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Piezoelectric Materials for Piezocatalysis and Piezo-Photocatalysis: Fundamentals, Mechanisms, Materials and Environmental Applications

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ABSTRACT: Piezocatalysis and piezo-photocatalysis have emerged as promising approaches for environmental remediation by utilizing mechanical energy alone or in combination with light to drive redox reactions. This review systematically summarizes the fundamental principles and mechanisms of piezoelectricity, piezocatalysis, photocatalysis, and piezo-photocatalysis, with particular emphasis on charge separation and reactive species generation. Recent advances in piezoelectric materials, including conventional and emerging materials, transition-metal chalcogenides, perovskites, and layered bismuth-based materials, are discussed together with strategies for improving catalytic performance. Their applications in pollutant degradation, heavy-metal removal, water purification, disinfection, and microbial inactivation are further reviewed. Finally, current challenges and future perspectives related to material design, energy utilization, mechanistic understanding, stability, and practical application are highlighted. This review provides an integrated perspective on piezoelectric catalytic systems and their potential for sustainable environmental remediation.

KEYWORDS: Piezoelectric materials; Piezocatalysis; Piezo-photocatalysis; Environmental remediation; Pollutant degradation.

INTRODUCTION

Environmental pollution, including solid waste, water pollution, and air pollution, poses significant risks to human health and ecosystems[1]. Therefore, preventing and controlling environmental pollution and developing effective remediation technologies have become important research priorities.

The increasing water contamination associated with industrial expansion and population growth has prompted the development of diverse strategies for pollutant remediation[2]. Among these approaches, advanced oxidation processes (AOPs), introduced in 1987 [3], have attracted considerable attention because of their ability to degrade refractory organic pollutants through the generation of highly reactive oxidative species (ROS), such as $\bullet O_2^-$ and •OH[4], [5]. Photocatalytic technology, which utilizes solar energy to drive the degradation of organic contaminants in water, has demonstrated significant potential for environmental remediation. However, its practical application is still limited by the rapid recombination of photogenerated electron–hole pairs and insufficient utilization of reactants at the catalyst surface[6], [7].

As an emerging research field, piezocatalysis has attracted considerable academic interest over the past decade. Piezocatalytic processes utilize mechanical stress to induce charge separation in piezoelectric materials, thereby generating piezoelectric potential and driving redox reactions without requiring light irradiation[8]. External mechanical stimuli, including ultrasonic cavitation, eddy shear forces, and physical bending, can deform piezoelectric materials and induce directional separation of charge carriers[9], [10]. When the piezoelectric potential generated within the material is sufficiently large, an internal electric field is established, which promotes the separation and migration of charge carriers toward different surfaces and facilitates their participation in redox reactions[11]. Mechanical vibrations provide an important driving force for piezocatalytic reactions, allowing piezoelectric materials to convert mechanical stimuli into chemical activity[12]. Consequently, piezocatalysis has demonstrated considerable potential for environmental remediation, particularly in the degradation of organic pollutants and the inactivation of microorganisms, making it an attractive strategy for environmental pollution control and cleanup[13].

In recent years, an emerging strategy that integrates the piezoelectric effect of materials with photocatalytic processes, namely piezo-photocatalysis, has been proposed as a promising approach to overcome the limitations of conventional photocatalysis. When piezoelectric materials are subjected to external mechanical stimuli, such as ultrasonic vibration[14], stirring [15], and fluid fluctuations[16], mechanical deformation induces a dynamic piezoelectric field within the material. This built-in electric field

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provides an additional driving force for the separation and migration of photogenerated charge carriers, thereby suppressing their recombination and enhancing the utilization of photogenerated electrons and holes. In addition, the piezoelectric field can modulate the charge-transfer behavior and redox properties of the photogenerated carriers, thereby promoting surface oxidation–reduction reactions[17]. The synergistic coupling of the piezoelectric and photocatalytic effects can consequently improve photocatalytic activity under combined mechanical and light irradiation conditions, providing an effective strategy for enhancing the degradation of environmental pollutants.

Despite its considerable potential, research on piezocatalysis and piezo-photocatalysis is still developing rapidly, and several aspects require further systematic investigation, particularly the fundamental mechanisms underlying piezoelectric and piezo-photocatalytic processes, the synergistic effects between mechanical and light-induced processes, the relationship between material characteristics and catalytic performance, and the rational design of effective piezoelectric and piezo-photocatalytic systems. In response to these needs, this review provides a comprehensive overview of piezoelectric materials for piezocatalysis and piezo-photocatalysis, with a particular focus on environmental applications. First, the fundamental principles of piezoelectricity, piezocatalysis, photocatalysis, and piezo-photocatalysis are introduced, followed by a discussion of their underlying mechanisms and coupling effects. Subsequently, the classification and recent research progress of piezoelectric materials, including conventional and emerging materials, transition-metal chalcogenides, perovskite materials, and layered bismuth-based piezoelectric materials, are summarized. The material systems and structural design strategies for piezo-photocatalysis are then discussed. Finally, the environmental applications of piezocatalysis and piezo-photocatalysis, including pollutant degradation, heavy-metal removal, disinfection, water purification, pollutant removal, and sterilization, are systematically reviewed. Through this comprehensive discussion, this review aims to provide a clear understanding of the fundamental mechanisms, material development, and environmental applications of piezocatalysis and piezo-photocatalysis and to provide useful guidance for their further development in environmental remediation.

Foundations of Piezoelectric Piezocatalysis

Piezoelectricity

The term “piezoelectricity” originates from the combination of the words “piezo,” referring to pressure or mechanical stress, and “electricity,” reflecting the generation of electrical charge. [18]. The piezoelectric effect was first experimentally discovered by the Curie brothers in 1880, who demonstrated that mechanical stress applied to certain materials could induce the development of electrical charges[19]. This phenomenon, in which mechanical deformation is converted into an electrical response, is known as the piezoelectric effect. At the structural level, piezoelectricity arises from the non-centrosymmetric crystal structure of piezoelectric materials [20]. In the absence of an external mechanical stimulus, these materials generally exhibit no net macroscopic polarization, as illustrated in Figure 1a. However, when a piezoelectric material is compressed, stretched, or otherwise mechanically deformed along an appropriate direction, the relative displacement of positive and negative charge centers occurs within the crystal lattice. This deformation produces a net polarization and results in the accumulation of opposite charges on different surfaces of the material, as illustrated in Figure 1b and 1c. The resulting polarization and potential difference constitute the fundamental electrical response associated with the piezoelectric effect.

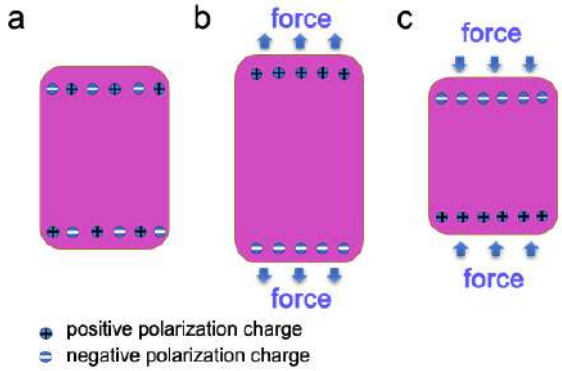

Figure 1. Schematic illustration of the piezoelectricity: (a) charge distribution in a piezoelectric material in the absence of external mechanical stress; (b) charge redistribution induced by tensile deformation; and (c) charge redistribution induced by compressive deformation.

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Origin and Mechanism of Piezoelectricity

Piezoelectric materials can be mechanically deformed by various external stimuli, including ultrasonic waves, mechanical stress, biomechanical energy, water flow, and wind[21]. Among these approaches, ultrasound is widely used because of its strong penetration, long propagation distance in water, and adjustable power, making it a convenient method for inducing piezoelectric deformation[22]. Mechanical stimuli such as vibrating cantilevers and ball milling can also generate sufficient deformation and mechanical energy to activate piezoelectric materials[23]. A motor-controlled vibrating cantilever enables precise control of deformation, whereas ball milling provides intense mechanical energy that can promote redox reactions and facilitate the treatment of solid-state contaminants[24]. However, externally powered mechanical methods require additional energy input. Therefore, natural and biomechanical energy sources, such as blood circulation, physical movement, heartbeat, breathing, water flow, and wind, have also attracted attention as sustainable driving forces for piezoelectric processes[25].

Principles of Photocatalysis, Piezocatalysis, and Piezo-Photocatalysis

Photocatalysis and piezocatalysis, as advanced oxidation technologies for environmental remediation and energy conversion, have demonstrated considerable potential in applications such as water purification, H_2 production, CO_2 reduction, N_2 fixation, and H_2O_2 synthesis[26]. The fundamental distinction between these technologies lies in their activation mechanisms for generating reactive species. In photocatalytic processes, light irradiation with photon energy equal to or higher than the bandgap excites electrons from the valence band (VB) to the conduction band (CB), generating electron–hole (e^-–h^+) pairs (Fig 2A). These photogenerated carriers migrate to active sites through diffusion or electric-field-driven transport, where they participate in redox reactions and generate reactive species such as •OH, $•O_2^-$, and $^1O_2$. However, the rapid recombination of e^-–h^+ pairs significantly limit photocatalytic efficiency and practical applications.

Piezocatalysis addresses this limitation through the generation of an internal electric field induced by mechanical stress. The term “piezocatalysis” originates from the polarization behavior of piezoelectric materials, first identified by the Curie brothers in 1880 during their investigation of tourmaline[27]. Mechanistically, mechanical deformation of non-centrosymmetric crystals causes the relative displacement of positive and negative charge centers, producing polarization and a measurable surface potential difference (Fig 2B, D). This electromechanical coupling is reversible: the direct piezoelectric effect converts mechanical energy into electrical energy, whereas the inverse effect converts electrical energy into mechanical deformation. In catalytic processes, the polarization electric field promotes charge separation and facilitates interfacial redox reactions, leading to the generation of highly reactive species[28]. These species can subsequently degrade organic pollutants, remove heavy-metal ions, and inactivate harmful microorganisms. Piezoelectric materials can generate substantial voltage under medium-to-high mechanical strain, typically ranging from 10 to 100 V and, under certain conditions, even exceeding several hundred volts. The conventional vibration frequencies of $BaTiO_3$ nanowires (NWs) and nanoparticles (NPs) are approximately 40 and 60 kHz, respectively (Figure 1F, G)[29], [30]. Jia et al. reported a calculated normal vibration frequency of 91.69 kHz for Bi_2WO_6 NWs (Figure 1E)[31]. As the applied ultrasonic frequency approaches 91.69 kHz, the piezocatalytic H_2 production continues to increase. Nevertheless, piezocatalysis still faces challenges, including inefficient charge utilization due to carrier recombination and limitations in polarization-field strength associated with the intrinsic piezoelectric coefficient (d_{33}) and dielectric constant of the material, which may restrict reactions requiring high Gibbs free energy.

To overcome these limitations, researchers have coupled photocatalysis with piezocatalysis to develop piezo-photocatalytic technology. This strategy utilizes the piezoelectric response of materials under mechanical vibration to generate an internal electric field, which promotes the separation and migration of photogenerated charges and suppresses their recombination (Figure 2C). Since its initial concept[32], [33]. piezo-photocatalysis has developed rapidly and has also been extended to applications such as strain sensors, transistors, and nanogenerators. The polarization charges generated by mechanical deformation produce an internal electric field that regulates the separation and transport of light-excited carriers in the catalyst. This effect can prolong carrier lifetimes and modify redox pathways by regulating the surface charge distribution[34]. Moreover, the synergistic interaction between piezocatalysis and photocatalysis can alter the relative positions of the VB and CB and regulate redox potentials [35], thereby enhancing the generation and utilization of reactive species and providing an effective strategy for environmental remediation and related applications.

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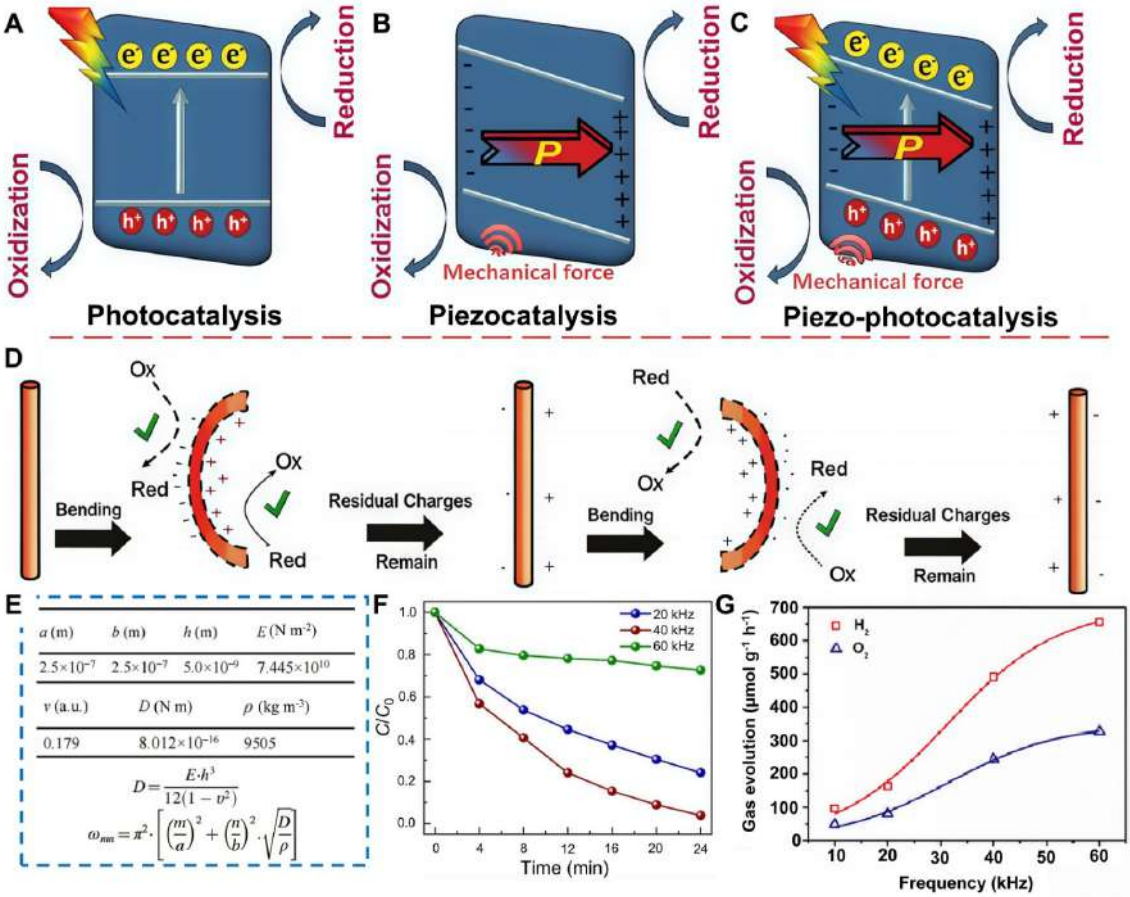

Figure 2. Schematic illustration of different catalytic mechanisms: (A) photocatalysis, (B) piezocatalysis, and (C) piezo-photocatalysis; (D) piezoelectric electrochemical effect; (E) parameters of a Bi_2WO_6 nanoplate for calculating the vibration resonance frequency; and (F, G) catalytic performance of $BaTiO_3$ NSs and NPs at different vibration frequencies. Panels (A–C) reproduced from Ref. [36]; (D) reproduced from Ref. [37]; (E) reproduced from Ref. [38]; (F) reproduced from Ref. [39]; and (G) reproduced from Ref. [40].

Piezoelectric Materials for Piezocatalysis

Classification of Piezoelectric Materials

According to their degree of symmetry, crystals can be classified into seven basic crystal systems: triclinic, monoclinic, orthorhombic, tetragonal, trigonal (rhombohedral), hexagonal, and cubic[41]. These seven crystal systems can be further classified into 32 distinct crystal point groups based on different combinations of symmetry elements. Among these, 11-point groups possess a center of symmetry, whereas 21 are non-centrosymmetric. Of the 21 non-centrosymmetric point groups, 20 exhibit a piezoelectric effect, while the remaining one corresponds to non-polar materials[42]. Based on their distinctive properties, non-centrosymmetric crystals can be categorized into four major classes: piezoelectric, pyroelectric, ferroelectric, and nonlinear optical materials. Piezoelectric materials can be polarized under the application of an external mechanical force[43]. Piezoelectric materials can be further classified into chalcogenides, perovskites, layered bismuth-based piezoelectric materials, and other piezoelectric materials. In this section, we provide a clear discussion of the structure–piezoelectricity relationship. Table 1 summarizes the crystal systems, point groups, and representative applications of piezoelectric materials.

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Table 1. Summary of piezoelectric materials according to their crystal systems and applications in environmental remediation

Crystal system	Piezoelectric materials	Environmental Application	Reference
Hexagonal	ZnO	Degradation of tetracycline	[44]
	CdS	Degradation of RhB	[45]
	ZnS	Degradation of MB	[46]
	h-BN	Degradation of bisphenol A	[47]
Triclinic	Bi_4O_7	None	[48]
Orthorhombic	Bi_2MoO_6	Degradation of methylene blue (MB)	[49]
	Bi_2WO_6	Degradation of MB	[50]
	$AgNbO_3$	Degradation of Rhodamine B (RhB)	[51]
	SbSI	Degradation of MO	[52]
Cubic	g-C_3N_4	Degradation of dichlorophenols	[53]
	$Bi_{25}FeO_{40}$	Degradation of 4-chlorophenol	[54]
Tetragonal	$BaTiO_3$	CO2 reduction	[55]
	$BiPrFeMnO_3$	Degradation of MB	[56]
	WS_2	disinfection	[57]
Monoclinic	$Cu_3B_2O_6$	Disinfection	[58]
	$Fe_2(MoO_4)_3$	Degradation of tetracycline	[59]
	Bi_2O_4	Degradation of methyl orange (MO)	[60]
Trigonal	La1−xMn1−yO3	Degradation of paracetamol (PCT)	[61]
	$LiNbO_3$	Degradation of MB	[62]
	$Pb(Zr_{0.52}Ti_{0.48})O_3$	Degradation of RhB	[63]
	Pb_2BO_3X (X = Cl, Br, I)	Degradation of MB	[64]

Recent Advances in Piezoelectric Materials

In recent years, advances in piezocatalysis (Figure 3) [65], [66] have broadened the applications of piezoelectric materials and promoted their market growth (Figure 4A). These materials enable bidirectional conversion between mechanical and electrical energy, primarily due to their non-centrosymmetric crystal structures. Among the 32 crystallographic point groups, only 21 are non-centrosymmetric and exhibit piezoelectricity[67]. Below the Curie temperature (Tc), spontaneous polarization enables piezoelectric behavior, whereas above Tc, structural symmetry is restored and the piezoelectric effect disappears [68]. Based on their polarization

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characteristics, non-centrosymmetric materials include piezoelectric, ferroelectric, and thermoelectric materials (Figure 4B, C), with ferroelectric and thermoelectric materials also exhibiting piezoelectric properties due to their spontaneous polarization[69]. Piezocatalytic and piezo-photocatalytic materials are generally classified as conventional and emerging piezoelectric materials.

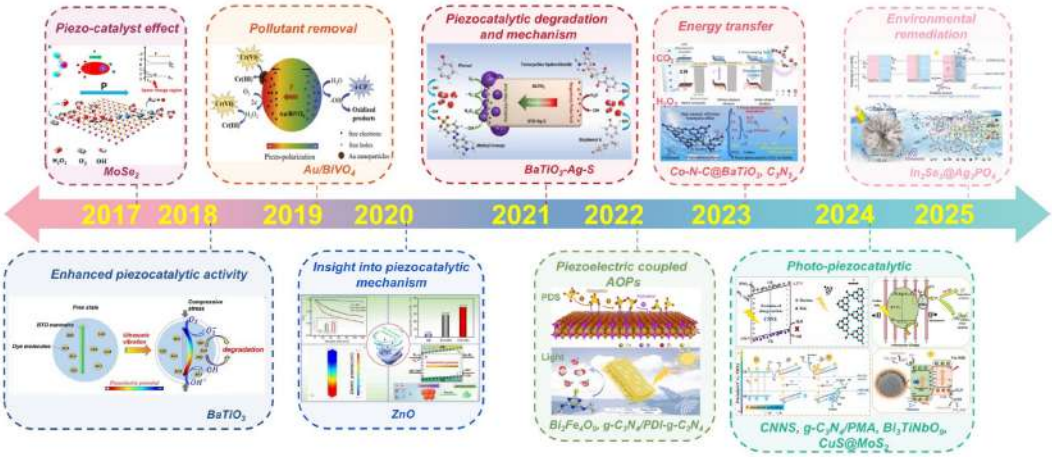

Figure 3. Evolution of piezoelectric materials[70], [71].

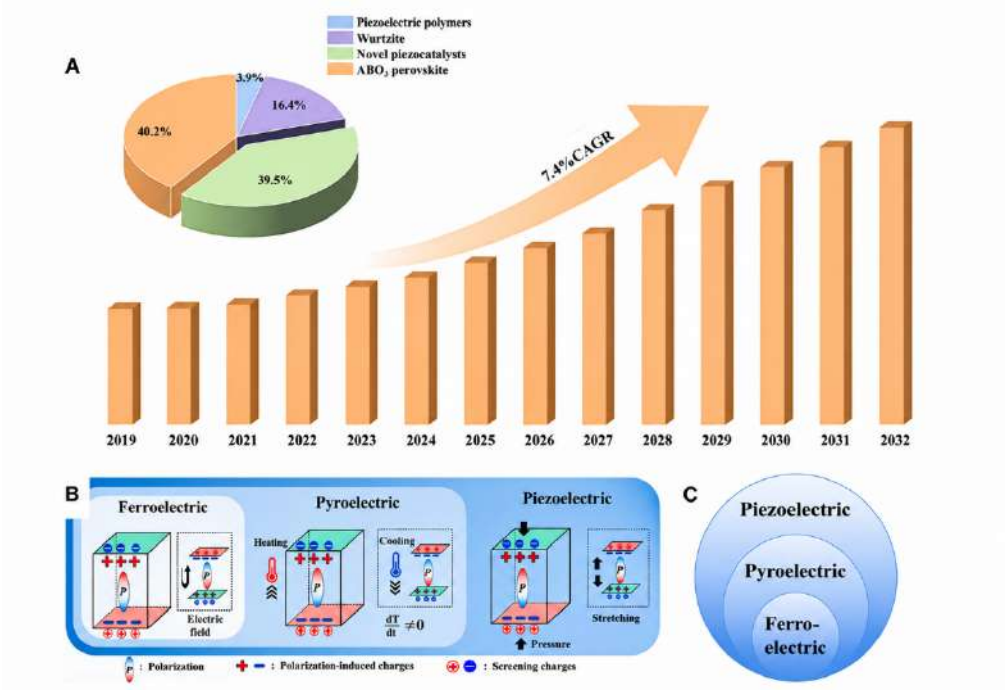

Figure 4. Prospects and mechanisms of piezoelectric catalytic materials. (A) Market size of piezoelectric materials in the Asia–Pacific region and recent distribution of different piezocatalyst types[72], [73]. (B) Mechanisms of ferroelectric, thermoelectric, and piezoelectric effects[74]. Copyright 2025, Elsevier. (C) Relationship among piezoelectric, pyroelectric, and ferroelectric crystals[75], [76], [77].

Piezo-photocatalytic mechanism

Photocatalytic and piezoelectric catalytic mechanisms

Photocatalytic reactions involve three main processes: (i) light excitation, where photons with energy is equal to or greater the semiconductor band gap (Eg) generate electron–hole pairs; (ii) charge separation and transfer, where built-in electric fields suppress

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electron–hole recombination and promote their migration; and (iii) surface redox reactions, in which photogenerated holes produce reactive species such as •OH, while electrons drive reduction reactions[78], [79]. The overall efficiency is also influenced by reactant adsorption, interfacial electronic structure, and surface-active sites[80]. Co-catalysts can further facilitate charge separation, lower interfacial reaction barriers, and improve charge utilization[81], [82]. External mechanical stress deforms the crystal lattice, displacing positive and negative charge centers and generating surface polarization and an internal electric field[83]. This field promotes electron–hole separation and drives surface redox reactions. In 2010, Hong et al.[84] demonstrated ultrasound-induced piezoelectric water splitting using ZnO and $BaTiO_3$, introducing the piezoelectric electrochemical (PZEC) effect. Starr et al. [85] later established its theoretical basis and identified the piezoelectric coefficient, conductivity, and dielectric constant as key factors. In 2015, Starr et al.[86] reviewed piezoelectric–electrochemical coupling, accelerating the development of piezoelectric catalysis and its integration with photocatalysis for CO_2 reduction and pollutant degradation. The piezoelectric effect originates from non-centrosymmetric crystal structures, where mechanical stress induces ionic displacement and macroscopic polarization; 20 of the 32 crystal point groups exhibit piezoelectricity[87], [88]. Based on structural characteristics, piezoelectric materials are classified into four groups: displaceable cationic materials, covalent polar semiconductors, rigid polar networks, and flexible polar chains. Displaceable cationic materials generally show stronger piezoelectric responses, while rigid structures and flexible polar chains exhibit weaker macroscopic polarization due to limited distortion or insufficient long-range order. Their key characteristics are summarized in Table 2. Catalytic performance does not necessarily depend on a large piezoelectric field[89], [90], [91]. Therefore, catalyst design should consider piezoelectric coefficients, band gaps, crystal structures, surface properties, and chemical bonding. Integrating these parameters with artificial intelligence and multimodal learning can accelerate the screening and prediction of new piezoelectric photocatalysts. Moreover, polarization can be induced by various mechanical stimuli, including ultrasound, stirring, gravitational loading, acoustic waves, and shock waves, providing diverse strategies for enhancing catalytic performance.

Table 2. Piezoelectric and photocatalytic properties of different piezo photocatalytic systems

Systems	Crystalline phase/structure	Piezoelectric function	Photocatalytic function	Reference
$BaTiO_3$	Tetragonal phase	Yes	Yes	[92]
$PbTiO_3$	Tetragonal phase	Yes	Yes	[93]
$SrTiO_3$	Applied stress/strain	Yes	Yes	[94]
PZT	Orthogonal and tetragonal phases coexist	Yes	Yes	[95]
ZnO	Wurtzite	Yes	Yes	[95]
CdS	Hexagonal	Yes	Yes	[96]
GaN	Hexagonal	Yes	Yes	[97]
TiO_2	-	No	Yes	[98]
$CaCu_3Ti_4O_{12}$	-	No	Yes	[99]
C_5N_2	-	Yes	Yes	[100]
C_3N_4	Ultrathin/asymmetric 2D	Yes	Yes	[101]
$ZnSnO_3$	-	Yes	Yes	[102]
MoS_2	Single layer	Yes	Yes	[103]
Bi_2SiO_5	Monoclinic system	Yes	Yes	[104]
$SrBi_2Nb_2O_9$	Orthogonal phase	Yes	Yes	[105]
$NaNbO_3$	Orthogonal phase	Yes	Yes	[106]
$KNbO_3$	Orthogonal phase	Yes	Yes	[107]
$BiFeO_3$	Rhombohedral	Yes	Yes	[108]

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Quartz	α-Quartz	Yes	No	[109]
PVDF	Stretch-high β phase	Yes	No	[110]
SnSe	Two-dimensional layered	Yes	No	[111]

Piezo-photocatalysis coupling mechanism

In 2010, Wang et al. [112] established a theoretical framework integrating semiconductor properties, photoexcitation, and piezoelectric effects, providing a basis for piezoelectric photocatalysis. The theory showed that strain-induced piezoelectric potentials in ZnO can regulate photoelectrochemical responses. Since then, coupling piezoelectric and optical fields has developed rapidly. Conventional photocatalysis is limited by rapid charge recombination, poor light utilization, and slow surface reaction kinetics[113], [114], [115]. In contrast, piezoelectric coupling can synergistically improve photocatalytic efficiency by enhancing energy utilization and optimizing reaction pathways.

Materials with non-centrosymmetric structures and asymmetric dipoles develop net piezoelectric polarization when external stress causes unequal charge displacement (Fig. 5a, b) [116], [117]. The resulting built-in electric field promotes photogenerated carrier separation and directional transport (Fig. 5c), while inducing band bending and alignment changes that regulate the reduction and oxidation potentials of electrons and holes or activate otherwise restricted reaction pathways (Fig. 5d) [118], [119].

Light irradiation generates photogenerated electron–hole pairs, while external mechanical stimulation induces polarized charges, producing an internal electric field that promotes the separation and migration of charge carriers. In piezoelectric materials, stress-induced polarization charges are mainly distributed within the bulk, whereas only surface or near-surface charges can directly participate in catalytic reactions. This spatial limitation restricts carrier transport and makes it challenging to simultaneously optimize photocatalytic and piezoelectric performance. Consequently, recent research has focused on regulating catalyst structure, charge distribution, and local interfacial electric fields through atomic and defect engineering, interfacial reaction-pathway modulation, nanostructure design, and macroscopic structural engineering. These strategies aim to strengthen the coupling between piezoelectric polarization and photocatalytic reactions and thereby improve overall catalytic efficiency.

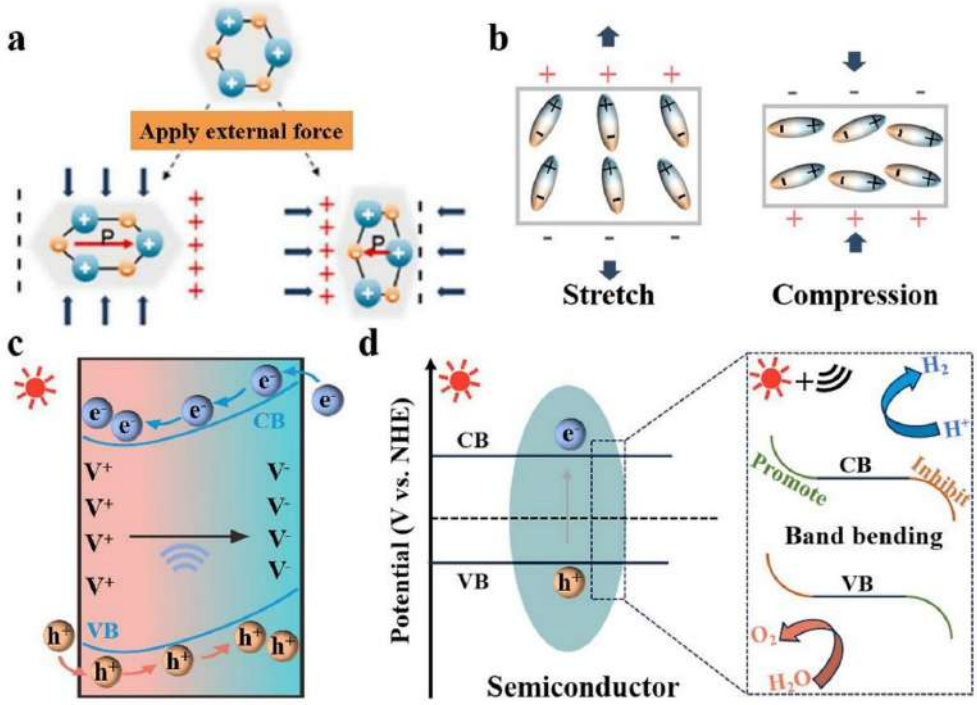

Figure 5. (a) Schematic illustration of mechanically induced piezoelectricity, adapted from Ref. [120]. (b) Variation in the dipole moment of a piezoelectric material. (c) Schematic illustration of piezoelectric-field-induced separation of photogenerated charge carriers. (d) Piezoelectric-field-modulated band structure.

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Piezo-catalysis in environmental remediation

Although piezocatalysis shares a similar reaction mechanism with conventional electrocatalysis, its distinctive advantage lies in directly harnessing mechanical energy as the driving force for catalytic reactions. This enables the effective utilization of even weak and ubiquitous mechanical vibrations from the surrounding environment. Consequently, piezocatalysis has attracted considerable attention in environmental applications, with various piezoelectric materials, including ZnO-based materials, perovskites, and metal–organic frameworks (MOFs), exhibiting promising catalytic performance. Recent advances in piezoelectric photocatalysis for environmental applications have mainly focused on pollutant degradation, disinfection, and CO_2 reduction.

Piezoelectric-Catalytic Pollutant Degradation

Water pollutants

Organic dyes are widely used in construction, textile, and printing industries[121], while the discharge of toxic and poorly biodegradable pollutants poses serious environmental and health risks[122]. Therefore, piezocatalysis has attracted increasing attention for water pollutant degradation[123]. ZnO is widely studied because of its facile preparation, environmental compatibility, and stability[124]. Various ZnO structures, including nanorods/nanowires [125], nanoparticles[126], nanosheets[127], metal/ZnO composites[128], and heterojunctions[128], have been investigated. Ning et al. reported higher dye-degradation activity for ZnO nanorods than nanoparticles[126]. Peng et al. further enhanced ZnO nanorod activity by regulating polarized surface exposure, which also affected dye adsorption and migration[129]. ZnO/CuO, CdS/ZnO, and MoO_x/ZnS/ZnO heterojunctions have also shown promising performance[130], [131], with ZnO/CuO achieving 71.06% degradation at a Zn/Cu ratio of 9:1[130].

Perovskite materials have also shown strong potential for piezocatalytic water treatment. Hong et al. first reported the PZEC effect using $BaTiO_3$ microdendrites for Acid Orange degradation under ultrasound[132]. Subsequent studies investigated $Bi_4Ti_3O_{12}$[133], $(Ba,Sr)TiO_3$[134], $PbZr_xTi_{1-x}O_3$ [135], $SrTiO_3$ [136], $K_{0.5}Na_{0.5}NbO_3$ [137], $LiNbO_3$ [138], and $NaNbO_3$ [139]. Singh et al. demonstrated piezocatalytic dye degradation using $LiNbO_3$ and showed that even unpolarized $LiNbO_3$ remained active, indicating a contribution from local piezoelectric domains [140]. Other emerging catalysts include Pb_2BO_3X (X = Cl, Br, I), Fe@MoS_2, and piezoelectric MOFs. Pb_2BO_3I degraded CIP and NOR [58], while Fe@MoS_2 achieved ~99% tetracycline degradation and remained stable over 50 cycles[141]. ZIF-8 achieved ~94.5% RhB degradation within 90 min under vibration, while adenine-modified UiO-66 showed enhanced DCF degradation[142].

Piezoelectric composites, including PVDF/$BaTiO_3$ [143], E-MoS_2/PVDF[144], $BaTiO_3$/TiO_2 [145], $KNbO_3$/MoS_2 [146], $BaTiO_3$–PDMS [147], $BaTiO_3$/g-C_3N_4 [148], and ZnO–Al_2O_3/GO [149], have further improved water pollutant treatment. Oxygen-vacancy-rich $BaTiO_3$/PVDF enhanced BPA adsorption and degradation (Figure 6a) [150], while E-MoS_2/PVDF achieved 93.08% OTC degradation through enhanced active sites and charge carriers (Figure 6b) [151]. $BaTiO_3$–PDMS foam achieved ~94% RhB degradation and retained ~50% activity after 12 cycles, while the polymer matrix reduced secondary contamination (Figure 6c) [152].

Air pollutants

Volatile organic compounds (VOCs) are major indoor air pollutants that pose significant risks to human health. Yang et al.[153] were the first to apply the piezoelectric effect for VOC removal from air. They developed Ag/$BaTiO_3$ by depositing Ag clusters onto $BaTiO_3$ nanorods, achieving the piezoelectric-catalytic oxidation of CH_3SH into non-toxic products with a removal efficiency of 92.0% (Figure 6e). This high degradation efficiency was attributed to the strong piezoelectric potential generated along the polar axis of $BaTiO_3$ nanorods, which enhanced the surface enrichment of CH_3SH and facilitated its oxidation. This study demonstrates the potential of piezoelectric catalysis as an effective strategy for VOC purification.

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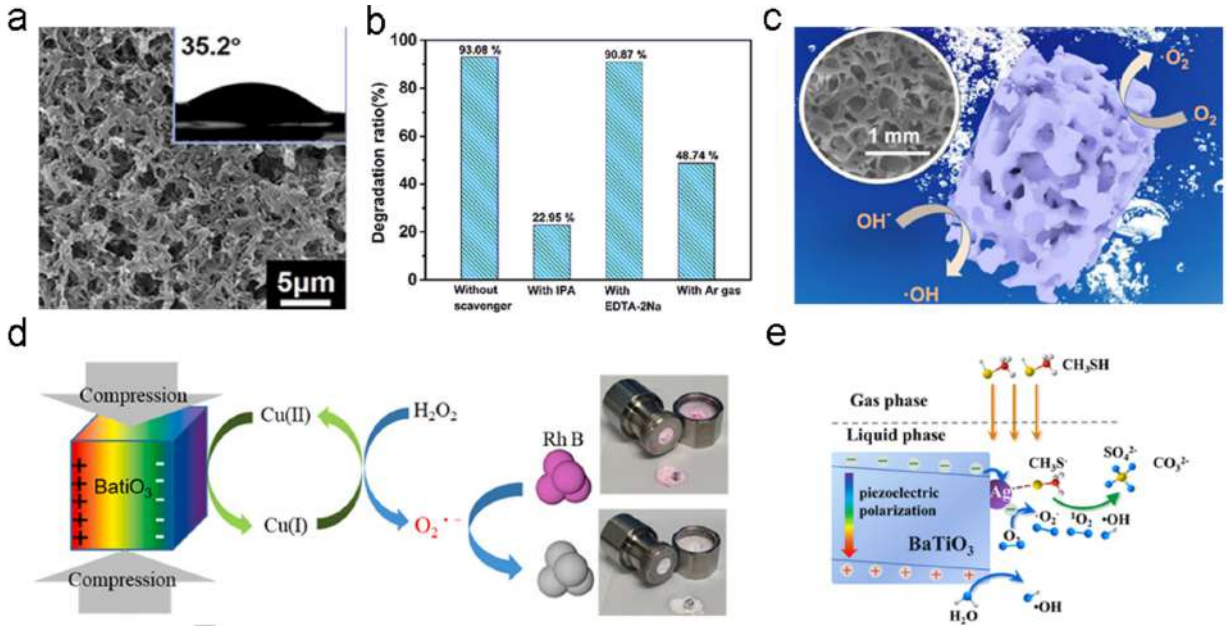

Figure 6. (a) SEM images of PVDF/$BaTiO_3$, with the water contact angle shown in the inset, adapted from Wan et al. [150]. (b) Corresponding degradation efficiencies of 10.0 wt% E-MoS_2/PVDF, adapted from Ma et al. [151]. (c) Schematic illustration of the porous $BaTiO_3$–PDMS fabrication process, adapted from Qian et al. [152]. (d) Proposed mechanism of the electro-mechanochemical redox process, adapted from Zhou et al. [154]. (e) Schematic representation of the working mechanism of the Ag/$BaTiO_3$ hybrid piezocatalyst under ultrasonic vibration, adapted from Yang et al. [155].

solid pollutants

Although organic pollutants are primarily present in wastewater, they can also penetrate soil and accumulate as solid-state pollutants. Moreover, adsorption can further concentrate organic pollutants in solid matrices. Therefore, the direct degradation of organic pollutants in the solid state, without redispersion in solvents, is highly important. Ball milling has been recognized as an efficient and environmentally friendly alternative to conventional solution-based methods[156]. Zhou et al. achieved the direct degradation of solid organic dyes by integrating piezoelectric $BaTiO_3$ with ball milling (Figure 6d) [157]. During the ball-milling process, $BaTiO_3$ nanoparticles were polarized and promoted the reduction of Cu (II) to catalytically active Cu(I) species. Subsequently, Cu(I) catalyzed H_2O_2 to generate reactive $\cdot O_2^-$ species, thereby enhancing dye degradation.

Removal of Heavy Metals

Heavy metal contamination of surface and groundwater is a major global environmental and public health concern [158]. Consequently, the removal of heavy metals from wastewater has become an important aspect of environmental remediation, attracting considerable interest in both research and industrial applications [159]. In recent years, piezocatalytic processes have emerged as a promising approach for heavy metal removal. Hexavalent chromium (Cr (VI)) is particularly concerning because of its high toxicity to humans and other living organisms [160]. Tian et al. developed a SnS_2/CNFs membrane by depositing single- and few-layer SnS_2 nanosheets onto carbon nanofibers and applied it to the simultaneous piezocatalytic reduction of Cr (VI) and degradation of BPA [161]. The enhanced removal performance under ultrasonic irradiation was attributed to the internal electric field and band bending generated by SnS_2, together with the high electron mobility of the CNF substrate. Wei et al. synthesized Au/$BiVO_4$ through a urea-assisted deposition–precipitation method, where surface-deposited Au nanoparticles promoted charge separation and enhanced the piezocatalytic reduction of Cr(VI), achieving an 83% reduction within 120 min [162]. Similarly, Li et al. constructed a CuS/MoS_2 heterojunction for Cr(VI) removal, achieving complete removal within 180 s. This enhanced performance was attributed to the synergistic effect of heterojunction formation and the induced piezoelectric field, which facilitated charge separation and transfer[163].

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Reduction of CO_2

The continuous increase in CO_2 emissions from fossil-fuel consumption has intensified global climate and environmental concerns, highlighting the need for efficient CO_2 conversion technologies. Compared with photocatalysis and electrocatalysis, piezocatalysis can drive CO_2 reduction without light by harvesting mechanical energy from environmental vibrations. The induced piezoelectric potential can lower reaction barriers and facilitate CO_2 conversion [164]. In 2022, Phuong et al. first demonstrated piezocatalytic CO_2 reduction using lead-free Li-doped (K,Na)NbO_3 (KNN), achieving CO production at 438 μmol g^{-1} h^{-1} [164]. He et al. subsequently reported CO and CH_4 production rates of 28.7 and 17.9 μmol g^{-1} h^{-1}, respectively, over $BiFeO_3$ (Figure 7A) [165]. DFT calculations indicated that CO_2 adsorption and activation mainly occurred on the (012) surface, while ultrasonic stimulation facilitated proton-coupled electron-transfer pathways and lowered reaction barriers (Figure 7B) [165]. These studies demonstrated the feasibility of converting CO_2 into valuable chemicals through piezocatalysis.

However, the activity and selectivity of piezocatalytic CO_2 reduction remain limited. Various strategies, including elemental doping, piezo-photocatalytic coupling, and heterostructure construction, have therefore been developed to improve performance[55], [164]. Zhang et al. reported Nb-doped lead zirconate titanate with a CO_2 reduction rate of 789 μmol g^{-1} h^{-1} under optimized conditions [166]. Ma et al. further developed a piezoelectric-catalytic-electrochemical coupling system that produced CO at 31.65 μmol g^{-1} h^{-1} with nearly 100% selectivity in the absence of sacrificial agents (Figure 7C) [167]. First-principles calculations and COMSOL simulations further clarified the roles of reaction intermediates, free-energy changes, and reaction potentials (Figure 7D) [167]. Ni et al. developed intergrowth ferroelectric $Bi_7Ti_4NbO_{21}$ nanosheets for piezo-photocatalytic CO_2 reduction, achieving a CO generation rate of 426.97 μmol g^{-1} h^{-1}. The enhanced activity was attributed to interlayer lattice mismatch and stress-induced octahedral distortion, which increased polarization and promoted charge separation [168].

Overall, piezocatalytic CO_2 reduction provides a promising mechanically driven route for converting CO_2 into value-added chemicals. Nevertheless, its mechanisms, activity, and product selectivity remain insufficiently understood. Future research should focus on rational catalyst design, mechanistic studies, and advanced theoretical and characterization techniques to clarify active sites, charge-transfer processes, and reaction intermediates, thereby improving the efficiency and selectivity of CO_2 conversion.

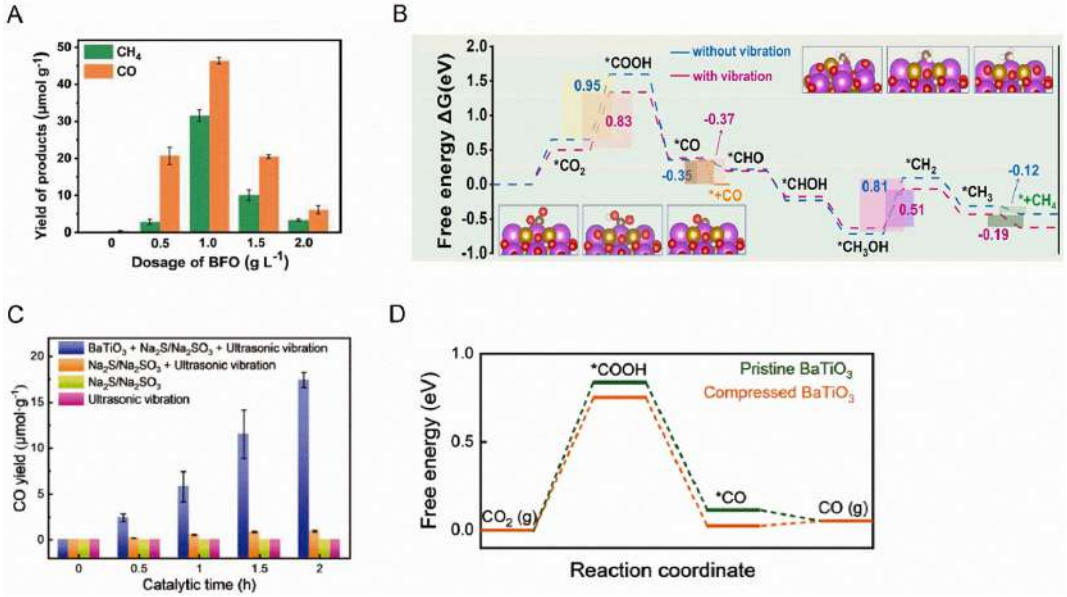

Figure 7. (a) CO_2 reduction product yields at different $BiFeO_3$ dosages, adapted from He et al. [165]. (b) ΔG profiles for CH_4 and CO formation during CO_2 reduction, adapted from He et al. [165]. (c) CO yield over $BaTiO_3$ with Na_2S/Na_2SO_3 as sacrificial agents, adapted from Ma et al. [167]. (d) Free-energy profiles and corresponding structures for CO_2 reduction to CO on the BaO-terminated (001) surface of $BaTiO_3$ based on DFT calculations, adapted from Ma et al. [167].

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Table 3. Piezocatalytic and piezo-photocatalytic degradation of pollutants.

Type	Catalysts	Substrate	Reaction conditions	Reaction rate (min −1)	Degradation efficiency	References
Piezo-catalytic	ZnO	MB (5 mg L −1)	Ultrasonic (200 W, 40 kHz)	0.0004	2.0%, 20 min	[169]
	BaTiO	RhB (10 mg L −1)	Ultrasonic (100 W, 40 kHz)	0.0736	97.6%, 110 min	[170]
	E-MoS_2 / PVDF	TC (20 mg L −1	Ultrasonic (100 W, 40 kHz)	0.0912	93.1%, 24 min	[171]
	Bi_2S_3–Bi_2WO	CBZ (5 ppm)	Ultrasonic (100 W, 40 kHz)	0.0870	92.0%, 30 min	[172]
	h-PTFE@TiO_2	RhB (10 ppm)	Ultrasonic (200 W, 40 kHz)	0.1388	/	[173]
	$BaTiO_3$ – TiO_2	IC (10 mg L −1	Ultrasonic (200 W, 45 kHz)	0.1090	100%, 30 min	[174]
piezo-photocatalytic	$BaTiO_3$ @ReS_2	RhB (10 mg L −1	300 W Xe lamp + ultrasonic (100 W, 40 kHz)	0.1330	95.8%, 25 min	[175]
	ZnO/$BaTiO_3$	RhB (10 mg L −1	500 W Xe lamp + ultrasonic (120 W, 40 kHz)	0.1200	97.0%, 30 min	[176]
	MoS_2@Ag_2O	MO (20 mg L −1	300 W lamp + ultrasonic (40 kHz)	/	95.0%, 30 min	[177]
	ZnO/ZnS/MoS	MB (10 mg L −1	300 W Xe lamp + stirring	0.0411	87.2%, 50 min	[178]
	$KNbO_3$	RhB (10 mg L −1)	300 W Xe lamp + ultrasonic (110 W, 40 kHz)	0.0220	32.4%, 120 min	[179]
	La–($BiFeO_3$)	CBZ (5 mg L −1	300 W Xe lamp + ultrasonic (100 W, 40 kHz)	/	94.5%, 30 min	[180]

CONCLUSIONS

In this review, we have summarized and critically discussed recent advances in piezocatalysis and piezo-photocatalysis, with particular emphasis on their fundamentals, mechanisms, material development, structural design, and environmental applications.

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The principles of piezoelectricity, piezocatalysis, photocatalysis, and piezo-photocatalysis, together with their coupling mechanisms, have been discussed. Various piezoelectric materials, including conventional and emerging materials, transition-metal chalcogenides, perovskites, layered bismuth-based materials, and composite heterostructures, have been reviewed, with particular attention to the relationships among structure, polarization, charge transport, and catalytic activity. Furthermore, the environmental applications of these technologies, including water pollutant degradation, heavy-metal removal, disinfection, air pollution control, solid-state and soil-associated pollutant remediation, and CO_2 reduction, have been systematically summarized. Despite the considerable progress achieved, several important issues remain unresolved and require further investigation to advance piezocatalysis and piezo-photocatalysis toward practical environmental applications.

First, the rational design of piezoelectric materials with simultaneously enhanced piezoelectric and catalytic properties remains a major challenge. The catalytic performance of these materials is strongly influenced by crystal structure, non-centrosymmetry, polarization, morphology, defects, surface chemistry, electronic structure, and interfacial charge-transfer pathways. Therefore, strategies such as elemental doping, defect engineering, morphology and facet control, strain engineering, polarization regulation, surface modification, and heterostructure construction should be further explored to improve both mechanical responsiveness and catalytic activity. In particular, heterostructured systems may provide enhanced charge separation and transport while simultaneously improving light utilization in piezo-photocatalysis. However, increasing one material property does not necessarily lead to higher overall catalytic performance. Establishing clear structure–property–activity relationships and developing integrated rather than isolated material optimization strategies will therefore be essential.

Second, the nature and efficiency of the mechanical energy used to activate piezoelectric materials require greater attention. Ultrasound is currently the most widely employed mechanical stimulus because its intensity and frequency can be conveniently controlled; however, externally generated ultrasound requires additional energy input and may complicate the overall energy balance of the process. Other mechanical stimuli, including vibration, water flow, wind, fluid fluctuations, and biomechanical motion, provide potentially more sustainable driving forces. Nevertheless, these natural or low-grade mechanical sources are generally weaker and less controllable than laboratory ultrasound. Therefore, improving the sensitivity of piezoelectric materials to weak, irregular, and low-frequency mechanical stimuli is an important prerequisite for practical applications. Future studies should also systematically evaluate the relationship between mechanical input, polarization response, catalytic activity, and overall energy efficiency.

Third, the environmental applications of piezocatalysis and piezo-photocatalysis need to move beyond simplified laboratory systems toward complex and realistic environmental conditions. Current studies have demonstrated promising performance in the degradation of organic pollutants and the removal of heavy metals from water, as well as in microbial disinfection. Emerging applications in air pollution control and the degradation of solid-state and soil-associated pollutants further demonstrate the versatility of these technologies. Piezocatalytic CO_2 reduction also provides an attractive route for coupling mechanical energy utilization with carbon conversion, although activity and product selectivity remain limited. Future research should therefore investigate realistic wastewater containing multiple contaminants, natural organic matter, inorganic ions, and suspended solids, as well as realistic air and soil matrices. Long-term stability, mineralization, degradation intermediates, toxicity evolution, catalyst recyclability, elemental leaching, and potential secondary pollution should be systematically evaluated. For CO_2 conversion, particular attention should be given to CO_2 activation, active sites, charge-transfer pathways, and product selectivity.

Fourth, several fundamental mechanistic questions concerning piezocatalysis and piezo-photocatalysis remain to be clarified. Although the generation of polarization and internal electric fields under mechanical deformation is widely accepted, it is still necessary to establish more direct evidence for the relationship between mechanical deformation, polarization potential, charge separation, reactive species formation, and surface reactions. In particular, distinguishing mechanically induced charge carriers from intrinsic free charges and separating piezocatalytic contributions from other processes that may accompany mechanical stimulation are important for accurately identifying the catalytic mechanism. For piezo-photocatalysis, the quantitative contribution of the piezoelectric internal electric field to the separation and migration of photogenerated carriers remains insufficiently understood. Advanced in situ/operando characterization, together with theoretical calculations and multiphysics modeling, should therefore be developed to monitor electronic states, band structures, polarization, internal electric fields, charge-transfer processes, and reaction intermediates under simultaneous mechanical and light stimulation.

Overall, piezocatalysis and piezo-photocatalysis provide a promising platform for converting mechanical energy into chemical activity and for enhancing light-driven reactions through piezoelectric polarization. Their expanding applications in water

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and air purification, heavy-metal removal, disinfection, solid and soil remediation, and CO_2 conversion demonstrate their broad environmental potential. Continued efforts to develop highly responsive materials, utilize sustainable mechanical energy, clarify coupled reaction mechanisms, and evaluate performance under realistic environmental conditions will be essential. With the integration of advanced material engineering, mechanistic characterization, theoretical modeling, and scalable reactor design, piezocatalytic and piezo-photocatalytic technologies may progress from laboratory-scale demonstrations toward efficient and sustainable environmental remediation and carbon-conversion applications.

Credit Authorship Contribution Statement

Mila Joya Halimi: Writing – original draft, Data curation, Visualization. Shodonali Sharifov: Writing – review & editing, Validation, Literature review. Shohjahon Yunusov: Writing – original draft, Methodology, Literature review, Visualization. Muhammad Babur Joya: Conceptualization, Supervision, Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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