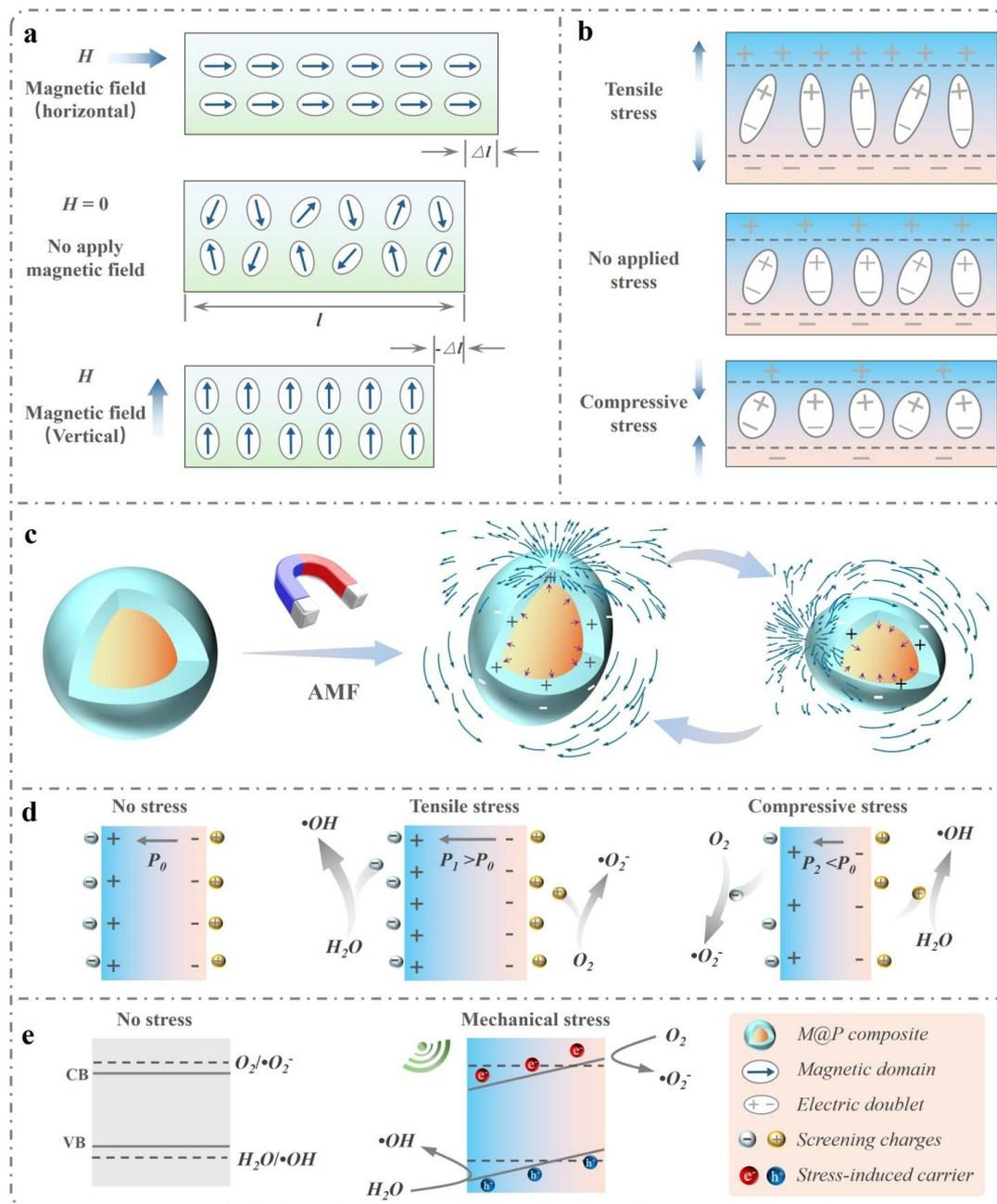
contraction of the core along the field direction. The resulting interfacial strain is transmitted to the piezoelectric shell, generating polarization charges on its surface, corresponding to the direct ME effect. Conversely, an external electric field applied to the piezoelectric phase can induce magnetization in the magnetostrictive core, known as the inverse ME effect. The efficiency of ME coupling is highly sensitive to interfacial properties, including lattice strain, charge distribution, and domain rotation. Even subtle modifications at the interface, such as nanoscale strain gradients or charge accumulation, can significantly influence the magnitude of polarization or magnetization. Therefore, precise engineering of the magnetostrictive-piezoelectric interface is critical to achieve high-performance ME coupling, particularly under low-intensity magnetic fields suitable for biomedical applications.

## 2.4 Piezocatalytic Therapy: Mechanism and Biomedical Applications

Piezocatalytic therapy (PCT) has emerged as a non-invasive and highly versatile biomedical treatment strategy, which is fundamentally driven by the conversion of mechanical energy into chemical activity, mediated by piezoelectric materials. Two distinct theoretical frameworks underpin this process: screening charge effect and energy band theory.

The screening charge effect provides an alternative yet complementary mechanism (Figure 1(d)). Mechanical deformation induces polarization charges on opposite surfaces of the piezoelectric material ascribed to piezoelectric effect, creating localized electric fields. The surrounding charged ions are attracted to the surface with opposite polarization charges and react with water and oxygen molecules, facilitating redox reactions and generating hydroxyl radicals ( $\bullet\text{OH}$ ) and superoxide anions ( $\bullet\text{O}_2^-$ ). The types of ROS generated and their production rates are governed by the magnitude of piezoelectric polarization, which can be effectively tuned by the applied mechanical strain as well as the crystal structure and phase composition of the piezoelectric catalysts.

According to energy band theory, the application of mechanical stress to a piezoelectric material induces piezoelectric polarization, which drives the excitation of electrons from the valence band (VB) to the conduction band (CB), leaving corresponding holes in the VB [18]. Simultaneously, the strain-induced polarization establishes a built-in electric field within the piezoelectric semiconductor, resulting in band bending (tilting) of both the CB and VB. This internal electric field promotes the spatial separation and directional migration of photogenerated charge carriers [19], enabling electrons and holes to participate in redox reactions with dissolved oxygen and water to produce  $\bullet\text{O}_2^-$  and  $\bullet\text{OH}$ , respectively (Figure 1e). Recent studies have demonstrated that the relative energy positions of the CB and VB, together with the magnitude and orientation of piezoelectric polarization, critically determine the redox driving force and overall catalytic efficiency [20]. Accordingly, material engineering strategies such as defect engineering and heterojunction construction can effectively modulate the internal electric field, reduce carrier transport barriers, and optimize band-edge alignment with the redox



**Figure 1:** Schematic diagrams illustrating the fundamental principles of (a) the magnetostrictive effect, (b) the piezoelectric effect, (c) the magnetoelectric coupling effect, and piezocatalytic processes based on (d) the screening charge effect and (e) the energy banding theory.

potentials required for ROS generation, thereby significantly enhancing ROS yield.

It should be noted that these ROS, whether generated by the screening charge effect or energy band theory, can selectively damage tumor cells, inducing immunogenic cell death, which releases tumor-associated antigens and triggers a systemic anti-tumor immune response. This cascade ultimately contributes to the effective eradication of malignant cells. Importantly, PCT offers a robust platform for deep-tissue tumor therapy, as ROS generation can be activated remotely through mechanical stimuli, such as ultrasound induced strain within piezocatalytic materials. The synergy between remote actuation, efficient ROS generation, and immunogenic activation positions piezocatalysis as a promising modality for

next-generation cancer therapies with high spatial precision, minimal invasiveness, and broad clinical potential.

### 3 Magnetic Field-Enabled Piezocatalytic Therapy: Recent Advances and Opportunities

Based on the principles of piezocatalytic therapy and strain-mediated magnetoelectric coupling, the concept of magnetic field-enabled piezocatalytic therapy was first put forward by Jianlin Shi and his colleagues in 2021, which has evolved into a novel and non-invasive strategy for biomedical treatment [8]. It should be noted that there exists a significant

disparity between magnetoelectric stimulation and magnetic field-enabled piezocatalytic therapy. Magnetoelectric stimulation predominantly depends on the physical interaction between the induced electric field and biological tissues, for example, modulating ion channels or membrane potentials, without necessarily entailing chemical transformations. In contrast, magnetic field-enabled piezocatalysis is fundamentally characterized as an electrochemical process regulated by a cascade of multiphysics events. These events include magnetic field triggering magnetostrictive strain, strain stimulating piezoelectric polarization, polarization introducing piezocatalytic ROS generation, and ROS exerting therapeutic effects via oxidative stress.

Specifically, core-shell structured  $\text{CoFe}_2\text{O}_4\text{-BiFeO}_3$  magnetostrictive-piezoelectric nanoparticles were synthesized to integrate remote magnetic actuation with piezocatalytic ROS generation in Shi's work. As illustrated in Figure 2(a) [8], the  $\text{CoFe}_2\text{O}_4$  core underwent elongation along the direction of an applied magnetic field, generating interfacial strain at the core-shell interface. This strain then transferred to the  $\text{BiFeO}_3$  shell, inducing surface polarization charges that drive piezocatalytic reactions. The resulting ROS, including  $\bullet\text{O}_2^-$  and  $\bullet\text{OH}$ , effectively inhibited the growth of 4T1 murine breast cancer cells, achieving an inhibition rate of 93.6%. In addition, standard CCK-8 assays revealed that the cell viability of 4T1 cells remained above 90% even after incubation with a high concentration ( $500 \mu\text{g mL}^{-1}$ ) of  $\text{CoFe}_2\text{O}_4\text{-BiFeO}_3$  nanoparticles for 24 hours in the absence of a magnetic field, corroborating that the therapeutic effect was derived from the field-triggered piezocatalysis rather than intrinsic material toxicity. Compared with ultrasound-enabled piezocatalytic therapy, which may inadvertently cause mechanical damage to surrounding healthy tissues, magnetic field-induced activation offers deep tissue penetration [21], non-invasiveness, and precise spatial control, highlighting its potential for more safe and effective biomedical applications.

Notably, beyond  $\text{CoFe}_2\text{O}_4\text{-BiFeO}_3$  system, several other magnetostrictive-piezoelectric composites have been reported, including  $\text{Ba}_{0.85}\text{Ca}_{0.15}\text{Zr}_{0.1}\text{Ti}_{0.9}\text{O}_3\text{@MnFe}_2\text{O}_3$  [22],  $\text{PVDF/CoFe}_2\text{O}_4\text{@BaTiO}_3$  [23],  $\text{P(VDF-TrFE)/Fe}_3\text{O}_4$  [24]. These materials have demonstrated the ability to promote osteogenic differentiation of human adipose-derived stem cells (Figure 2(b)), accelerate wound healing (Figure 2(c) and (d)), and enhance peripheral nerve regeneration via piezoelectric stimulation therapy under a magnetic field, respectively. However, the contribution of piezocatalytic therapy was not examined in these studies. From this perspective, although magnetic field-enabled piezocatalytic therapy stands as a revolutionary platform at the crossroads of materials science, physics, and biomedicine, it remains at a nascent stage, hindered by the limited availability of materials with sophisticated architectures and tunable compositions, as well as by the lack of a clear correlation among magnetic field parameters, piezoelectric polarization, ROS generation kinetics, and biological outcomes. Addressing these challenges requires coordinated advances in both materials design and theoretical modeling to elucidate the underlying mechanisms for guiding the rational development of next-generation magnetic field-activated piezocatalytic therapeutics.

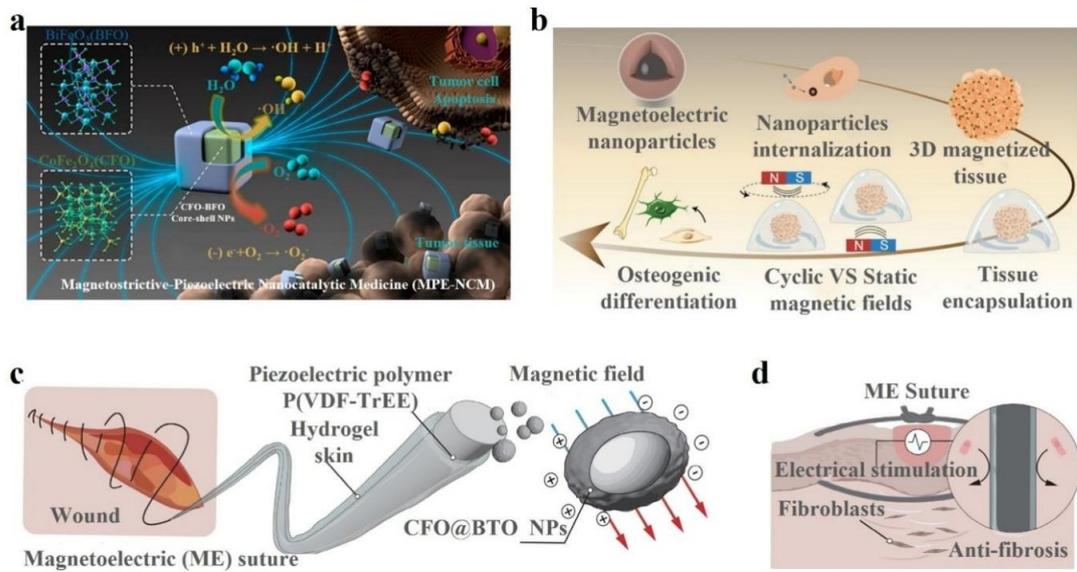
## 4 Summary and Outlook

In summary, this Perspective elucidated the fundamental principles underlying the piezoelectric effect, magnetostrictive effect, magnetoelectric coupling, and piezocatalytic therapy, and highlighted the emerging strategy of magnetic field-enabled piezocatalytic therapy as a pioneering proof-of-concept approach for non-invasive, deep-tissue biomedical interventions. While these developments are highly promising, significant challenges remain for advancing both the materials and mechanistic understanding required to translate this strategy into practical therapeutic platforms.

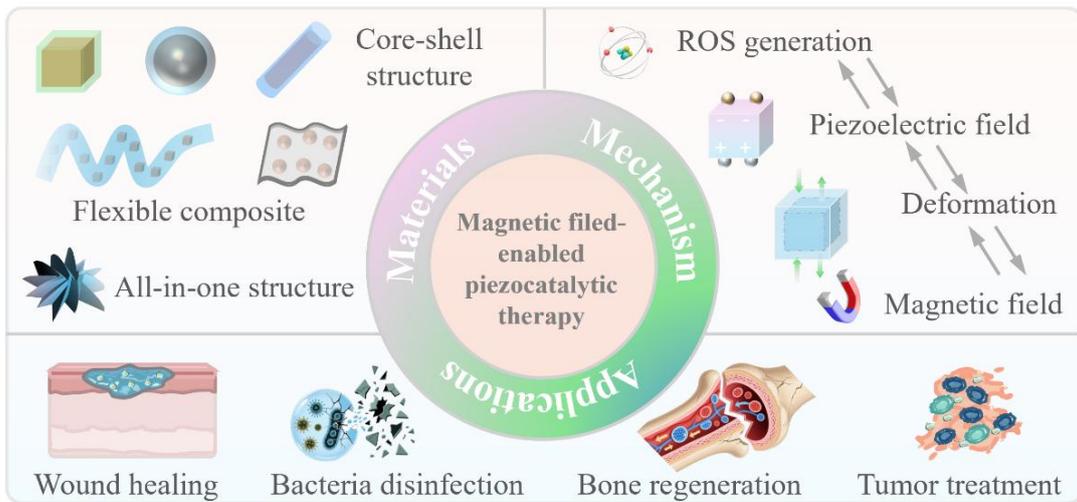
First, the therapeutic efficacy of magnetic field-enabled piezocatalysis is critically dependent on the efficiency of sequential energy conversions: from the applied magnetic field to lattice strain through magnetostriction, from strain to electric polarization through the piezoelectric effect, and finally from the generated electric field to ROS production (Figure 3). Therefore, it is imperative to develop a deeper mechanistic understanding of how magnetic field parameters regulate interface strain, piezoelectric polarization, ROS generation kinetics, and biomedical therapy efficacy. Such insights will contribute to the rational optimization of magnetic field strength, frequency, and exposure patterns. Moreover, they will guide the design of next-generation magnetostrictive-piezoelectric materials with customized properties to achieve maximal therapeutic efficacy.

Second, current studies predominantly focus on core-shell magnetostrictive-piezoelectric nanocubes or nanospheres, which rely on robust interfacial bonding and precise lattice matching between the magnetostrictive and piezoelectric components to achieve efficient strain transfer and strong magnetoelectric coupling. From this perspective, as depicted in Figure 3, future research should move toward the development of single-phase or all-in-one materials that intrinsically integrate both functionalities. In addition, alternative architectures, such as flexible piezoelectric substrates integrated with magnetostrictive nanoparticles, offer promising strategies to optimize structural design and expand the range of available material choices. Enabled by advances in materials chemistry and nanoscale engineering, these systems should simultaneously deliver strong magnetostrictive and piezoelectric responses together with excellent biocompatibility, thereby expanding the design space and practical applicability of magnetic field-enabled piezocatalytic therapies.

Third, beyond deep-tissue tumor therapy, the application scope of magnetic field-enabled biomedical therapies can be substantially broadened (Figure 3). In particular, such strategies hold great promise for wound healing management by enabling noninvasive, on-demand stimulation to regulate inflammation, angiogenesis, and tissue remodeling. In bone regeneration, magnetic field-enabled piezoelectric or piezocatalytic stimulation may promote osteogenesis and mineralization, offering a remote and controllable alternative to conventional electrical stimulation approaches. Moreover, magnetic field-enabled therapies can be extended to the disinfection of pathogenic bacteria or viruses, where controllable ROS generation may provide efficient antimicrobial activity while minimizing drug resistance. In addition, the integration of magnetic field-responsive functional materials into



**Figure 2:** Schematic diagrams illustrating (a) the magnetic field-enabled piezocatalytic tumor therapy using CoFe<sub>2</sub>O<sub>4</sub>-BiFeO<sub>3</sub>, adapted with permission [8], Copyright © 2021, American Chemical Society; (b) the magnetic field-enabled piezoelectric stimulation for promoting osteogenic differentiation of human adipose-derived stem cells using Ba<sub>0.85</sub>Ca<sub>0.15</sub>Zr<sub>0.1</sub>Ti<sub>0.9</sub>O<sub>3</sub>@MnFe<sub>2</sub>O<sub>3</sub>, adapted with permission [22], Copyright © 2025, American Chemical Society; and (c, d) accelerating wound healing using PVDF/CoFe<sub>2</sub>O<sub>4</sub>@BaTiO<sub>3</sub>, adapted with permission [23], Copyright © 2025, John Wiley and Sons.



**Figure 3:** Schematic diagram presenting the future development directions for magnetic field-enabled piezocatalytic biomedical therapy.

implantable or wearable platforms opens new opportunities for developing intelligent theranostic devices that combine real-time biosensing, feedback-controlled therapy, and personalized treatment. These emerging directions highlight the versatility and translational potential of magnetic field-enabled biomedical therapies across a wide range of clinical scenarios.

## Funding

This work is financially supported by the National Natural Science Foundation of China (22202106, 62288102), Beijing Key Laboratory of High-Entropy Energy Materials

and Devices, Beijing Institute of Nanoenergy and Nanosystems (GS2025MS031), Basic Research Program of Jiangsu (BK20243057, BK20250039), and National Key Research and Development Program of China (2021YFA1202904).

## Author Contributions

Conceptualization, Baoying Dai and Chuyi Zhou; Methodology, Chuyi Zhou; writing—original draft preparation, Chuyi Zhou; writing—review and editing, Baoying Dai, Hang Yin, Rui Kong, and Hao Wang; supervision, Baoying Dai; project administration, Baoying Dai; funding acquisition, Baoying

Dai. All authors have read and agreed to the published version of the manuscript.

## Conflict of Interest

The authors declare that they have no competing financial interests or personal relationships that could have influenced the work reported in this article.

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