



Advances on piezocatalysis and tribocatalysis in energy conversion field: performance, mechanisms, applications and beyond

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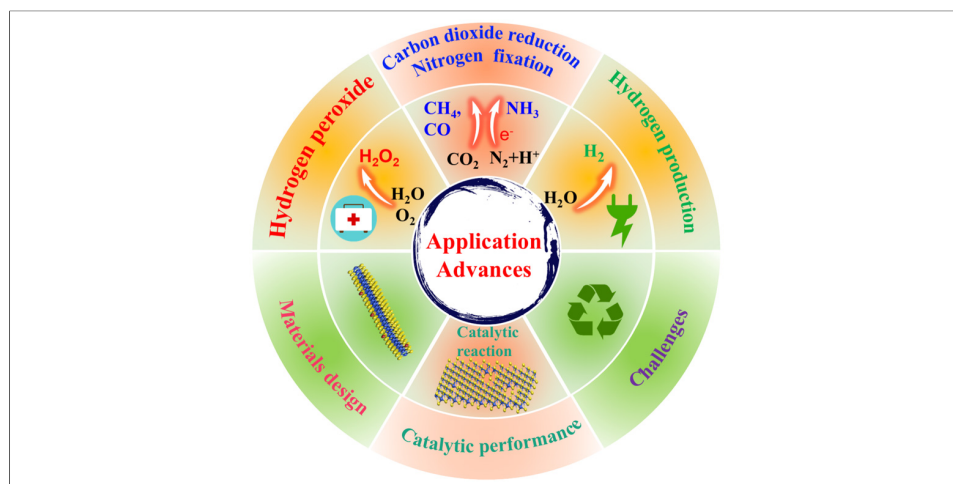
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Abstract

This review summarizes the latest advances in piezocatalysis and tribocatalysis for energy conversion, describing the challenges, potential development directions, and prospects. First, it overviews the evolution and development trends of piezocatalysis and tribocatalysis, the types of mechanical energy, the synthesis methods used to prepare piezocatalysts and tribocatalysts, and the underlying microscopic catalytic mechanisms. Second, it categorizes the catalytic applications, emphasizing recent breakthroughs in key areas such as water splitting for hydrogen production, nitrogen fixation for ammonia synthesis, carbon dioxide reduction, and hydrogen peroxide generation. This section highlights challenges across different application sectors, strategies for catalyst design, and methods for enhancing catalytic performance through microstructure control. Finally, this review discusses recent advances and the development roadmap of piezocatalysis and

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tribocatalysis, addressing current challenges and outlining potential trajectories for future research.

INTRODUCTION

At present, with the continued progress of industrialization, the energy crisis has become a major challenge. The combustion of fossil fuels remains the main energy source, but it rapidly depletes resources, causes serious environmental pollution, poses risks to human health, and hinders the sustainable development of society^[1–3]. Considerably, various catalytic technologies have been explored, such as electrocatalysis, photocatalysis and biocatalysis, which have addressed energy shortages^[4–6].

In this context, catalysis driven by mechanical energy - an abundant and ubiquitous clean energy source - represents a promising advance, as it does not require external inputs such as light or electricity. This approach employs mechanochemical activation to enhance catalytic activity; specifically, mechanical stimuli act as the driving force to facilitate physical or chemical electron transfer processes. The conversion of mechanical energy into chemical energy has been demonstrated through diverse mechanisms, including those based on piezoelectric and triboelectric effects^[7–9]. Consequently, piezocatalysis and tribocatalysis have emerged as advanced, green, and environmentally friendly new catalytic technologies, attracting widespread attention^[10–12]. [Figure 1A](#) shows that the number of publications on piezocatalysis and tribocatalysis has steadily increased in the past five years. As shown in [Figure 1B](#), piezocatalysis and tribocatalysis are mainly applied to hydrogen (H₂) production, carbon dioxide (CO₂) reduction, nitrogen (N₂) fixation and hydrogen peroxide (H₂O₂) synthesis. However, research on tribocatalysis remains in its infancy, and further advances are needed for practical applications.

Piezocatalysis can effectively harness various types of mechanical energy from nature, such as vibrational, wind, and tidal energies, to drive catalytic reactions, showing promising applications potential in energy conversion and environmental remediation^[13,14]. Initially, research on piezocatalysis focused on the degradation of organic pollutants and hydrogen production via water splitting, later evolving to applications in the energy and environmental sectors. Consequently, piezocatalysis has shown good application prospects in areas of energy conversion processes, such as carbon dioxide reduction, nitrogen fixation to synthesize ammonia and peroxide synthesis^[15,16]. As an emerging technology, tribocatalysis has also garnered considerable scientific and technological attention. However, relatively few comprehensive reviews have summarized the applications of piezocatalysis and tribocatalysis in energy conversion.

This review addresses this gap by outlining recent research progress, key challenges, development directions, and future prospects. First, the development of piezocatalysis and tribocatalysis is briefly introduced, with particular attention to the underlying microscopic catalytic mechanisms. Second, their applications are reviewed, highlighting advances in energy-related processes such as H₂ production via water splitting, N₂ fixation to synthesize ammonia, CO₂ reduction, and H₂O₂ synthesis. This section emphasizes key scientific and application challenges, catalyst design, microstructure control and modification strategies for enhancing the catalytic activity. Finally, future perspectives are described.

Overview of piezocatalysis and tribocatalysis

Piezocatalysis is closely associated with the positive piezoelectric effect. In 1880, the Curie brothers observed that applying mechanical stress to certain materials generated positive and negative polarization charges, thereby transforming mechanical energy into electrical energy; this phenomenon was termed the piezoelectric effect. Generally, the positive piezoelectric effect occurs in non-centrosymmetric crystals. Due to structural asymmetry, when an external force is applied to a piezoelectric material in a specific direction,

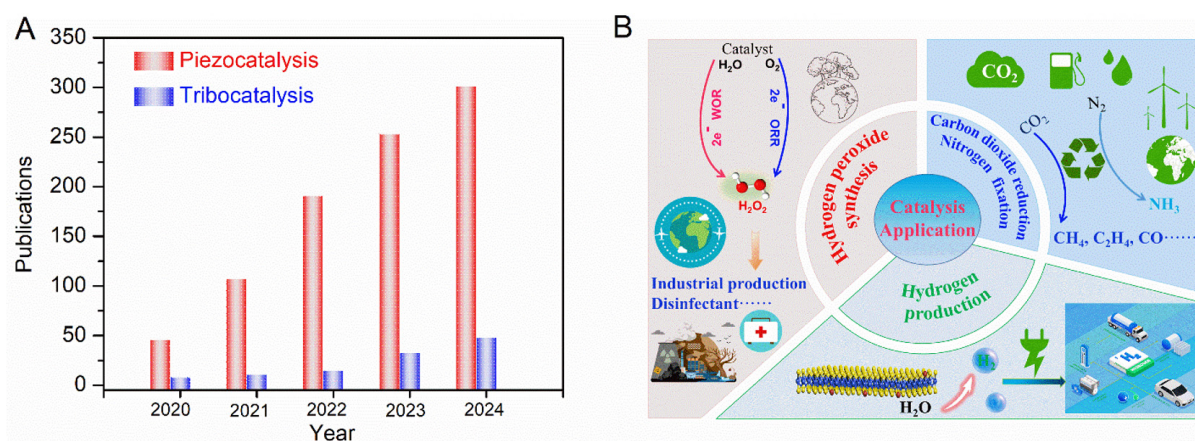


Figure 1. (A) Publications on piezocatalysis and tribocatalysis from 2020 to 2024. The publication numbers were collected from the “webofscience.com” using the keywords “piezocatalysis or piezocatalytic” and “tribocatalysis or tribocatalytic”. (B) Application fields of piezocatalysis and tribocatalysis.

deformation such as compression, stretching, or bending induces polarization charges and generates a built-in electric field. The resulting piezoelectric potential provides sufficient driving force for charge carrier separation, modulation of band bending, and carrier transport, thereby enabling subsequent redox reactions^[13,16–18]. In 2010, Hong *et al.* first employed zinc oxide (ZnO) and barium titanate (BaTiO_3) micro/nanofibers to harvest ultrasonic vibrational energy for hydrogen production via water splitting, introducing the concept of the piezoelectric electrochemical effect, later termed the “piezoelectric catalytic effect”^[19]. In 2012, Hong *et al.* demonstrated the effective degradation of Acid Orange 7 dye using BaTiO_3 -mediated piezocatalysis, marking the first expansion of piezocatalysis applications to environmental remediation^[20]. Since then, numerous studies have investigated the piezocatalytic degradation of organic pollutants. More recently, applications of piezocatalysis have expanded beyond environmental remediation to include nitrogen fixation for ammonia synthesis, carbon dioxide reduction, and hydrogen peroxide synthesis^[21–25].

Currently, the application of piezocatalysis in energy conversion is gradually gaining attention, offering new perspectives for addressing the energy crisis. Despite its promising potential, piezocatalysis still faces limitations such as slow reaction dynamics, low activity, and unclear microscopic mechanisms. To overcome these challenges, various design and modification strategies have been explored in recent years, including the development of novel piezocatalytic material systems, optimization of traditional piezoelectric materials, and microstructural engineering to enhance catalytic performance^[13,16]. Moreover, the applications of piezocatalysis have expanded from initial hydrogen production to diverse fields such as nitrogen fixation for ammonia synthesis, carbon dioxide reduction, hydrogen peroxide synthesis, organic synthesis, and biomass conversion, demonstrating significant practical value in energy storage and conversion. However, systematic reviews of catalyst design, modification strategies, and recent advances in piezocatalysis across different application areas remain limited. Therefore, analyzing and summarizing the latest progress, challenges, and development directions of piezocatalysis in energy conversion will provide valuable guidance and reference for both industry and the scientific community.

Besides, triboelectricity has fascinated researchers for millennia, largely because it can be readily observed in everyday phenomena such as rubbing a balloon on hair^[26]. Building on this foundation, recent insights into tribocatalysis integrate simple electrification processes with advanced catalytic applications. Unlike piezocatalysis, tribocatalysis enables the harnessing of mechanical energy through material contact and separation to drive chemical reactions, without the stringent material requirements of piezoelectric systems.

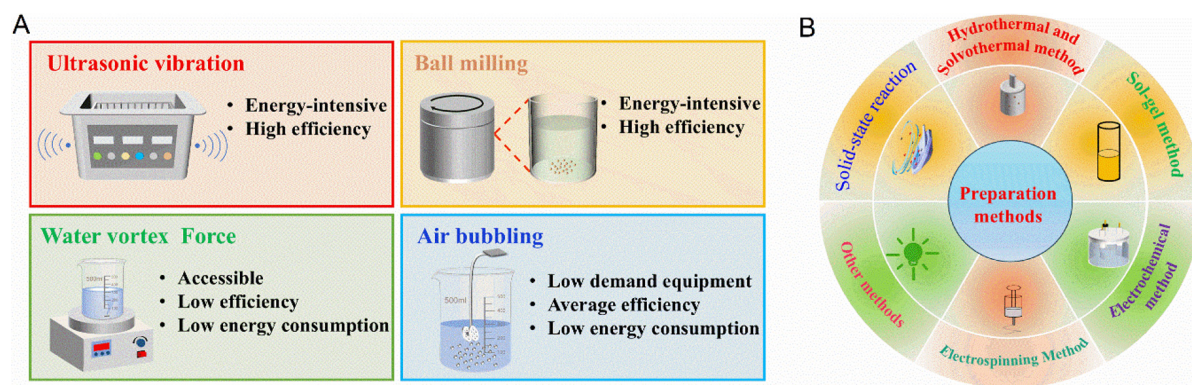


Figure 2. (A) Schematic diagrams of types of mechanical energy for piezocatalysis and tribocatalysis. (B) Preparation methods of piezocatalyst and tribocatalyst.

This distinction underscores its versatility, as tribocatalysis can employ a wide range of materials, thereby broadening opportunities for innovative applications. The recent surge in research interest is likely a response to global challenges such as environmental pollution and the demand for sustainable energy solutions. Tribocatalysis has been investigated for pollutant degradation and energy-related processes including water splitting and CO₂ reduction. The catalytic activity generated by charge transfer at material surfaces can lower the activation energy of chemical reactions, potentially enhancing efficiency^[27,28]. Despite these promising directions, tribocatalysis remains at an early stage of development. Comprehensive reviews and systematic syntheses of findings are needed to advance both understanding and practical applications. As interdisciplinary collaborations among materials science, electrochemistry, and environmental science expand, rapid progress in tribocatalysis can be anticipated. Furthermore, the broad range of applicable materials opens new opportunities for designing and engineering next-generation catalytic systems.

Types of mechanical energy and synthesis methods for piezocatalyst and tribocatalyst

Various forms of mechanical energy - including ultrasound waves, water flow, atmospheric pressure, and wind - can induce periodic deformation of materials^[16]. Predominantly employed methods inducing piezocatalytic and tribocatalytic reactions are ultrasonic vibration, ball milling, air-water vortex force, and air bubbling (see Figure 2A). Ultrasonic vibration, characterized by its high frequency, excellent directionality, robust penetration, and extended transmission distance in water, produces continuous cavitation bubble collapse pressure and ultrasonic wave pressure on materials, leading to periodic deformation^[13,16]. In ultrasonic vibration-driven catalytic systems, several parameters, including ultrasonic power and frequency, profoundly influence the piezocatalytic and tribocatalytic activity. Ultrasonic vibration can effectively trigger these catalytic processes; however, its occurrence in natural settings is rare and its artificial generation is energy-intensive. Despite these drawbacks, research on ultrasonic vibration-driven catalysis has developed sonocatalysis, which leverages sonochemistry by integrating a heterogeneous catalyst into the ultrasonic field. This solid catalyst interacts with ultrasound-induced radicals and absorbs cavitation energy, facilitating chemical reaction control. The underlying mechanism of sonocatalysis is acoustic cavitation, which is dynamic process, encompassing the formation, expansion and subsequent collapse of bubbles. This method enhances the product yield by promoting charge separation and improves product selectivity by modulating the adsorption and desorption of reactants and intermediates. Therefore, sonocatalysis provides a synergistic combination of sonochemical and heterogeneous catalytic effects activated by ultrasound. Its primary applications span wastewater treatment, medical therapies, biomass conversion, and various fields of green and sustainable chemistry^[29]. Notably, the mechanical input for piezocatalysis involves ultrasound, which may obscure the contributions of sonocatalysis to the overall piezocatalytic process. Consequently, sonocatalysis contributes to the piezocatalytic process during ultrasonic activation.

Ball milling is another viable source of mechanical energy that generates frictional heat, which can rapidly elevate local temperatures to hundreds or even thousands of degrees Celsius, subsequently facilitating various chemical reactions, such as bond formation and cleavage^[30]. Thus, ball milling has been leveraged in piezocatalysis and tribocatalysis. In contrast, air bubbling, which drives bubble rupture, represents a low-frequency mechanical force. The bursting of air bubbles provides gentle stimuli with reduced energy consumption, resulting in abrupt changes and chemical energy release at the gas-liquid interface. Air flotation processes facilitate the practical application of bubbling-driven catalysis, rendering air bubbling a promising method for reducing energy usage while enhancing catalytic efficiency. Meanwhile, the water vortex force, another naturally occurring low-frequency mechanical force, can serve as a sustainable and eco-friendly energy source for catalytic reactions. However, the pressure exerted by a water vortex on the catalyst surface is substantially lower than that produced by ultrasonic vibration, further reducing the catalytic efficiency^[30]. In summary, although ultrasonic vibration and ball milling trigger catalytic reactions owing to their higher mechanical energy supply, they are energy-intensive and less suitable for large-scale wastewater treatment. Conversely, water vortex force and air bubbling, as prevalent forms of mechanical energy, are promising driving forces of piezocatalysis and tribocatalysis for practical applications. As a consequence, improving efficiency of low-frequency force-driven catalysis is a challenging but encouraging research task.

The catalytic performance of piezocatalysts and tribocatalysts is intricately linked to various factors, including microstructure, crystal structure, surface state, and internal charge distribution, depending on the catalyst synthesis methods^[31]. Figure 2B illustrates the frequently used preparation methods for piezocatalysts and tribocatalysts. For example, the solid-state reaction strategy involves the simple processing of raw materials to obtain ultra-fine powders, subsequently subjected to high-temperature treatment. This classical approach is favored for its low cost, high yield, and relatively straightforward and stable preparation process. High-temperature solid-state sintering furnishes piezocatalysts with excellent piezoelectric properties. In addition, this process facilitates the incorporation of doping elements into the catalyst lattice, thereby enabling catalyst modification. However, despite being well-established and easy to implement, the solid-state sintering process has some drawbacks: high energy consumption and excessive use of organic solvents during raw material mixing. Consequently, developing solvent-free solid-state processes matching the performance of traditional methods is a focus of research^[31].

Additionally, numerous traditional material systems have been explored for piezocatalysts and tribocatalysts. The hydrothermal method, which involves inorganic synthesis and material treatment in a closed reactor using an aqueous solution, creates a relatively high-temperature and high-pressure reaction environment by heating and pressurizing the reaction system, allowing for the dissolution and recrystallization of insoluble substances. This method produces samples that are well-developed and uniformly distributed, minimizing impurity introduction and maintaining catalyst activity^[28,31]. A multitude of catalytic materials systems has been successfully synthesized via hydrothermal methods, demonstrating the high applicability and reliability of this technique. Key system parameters in hydrothermal reaction, including reaction time, temperature, pH value, precursor characteristics and concentration, are crucial determinants of catalyst synthesis. Similarly, solvothermal synthesis follows the same principle as the hydrothermal method, but utilizes organic or non-aqueous solvents (e.g., organic amines, alcohols, ammonia, or benzene) in place of water. This approach is particularly beneficial for the preparation of materials that cannot be synthesized in aqueous solution due to their susceptibility to oxidation, hydrolysis, or water-related issues. The choice of solvents influences the material performance of the synthesized products. Furthermore, because organic solvents typically possess a lower boiling point, they can achieve higher pressure than those attainable in hydrothermal synthesis under similar conditions, promoting favorable crystallization of the products. In addition, the functional groups of these solvents may interact with the reactants or products, resulting in the formation of new materials with

potential applications in catalysis and energy storage.

Fundamental principles of piezocatalysis and tribocatalysis

To effectively enhance the performance of piezocatalytic materials, a deep understanding of the microscopic mechanisms is crucial for their design and optimization. However, despite over a century of development in piezoelectric materials, research in the field of catalysis is still in its infancy. The dominant theories of piezocatalytic mechanisms currently include energy band theory and the screening charge effect^[32,33]. Energy band theory, similar to the mechanisms of photocatalysis, asserts that the ability to undergo catalytic reactions primarily depends on the energy levels of the band structure [valence band (VB) and conduction band (CB)]. In contrast, the screening charge effect highlights the interaction between the piezoelectric potential and external screening charges from adsorbed species. Energy band theory, derived from established photocatalytic and piezoelectric electronics theories, is more comprehensive^[32,34]. It is generally believed that the source of charge carriers in piezocatalytic reactions primarily arises from stress or the excitation of intrinsic free charges in the material. In this theory, the band structure of the piezoelectric catalyst and the excitation state of electrons are key determinants of catalytic activity. The piezocatalytic reaction occurs due to internal piezoelectric potential induced by the deformation of the piezoelectric material, which can exert control over the band structure, thereby favorably adjusting the energy levels towards oxidative and reductive reactions. Established band theory can explain the structure-activity relationships in different redox reactions^[35,36].

Unlike band theory, the screening charge effect mechanism focuses on the dominant effect of piezoelectric potential and surface screening charge behavior in piezoelectric materials. The accumulation and release of surface charges generated during the polarization process of piezoelectric materials are key processes that promote piezocatalytic reactions, with the piezoelectric potential regarded as the main driver of redox reactions. The magnitude of the piezoelectric potential should fully match the chemical energy required for redox reactions, thereby determining the capability of the piezocatalyst to drive these reactions^[31,37]. Furthermore, the charge carrier sources in the reaction processes of the two mechanisms are also different. Energy band theory posits that the primary source of reaction charges is internal charges excited by mechanical vibrational energy or defects, while the screening charge effect mechanism attributes the oxidative and reductive catalytic reactions to externally induced screening charge. Overall, both mechanisms have certain similarities and differences in specific aspects^[13,16,38]. Both energy band theory and screening charge effect can be used independently to explain relevant piezocatalytic experimental results. However, it has been reported that most piezoelectric materials possess a wide band gap greater than 2.0 eV. On the one hand, this characteristic of highly insulating materials supports the screening charges theory. On the other hand, if free charge carriers are available, the conduction and VB positions can be suitable for many catalytic reactions. Therefore, both mechanisms do most probably exist simultaneously in most piezoelectric materials, which is fundamentally the reason for the ongoing debate regarding piezocatalytic mechanisms. Furthermore, it is important to differentiate between piezocatalysis and flexocatalysis. The driving force behind flexocatalysis is flexoelectricity, a fundamental electromechanical property characterized by the electrical polarization of a material under inhomogeneous strain, such as mechanical bending. Unlike the piezoelectric effect, flexoelectricity can occur in both centrosymmetric materials - via the breaking of local centrosymmetry - and in materials with asymmetric structures. Flexocatalysis has the advantage of being applicable to a wide range of non-piezoelectric and piezoelectric materials. However, it is worth noting that flexocatalysis can also contribute to the piezocatalysis process under certain conditions. Clarifying the mechanisms of piezocatalysis is therefore crucial for designing efficient piezocatalysts. To this end, advanced *in situ* experimental characterization techniques and theoretical methods (e.g., first-principles calculations and multiphysics simulations) should be employed to study variations of charges and carriers during piezocatalytic processes. These approaches can elucidate how factors such as piezoelectric potential, charge

and carrier separation and migration, electronic structure, and active sites influence the performance of piezocatalytic materials, thereby enabling the design of high-performance piezocatalysts.

Currently, researchers have elucidated two primary mechanisms for tribocatalysis reactions: electron transfer across atoms and electron transition^[39]. In the electron transfer mechanism, mechanical force induces friction between the catalyst and the surrounding solid or liquid environment, facilitating electron transfer. The transferred electrons participate directly in the chemical reactions that characterize tribocatalysis. Materials that either gain or lose electrons contribute to the generation of active species, which are essential for subsequent redox reactions. Conversely, the electron transition mechanism involves mechanical energy exciting electrons from the VB to the CB, resulting in the formation of holes in the VB and free electrons in the CB^[28,39]. This process generates free radicals that interact with water and oxygen in the environment to drive tribocatalytic reactions. The generation of electrons and holes is primarily dictated by the energy band structure of the catalyst. Electron transfer across atoms is commonly invoked to explain tribocatalysis in polymer catalytic materials, which exhibit a strong capacity to acquire electrons through friction. In contrast, the electron transition mechanism is utilized in the analysis of tribocatalytic performance for semiconductor catalysts with well-defined energy band structures^[26,39]. As for whether the electron transition is through the direct action of friction energy or the action of thermal energy, there is no clear conclusion yet. Kajdas proposed a theory that the flash point temperature during friction causes electron emission. Although it still lacks quantitative analysis and experimental verification, it provides a possible theoretical support for the tribocatalysis theory^[40]. Thus, a deeper investigation into the relationship between these two mechanisms is essential for a more accurate understanding of the overall tribocatalysis mechanism.

Tribocatalysis represents an emerging technology capable of converting mechanical energy into chemical energy, offering a promising solution for environmental and energy crises and contributing to the pursuit of a sustainable society. Nevertheless, further advances in tribocatalysis are necessary for practical applications. A comprehensive understanding of the underlying mechanisms is critical, as it would assist researchers in identifying key factors involved in material selection and system design. The proposed mechanistic models approach tribocatalysis from different angles, yet these mechanisms may coexist within a single tribocatalytic process. Clarifying them will help researchers identify the predominant processes in specific material systems and simplify the complex aspects of tribocatalysis into manageable components. Addressing these complexities systematically is crucial for the continued development of tribocatalysis and will significantly advance the progress and practical applications of this promising technology.

PIEZOCATALYSIS AND TRIBOCATALYSIS FOR ENERGY CONVERSION APPLICATIONS

Application of piezocatalysis and tribocatalysis in water splitting for hydrogen production

Hydrogen energy, as a clean, efficient, safe, and sustainable renewable energy source, is beneficial for alleviating current issues such as the energy crisis. However, hydrogen is mainly synthesized via fossil fuels such as coal and oil, which leads to the over-consumption of non-renewable energy and causes serious environmental pollution problems. Therefore, developing new environmentally friendly, readily available and cost-effective hydrogen production strategies is crucial^[41]. Recently, various hydrogen production technologies have been explored, including electrocatalysis, photocatalysis and photo-electrocatalysis, which are based on the conversion of different types of energy, such as electrical and solar energy, into chemical energy through a series of reactions^[42–44].

Piezocatalysis has recently attracted increasing attention for hydrogen production under environmentally friendly and mild reaction conditions^[16]. To date, research has led to the development of numerous piezocatalysts for hydrogen production, including single or composite perovskite-based materials (e.g., BaTiO₃ and SrTiO₃), bismuth-based materials (e.g., BiFeO₃ and Bi₂WO₆), metal sulphide/selenide-based

materials (e.g., MoS₂ and Au@MoS₂) and polymer-based materials (e.g., UiO-66(Zr) and poly(vinylidene fluoride) (PVDF)) and more^[45–54]. For instance, You *et al.* found that the limitation of the CB position in traditional BiFeO₃ nanosheets could be overcome by inducing band bending via ultrasonic vibration, achieving a high hydrogen production rate of 124.1 $\mu\text{mol g}^{-1} \text{h}^{-1}$ ^[47]. Our group also reported various materials exhibiting excellent hydrogen production (e.g., O-MoS₂, Ce-BiOBr and BiOCl/UiO-66)^[49,55,56]. These studies confirm the promising applications of piezocatalysis for hydrogen production.

However, further advances in hydrogen production via piezocatalysis are limited by issues such as low activity, poor stability, and challenges in recycling and reuse of the piezocatalyst. To address these limitations, various strategies have been employed to enhance piezocatalyst performance, including optimization of sacrificial agents, doping engineering, loading of co-catalysts, construction of composite or heterojunction materials, and coupling with other catalytic technologies such as photocatalysis. Figure 3A summarizes material design approaches and modification strategies for hydrogen production, while Table 1 presents relevant performance metrics^[57–70].

Selecting appropriate modification strategies is crucial for developing and designing highly active piezocatalysts for hydrogen production^[16,71]. First, in the absence of sacrificial agents, tuning the piezocatalyst size to obtain ultra-thin structures can substantially shorten charge migration pathways. This adjustment not only provides abundant surface dangling bonds conducive to the separation and reaction of surface charges during piezocatalytic reactions but also induces the creation of active catalytic sites, enhancing the performance compared with other modification strategies^[72,73]. For instance, Su *et al.* found that the hydrogen production rate increased approximately by 130-fold when the BaTiO₃ particle size was decreased from 200 to 10 nm, achieving rates as high as 655 $\mu\text{mol g}^{-1} \text{h}^{-1}$ ^[72]. Furthermore, the construction of composite structures can greatly enhance the hydrogen production activity of piezoelectric materials. For example, Feng and colleagues encapsulated MoC quantum dots in nitrogen-doped graphene film bubbles (NG) to create a MoC@NG structure, achieving a hydrogen production rate of up to 1,690 $\mu\text{mol g}^{-1} \text{h}^{-1}$ ^[74]. This is currently the highest reported rate for piezocatalytic water splitting under sacrificial agent-free conditions, even outperforming similar photocatalytic material systems. Moreover, crystal defects, which considerably influence the physical and chemical properties of materials, can modify the electronic structure, enhance the dynamic transport of charge carriers and create highly active sites, thereby improving the catalytic performance^[75]. Furthermore, introducing vacancies or dislocations typically results in distortion of the lattice structure, which in turn enhances the catalytic performance^[31,76]. Zhang *et al.* successfully prepared high-dislocation density materials by introducing defects into single crystals of BaTiO₃ at elevated temperatures^[76]. These deformed BaTiO₃ crystals exhibited enhanced piezoelectric response, improved charge carrier transport capabilities, and an optimal hydrogen adsorption free energy, remarkably boosting water splitting efficiency for hydrogen production (53.8 $\text{mmol h}^{-1} \text{m}^{-2}$). Additionally, the dislocations served as catalytically active centers, with the stress and strain fields surrounding the dislocations considerably contributing to the activity. Figure 3B illustrates the hydrogen production mechanisms in the deformed crystals^[76].

To suppress the electron-hole recombination, hole scavengers such as methanol (CH₃OH), triethanolamine (TEOA), sodium sulfide (Na₂S), and sodium sulfite (Na₂SO₃) are usually added as sacrificial agents to trap the generated holes, thereby enhancing the piezocatalytic performance^[16,31]. For example, Du *et al.* found that the hydrogen production rate over Bi₂Fe₄O₉ nanosheets was 1,058 $\mu\text{mol g}^{-1} \text{h}^{-1}$ under sacrificial agent-free conditions but increased to 5,723 $\mu\text{mol g}^{-1} \text{h}^{-1}$ when using methanol as a sacrificial agent^[57]. Our group also constructed the Ti₃C₂T_x/Bi₂WO₆ Schottky junction and demonstrated a good piezocatalytic hydrogen evolution rate of 764.4 $\mu\text{mol g}^{-1} \text{h}^{-1}$ for optimal content Ti₃C₂T_x/Bi₂WO₆ under appropriate sacrificial agents, which is nearly eight times higher than that of pure Ti₃C₂T_x and twice that of Bi₂WO₆. Furthermore,

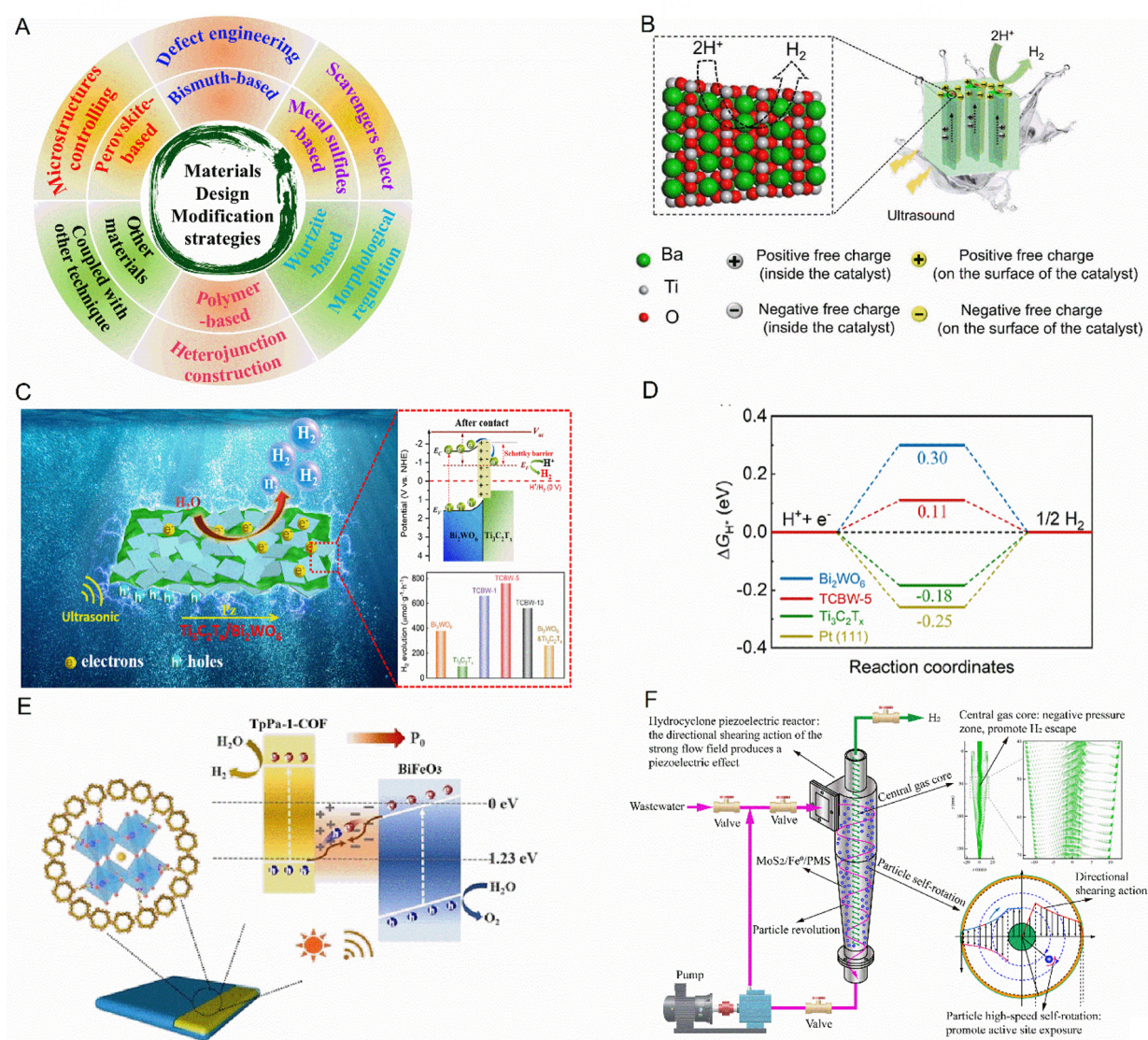


Figure 3. (A) The summary of typical piezocatalytic materials design and modification strategies for H_2 production. (B) Piezocatalytic mechanism for H_2 production of the deformed $BaTiO_3$ crystals. This figure is quoted with permission^[76]. (C and D) Piezocatalytic mechanism for H_2 production in $Ti_3C_2T_x/Bi_2WO_6$ and Gibbs free energy changes of intermediate states involved in HER processes. This figure is quoted with permission^[77]. (E) A schematic illustration of piezo-photocatalysis mechanism with the different directions of polarization for $BiFeO_3@TpPa-1-COF$ Z-scheme heterojunction. This figure is quoted with permission^[86]. (F) The designed cyclonic piezocatalytic reactor using $MoS_2/Fe^0/PMS$ ternary system for achieving substantial H_2 generation from various types of wastewater. This figure is quoted with permission^[91].

experimental results and density functional theory (DFT) calculations indicate that this Schottky junction created unique pathways for an efficient electron transfer, enhances the piezoelectric properties, optimizes the Gibbs free energy of water adsorption, lowers the activation energy for hydrogen atoms and ensures an efficient charge carrier separation [Figure 3C and D]^[77]. Collectively, these factors enhance the efficiency of the hydrogen evolution reaction. Therefore, selecting sacrificial agents is an effective method for improving the hydrogen production performance of piezocatalysts.

A heterojunction is typically defined as the interface between two distinct semiconductors with different band structures and, consequently, specific band alignments. Heterojunction catalysts can be divided into four types: straddling gap (type-I), staggered gap (type-II), zigzag scheme (Z-scheme) and step scheme

Table 1. Summary of the energy conversion for H₂ production application of piezocatalysis and tribocatalysis

Catalyst	Application type	Sacrificial agent	Conditions	H ₂ evolution (μmol g ⁻¹ h ⁻¹)	Ref.
Bi ₂ Fe ₄ O ₉	Piezocatalysis	None	200 W, 40 kHz	1,058	[57]
O-MoS ₂	Piezocatalysis	None	100 W, 40 kHz	47.8	[58]
V-NaNbO ₃	Piezocatalysis	None	192 W, 68 kHz	346.2	[59]
Au-Bi ₄ Ti ₃ O ₁₂	Piezocatalysis	None	100 W, 40 kHz	194.7	[60]
RbBiNb ₂ O ₇ /PTFE	Piezocatalysis	None	240 W, 68 kHz	260.8	[61]
SrTiO ₃	Piezocatalysis	None	300 W, 40 kHz	540	[62]
La ₂ NiO ₄	Piezocatalysis	None	300 W Xe lamp + 100 W, 40 kHz	1,097	[63]
g-C ₃ N ₄	Piezocatalysis	None	λ ≥ 420 nm + 240 W, 40 kHz	12,160	[64]
CH ₃ NH ₃ PbI ₃	Piezocatalysis	HI	70W	2.2	[65]
CH ₃ NH ₃ PbI ₃	Piezocatalysis	HI	500 W lamp + 70 W	23.3	[65]
BaTi _{0.89} Sn _{0.11} O ₃	Piezocatalysis	Triethanolamine	120 W, 40 kHz	141.1	[66]
Ag-BaTi _{0.89} Sn _{0.11} O ₃	Piezocatalysis	Triethanolamine	120 W, 40 kHz	360.2	[66]
Li-BaTiO ₃	Piezocatalysis	Triethanolamine	300 W Xe lamp + 100 W, 40 kHz	3,704	[67]
CaTiO ₃	Piezocatalysis	Methanol	250 W, 40 kHz	3,440	[68]
BaTiO ₃	Piezocatalysis	Methanol	180 W, 35 kHz	305	[69]
ZnSnO ₃	Piezocatalysis	Methanol	250 W, 40 kHz	3,453.1	[70]
Ba _{0.75} Sr _{0.25} Nb _{1.9} Ta _{0.1} O ₆	Tribocatalysis	None	Magnetic stirring	200	[95]

(S-scheme)^[78–82]. The construction of different heterojunctions can modulate the band structure, facilitating charge carrier separation and transfer and reducing electron-hole recombination, thereby enhancing the piezocatalytic activity. Various heterostructures have been reported, such as Bi₂MoO₆/BaTiO₃, FeCo-LDH@ZnO, ZnO/ZnS/MoS₂, ZnO/SrTiO₃, BiFeO₃@COF and CdS/BiOCl^[16,79,82–87]. For example, Xu *et al.* constructed a core-shell BiFeO₃@TpPa-1-COF Z-scheme heterojunction, which effectively altered the band structure by generating a piezoelectric field, thereby promoting the separation of carriers and lowering the Gibbs free energy of forming *H during the hydrogen evolution reaction, as revealed by first-principles calculations, achieving a hydrogen production rate of up to 1,416.4 μmol g⁻¹ h⁻¹^[86]. Figure 3E depicts a schematic of the piezo-photocatalysis mechanism with different polarization directions for the BiFeO₃@TpPa-1-COF Z-scheme heterojunction^[86]. Our group constructed CdS/BiOCl S-scheme heterojunction piezocatalysts for the first time, demonstrating a superior piezocatalytic H₂ generation rate of 1,048.2 μmol g⁻¹ h⁻¹, which is 2.3 and 3.4 times higher than those of pure BiOCl and CdS, respectively^[87].

Moreover, the loading or deposition of metal nanoparticles can remarkably promote the generation and interfacial transfer of carriers, thereby lowering the activation energy barrier for the piezocatalytic interfacial reaction and improving the catalytic efficiency^[88–90]. For instance, loading metal nanoparticles such as Pt, Pd, and Au onto the surface of piezocatalysts can endow them with higher carrier concentration and charge separation efficiency, effectively adjusting the band structure between catalyst and metal. This further enhances the electronic transfer at the material interface, increasing the piezocatalysts activity, as confirmed for relevant material systems such as BiFeO₃/Pd, Au@MoS₂, Au/ZnO and Ag@BaTi_{0.99}Sn_{0.11}O₃^[66,88–90]. Notably, combining the aforementioned individual modification methods with other strategies such as doping engineering, defect engineering and photocatalysis can greatly enhance the hydrogen production activity of piezocatalysts^[31,86,90].

Towards the industrialization of piezocatalysis application, Liu *et al.* coupled piezocatalysis with advanced

oxidation processes using the MoS_2/Fe^0 /peroxymonosulfate (PMS) ternary system, achieving a substantial H_2 production rate of $(901.0 \mu\text{mol g}^{-1} \text{h}^{-1})$ from various types of wastewater^[91]. Moreover, a cyclonic piezocatalytic reactor was designed to replace the ultrasonic action in the induction of the piezoelectric effect [Figure 3F]. This strategy offers a valuable pathway for wastewater recycling via fuel production and concurrent advanced treatment, contributing to carbon neutrality in energy conversion and environmental remediation. Compared with the investigation of piezocatalytic hydrogen production, reports on tribocatalysis are scarce. For example, Zhu *et al.* utilized $\text{Ba}_{0.75}\text{Sr}_{0.25}\text{Nb}_{1.9}\text{Ta}_{0.1}\text{O}_6$ powder to generate hydrogen via tribocatalysis, reaching a $15,892.8 \mu\text{mol g}^{-1}$ after 72 h of stirring, with an average production rate of $200 \mu\text{mol g}^{-1} \text{h}^{-1}$ ^[92]. This study highlights the potential of ferroelectric materials in tribocatalysis.

Overall, the piezocatalytic hydrogen production technology has rapidly developed over the past decade, considerably improving the piezocatalytic activity using optimized design strategies and achieving important research advances. However, further fundamental knowledge on the microscopic processes and intrinsic mechanisms of piezocatalysis is still required to enhance the piezocatalytic hydrogen production performance. Therefore, advanced *in situ* characterization techniques should be developed to delve into the complex catalytic reaction steps and charge transfer mechanisms to clarify the roles of charges and carriers in piezocatalytic reactions and the microscopic mechanisms. Further research on the tribocatalytic H_2 production will enable the development of improvement strategies towards practical applications. Notably, predictive models for catalytic materials, performance and modification strategies can be scientifically established using machine learning algorithms based on existing data on piezocatalytic and tribocatalytic performance. This approach will help select, predict and design high-performance catalysts and new catalyst systems.

Application of piezocatalysis and tribocatalysis for nitrogen fixation to ammonia synthesis

Ammonia is an important chemical raw material and a primary component of synthetic nitrogen fertilizers. Additionally, it is considered a sustainable fuel for achieving a global transition to clean energy^[93–95]. Currently, the primary method for synthetic ammonia production is the Haber-Bosch process, which catalytically combines hydrogen and nitrogen under high temperature and pressure conditions to produce ammonia gas. This method produces approximately 450 million tons of ammonia annually worldwide; however, it demands very stringent conditions and results in high energy consumption and pollutant emissions, which is not conducive to sustainable development strategies. Therefore, searching for a green, energy-efficient, and effective method for ammonia synthesis is crucial for sustainability.

Currently reported photocatalytic nitrogen fixation offers advantages such as being green and sustainable, operating under mild reaction conditions, and featuring low energy consumption and cost. However, it still faces challenges, including complex mass transfer steps of nitrogen gas reactants, limitations imposed by the oxidation-reduction capabilities of photogenerated electrons and holes, and low efficiency of charge carrier utilization^[96]. Electrocatalytic nitrogen fixation also offers low energy consumption, controllable reaction conditions, simple equipment, and environmental friendliness, but it faces limitations such as low Faradaic efficiency, low ammonia conversion efficiency, and susceptibility to external contamination^[97,98]. Thus, finding a more suitable nitrogen fixation for ammonia synthesis is vital for advancing the industrial development of green synthetic ammonia.

In recent years, with the extensive reporting of piezocatalysis in the field of energy conversion and water splitting applications, research on the application of piezocatalytic nitrogen fixation has gradually attracted increasing attention^[24]. Utilizing piezocatalysis for nitrogen fixation can break through the constraints of material band structures and energy level positions through the generated piezoelectric potential, effectively overcoming the thermodynamic energy barriers of chemical reactions, thus achieving effective nitrogen

fixation. Currently, research related to piezocatalytic nitrogen fixation is limited, primarily focusing on material systems such as $\text{KTa}_{0.75}\text{Nb}_{0.25}\text{O}_3$ (KTN), ZnO , Bi_2O_3 , I and Bi_2WO_6 [24,99–104]. However, the main challenges faced by most piezocatalysts in nitrogen fixation include weak adsorption of N_2 on the catalyst surface, a lack of sufficient reactive active sites during ammonia synthesis, and low charge carrier utilization efficiency. Thus, it is essential to design nitrogen fixation materials that possess excellent piezocatalytic performance alongside high catalytic activity. Typically, some methods such as composite formation, defect engineering, nanoparticle modification and heterojunction are employed to enhance the performance of piezocatalytic nitrogen fixation, as summarized in Table 2 [24,100–103]. For example, Chen *et al.* (2021) prepared 0.25% $\text{Bi}_2\text{S}_3/\text{KTN}$ nanocomposites and found that the ammonia synthesis rate via piezocatalysis was $14.9 \mu\text{mol L}^{-1} \text{g}^{-1} \text{h}^{-1}$, which was 4.0 and 6.4 times that of KTN and Bi_2S_3 , respectively [24]. This study confirmed that $\text{Bi}_2\text{S}_3/\text{KTN}$ could be utilized in piezocatalytic nitrogen fixation applications. Furthermore, Peng *et al.* designed and prepared oxygen-deficient ZnO rods and Ag-modified ZnO nanorods using defect introduction and nanoparticle modification strategies to study their activity, selectivity, and stability in piezocatalytic nitrogen fixation, as shown in Figure 4A [100]. It was confirmed that the oxygen vacancies on the ZnO surface could serve as active sites for N_2 adsorption and activation, effectively promoting the nitrogen fixation reaction and thereby enhancing piezocatalytic activity. Simultaneously, loading Ag nanoparticles onto ZnO enhanced the chemical adsorption of N_2 and effectively promoted the separation of electrons and holes, further improving its nitrogen fixation and ammonia synthesis performance. Additionally, Dai *et al.* synthesized CuS/KTN nanocomposites and reported that the optimized ratio of CuS/KTN had a piezocatalytic ammonia synthesis rate of $36.2 \mu\text{mol L}^{-1} \text{g}^{-1} \text{h}^{-1}$, which is 7.4 times that of pure KTN, with satisfactory performance attributed to CuS effectively capturing electrons, extending electron lifetimes, and accelerating nitrogen fixation reaction, thereby enhancing catalytic activity [101]. This research provides significant insights for designing active piezoelectric catalysts for nitrogen fixation and improving the nitrogen fixation performance of materials. Recently, our group designed $\text{CdS}/\text{Bi}_2\text{WO}_6$ S-scheme heterojunction piezocatalyst and demonstrated exceptional piezocatalytic nitrogen reduction reaction activity ($1.37 \text{ mmol L}^{-1} \text{g}^{-1} \text{h}^{-1}$), which is significantly higher compared to pure CdS ($0.06 \text{ mmol L}^{-1} \text{g}^{-1} \text{h}^{-1}$) and bare Bi_2WO_6 ($0.45 \text{ mmol L}^{-1} \text{g}^{-1} \text{h}^{-1}$), showing an almost 23-fold and 3-fold increase, respectively. This performance greatly exceeds previously reported piezocatalysts and piezo-photocatalysts. Relevant experimental and DFT calculation results verified that the excellent catalytic performance of $\text{CdS}/\text{Bi}_2\text{WO}_6$ was mainly attributed to significantly enhanced piezoelectric properties, improved charge-carrier separation and redox capacity, regulated electronic structure, optimized reaction dynamics, reduced reaction barriers, and the generation of additional active sites, as illustrated in Figure 4B [103]. This research extends the applications of S-scheme heterojunction in sustainable energy piezocatalysis and offers insights for designing efficient piezocatalysts systems.

Moreover, coupling individual modification strategies with photocatalysis can significantly enhance the performance of piezoelectric nitrogen fixation [99,101,104]. Recently, Chen *et al.* synthesized $\text{Ag}_2\text{S}/\text{KTN}$ composites and studied their piezocatalytic, photocatalytic, and piezo-photocatalytic nitrogen fixation performance [104]. They found that under illumination and ultrasonic vibration conditions, the ammonia synthesis rate for 0.5% $\text{Ag}_2\text{S}/\text{KTN}$ reached $225.2 \mu\text{mol L}^{-1} \text{g}^{-1} \text{h}^{-1}$, which is much higher than the combined activities of photocatalysis and piezocatalysis ($167.7 \mu\text{mol L}^{-1} \text{g}^{-1} \text{h}^{-1}$), indicating a significant synergistic effect [104]. This outstanding performance is attributed to Ag_2S nanoparticles improving the charge carrier separation on the KTN surface through type II mechanism. This finding illustrates the effectiveness of employing multiple strategies in enhancing piezocatalytic nitrogen fixation performance. Moreover, Yuan *et al.* combined defect catalysis with piezocatalysis to achieve unprecedented piezo-photocatalytic NH_3 evolution rate activity ($106.7 \mu\text{mol g}^{-1} \text{h}^{-1}$) by regulating the oxygen defects in BaTiO_3 , as depicted in Figure 4C [105]. The adsorption state of N_2 and the N_2 reduction reaction pathway on BaTiO_3 and $\text{BaTiO}_3\text{-O}_v$ were demonstrated via *in situ* diffuse reflectance infrared Fourier-transform spectroscopy (DRIFTS). The

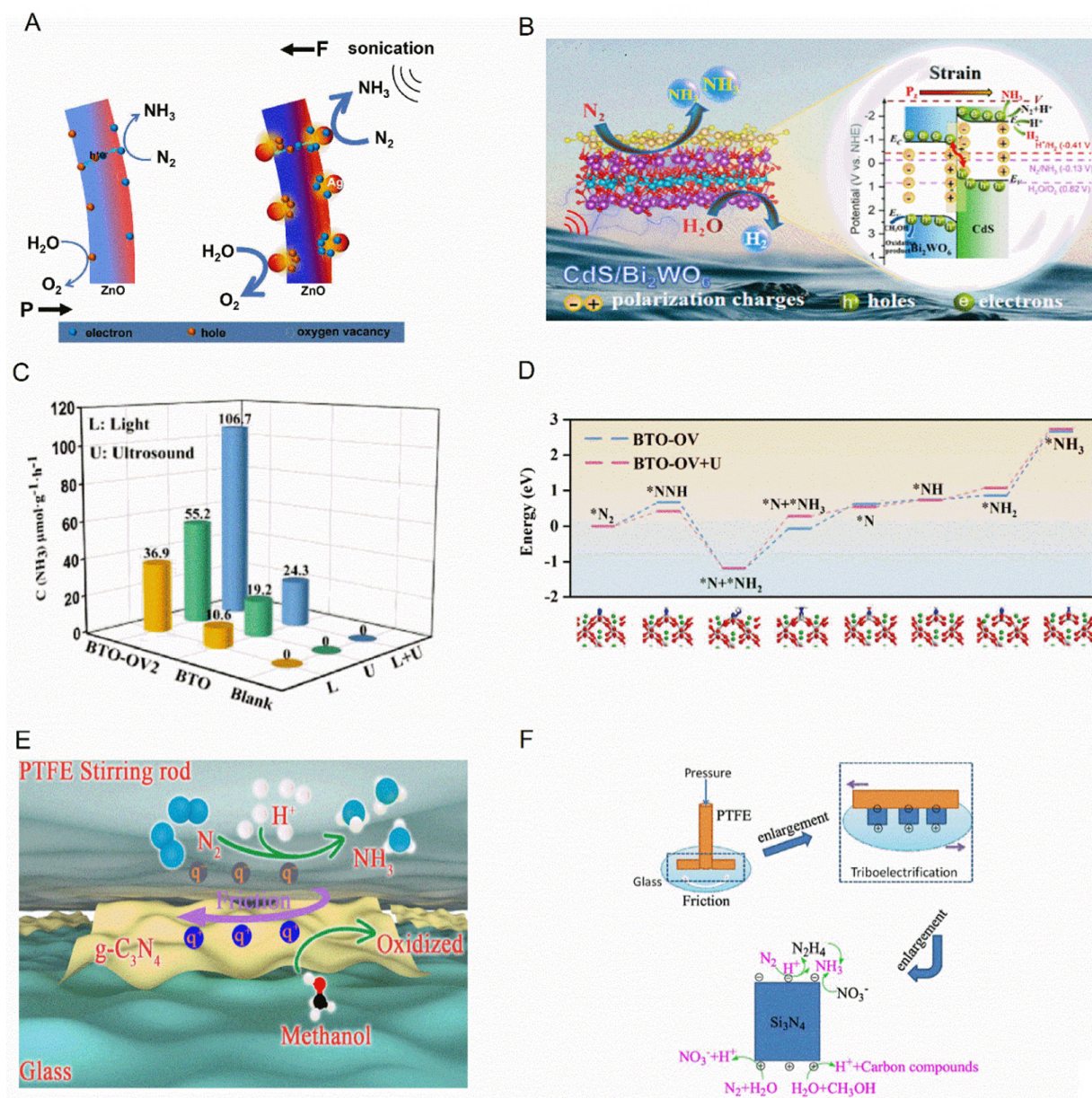


Figure 4. (A) Mechanism diagram of piezoelectric nitrogen fixation for ZnO-based catalysts. This figure is quoted with permission^[100]. (B) Piezocatalytic N₂ reduction for NH₃ yield versus time and schematic illustration for piezocatalytic mechanism of CdS/Bi₂WO₆. This figure is quoted with permission^[103]. (C and D) NH₃ production rate of blank, BTO, and BTO-OV under L, U, and L + U irradiation in the presence of sodium sulfide/sodium sulfite as sacrificial agent and reaction free energy diagrams of BTO-OV and BTO-OV + U. This figure is quoted with permission^[105]. (E) Schematic diagram of tribocatalytic nitrogen fixation by g-C₃N₄. This figure is quoted with permission^[106]. (F) Schematic diagram of tribocatalytic nitrogen fixation by Si₃N₄. This figure is quoted with permission^[107].

relevant experimental and density function theory calculations results indicated that the introduction of oxygen defects affected the local dipole state of BaTiO₃, enhanced its piezoelectric polarization, regulated the electronic structure of Ti³⁺, promoted the activation and dissociation of N₂ molecules, and significantly reduced the rate determining step energy barrier of nitrogen fixation reaction, as shown in Figure 4D^[105].

Compared to research on piezocatalytic nitrogen fixation, relatively few studies have focused on harnessing mechanical energy via tribocatalysis for nitrogen reduction to produce ammonia^[106,107]. For the first time, Wu *et al.* employed C₃N₄ as a catalyst to investigate the performance of tribocatalytic nitrogen fixation

Table 2. Summary of the energy conversion for N₂ fixation, CO₂ reduction and H₂O₂ production applications of piezocatalysis and tribocatalysis

Catalyst	Reaction condition	Application	Reaction product and rate	Ref.
Bi ₂ S ₃ /KTa _{0.75} Nb _{0.25} O ₃	Piezocatalysis	N ₂ fixation	NH ₃ , 14.9 μmol L ⁻¹ g ⁻¹ h ⁻¹	[24]
ZnO	Piezocatalysis	N ₂ fixation	NH ₃ , 21.4 μmol L ⁻¹ g ⁻¹ h ⁻¹	[100]
CuS/KTa _{0.75} Nb _{0.25} O ₃	Piezocatalysis	N ₂ fixation	NH ₃ , 36.2 μmol L ⁻¹ g ⁻¹ h ⁻¹	[101]
Ag/Bi ₅ O ₇ I	Piezocatalysis	N ₂ fixation	NH ₃ , 99.1 μmol L ⁻¹ g ⁻¹ h ⁻¹	[102]
Ag ₂ S/KTN	Piezocatalysis	N ₂ fixation	NH ₃ , 225.2 μmol L ⁻¹ g ⁻¹ h ⁻¹	[104]
g-C ₃ N ₄	Tribocatalysis	N ₂ fixation	NH ₃ , 100.56 μmol g ⁻¹ h ⁻¹	[106]
Si ₃ N ₄	Tribocatalysis	N ₂ fixation	NH ₃ , 254.68 μmol g ⁻¹ h ⁻¹	[107]
(K _{0.5} Na _{0.5}) _{0.97} Li _{0.03} NbO ₃ (KNLN)	Piezocatalysis	CO ₂ reduction	CO, 438 μmol g ⁻¹ h ⁻¹	[115]
BiFeO ₃	Piezocatalysis	CO ₂ reduction	CH ₄ , 17.9 μmol g ⁻¹ h ⁻¹	[116]
BiFeO ₃	Piezo-photocatalysis	CO ₂ reduction	CO, 28.7 μmol g ⁻¹ h ⁻¹	[116]
Nb@Pb _{0.99} (Zr _{0.95} Ti _{0.05}) _{0.98} Nb _{0.02} O ₃	Piezocatalysis	CO ₂ reduction	CO, 789 μmol g ⁻¹ h ⁻¹	[117]
BiTiO ₃	Piezocatalysis	CO ₂ reduction	CO, 31.7 μmol g ⁻¹ h ⁻¹	[118]
Cd _{0.5} Zn _{0.5} S	Piezocatalysis	H ₂ O ₂ production	H ₂ O ₂ , 151.6 μmol g ⁻¹ h ⁻¹	[129]
C ₃ N _{5-x} -O	Piezocatalysis	H ₂ O ₂ production	H ₂ O ₂ , 615 μmol g ⁻¹ h ⁻¹	[131]
BaCaZrTi	Piezocatalysis	H ₂ O ₂ production	H ₂ O ₂ , 692 μmol g ⁻¹ h ⁻¹	[134]
Ag-Bi _{0.5} Na _{0.5} TiO ₃ - AgNbO ₃	Piezocatalysis	H ₂ O ₂ production	H ₂ O ₂ , 469 μmol g ⁻¹ h ⁻¹	[135]
g-C ₃ N ₄	Piezocatalysis	H ₂ O ₂ production	H ₂ O ₂ , 34 μmol g ⁻¹ h ⁻¹	[136]
Bi ₃ TiNbO ₉	Piezocatalysis	H ₂ O ₂ production	H ₂ O ₂ , 407.1 μmol g ⁻¹ h ⁻¹	[137]
BaTiO ₃ :Nb:CDs	Piezocatalysis	H ₂ O ₂ production	H ₂ O ₂ , 628 μmol g ⁻¹ h ⁻¹	[139]
BaTiO ₃ :Nb:CDs	Piezo-photocatalysis	H ₂ O ₂ production	H ₂ O ₂ , 1,360 μmol g ⁻¹ h ⁻¹	[139]
FEP	Tribocatalysis	H ₂ O ₂ production	58.87 mmol L ⁻¹ g ⁻¹ h ⁻¹	[141]
PTFE	Tribocatalysis	H ₂ O ₂ production	313 μmol L ⁻¹ h ⁻¹	[142]

through magnetic stirring^[106]. They also examined the effects of various sacrificial agents on nitrogen fixation activity. When methanol was employed as the sacrificial agent and stirred for 10 h, the generation rate of NH₄⁺ reached 100.56 μmol g⁻¹ h⁻¹, which was 3.91 times higher than the rate observed in the absence of a sacrificial agent. Comparative experiments revealed that no NH₄⁺ was produced without the catalyst and stirring, indicating that tribocatalysis resulted from electron transfer caused by friction between the C₃N₄ and the stirring rod as shown in Figure 4E^[106]. They also demonstrated that tribocatalytic nitrogen fixation can enhance catalytic efficiency by optimizing the contact area and friction rate, presenting promising, efficient, and environmentally friendly approach to nitrogen fixation. Recently, Zhang *et al.* also designed Si₃N₄ catalyst achieving high efficiency in tribocatalytic nitrogen fixation at room temperature^[107]. For direct nitrogen fixation from air and water to produce ammonia, the yield can reach 1,273.4 μmol g⁻¹ within 5 h. In controlled environment using pure nitrogen and water, the ammonia yield can increase to 1,865.2 μmol g⁻¹ within the same timeframe. The rapid contact and separation between a polytetrafluoroethylene (PTFE) rod, Si₃N₄ particles, and a glass reactor led to the continuous formation of positive and negative charges on the surface of Si₃N₄. The positive charges interact with the sacrificial agent methanol and water to generate hydrogen ions. This interaction not only consumes positive charges, inhibiting their recombination with negative charges and thereby enhancing electron utilization, but also provides a substantial source of hydrogen ions for the reaction. They also conducted DFT calculations, which indicate that silicon atoms on the surface of silicon nitride lack catalytic activity, whereas nitrogen atoms can effectively activate nitrogen molecules and catalyze the nitrogen fixation reaction. Consequently, they proposed a tribocatalysis process

aimed at continuously breaking catalyst particles to expose additional surface nitrogen atoms as active sites *in situ*, thereby promoting the nitrogen fixation reaction. Furthermore, the friction force generates energy during the instantaneous process, which aids in the activation of nitrogen molecules and accelerates the reaction. Together with the continuous charge supplied by the friction process, these mechanisms enable Si_3N_4 to efficiently catalyze nitrogen fixation at room temperature as depicted in Figure 4F^[107].

Generally, piezocatalytic and tribocatalytic nitrogen fixation, as newly developed technologies, have broad application prospects and significant development potential but currently remain underexplored. Notably, the enhancement of their performance still requires attention, with insufficient investigation into N_2 adsorption and activation sites, and the microscopic reaction mechanisms remain unclear. To address these challenges, DFT calculations can be employed to study the structure-activity relationships of piezocatalytic and tribocatalytic nitrogen fixation materials, clarifying the effects of defects, heterostructures, chemical bonding, carriers, and active sites on ammonia synthesis performance. Simultaneously, advanced characterization techniques such as *in situ* infrared spectroscopy X-ray absorption spectroscopy should be employed to elucidate the key reaction steps and carrier variation patterns in piezocatalysis and tribocatalysis during the nitrogen fixation process, clarifying the contributions of active sites and intermediate products related to piezocatalytic and tribocatalytic reactions, therefore scientifically guiding the design and development of high-activity catalytic nitrogen fixation materials.

Application of piezocatalysis and tribocatalysis for carbon dioxide reduction

In today's society, the extensive consumption of fossil fuels has led to a continuous increase in CO_2 emissions, triggering a series of global climate and environmental problems that severely threaten the green, low-carbon, and sustainable development of human society. Recently, there has been a surge in global research on the conversion of CO_2 into high-value-added chemical products using catalytic technologies such as photocatalysis, electrocatalysis, and photo-electrocatalysis, driven by renewable solar energy and electrical energy. This aligns with China's development strategy of "carbon peak and carbon neutrality", highlighting the significance of converting renewable energy sources into high-value chemical fuels^[108–114]. Compared to the aforementioned technologies, piezocatalysis can achieve CO_2 reduction in the absence of light by harvesting vibrational energy from the environment. Similar to electrocatalytic technologies, piezocatalysts can generate appropriate piezoelectric potential to overcome reaction barriers and facilitate corresponding CO_2 catalytic reactions^[115]. In 2022, the piezocatalytic reduction of CO_2 was reported for the first time, sparking significant research interest. Initial studies conducted by Phuong *et al.* synthesized lead-free lithium-doped $(\text{K},\text{Na})\text{NbO}_3$ (KNN) ferroelectric ceramic particles and applied them to piezocatalytic CO_2 reduction, demonstrating for the first time that lithium-doped KNN can achieve the piezocatalytic reduction of CO_2 to CO, with a conversion rate of $438 \mu\text{mol g}^{-1} \text{h}^{-1}$ ^[115]. Additionally, He *et al.* discovered that the piezocatalytic reduction rate of CO_2 on BiFeO_3 was $28.7 \mu\text{mol g}^{-1} \text{h}^{-1}$ for CO and $17.9 \mu\text{mol g}^{-1} \text{h}^{-1}$ for CH_4 in Figure 5A^[116]. They further proposed a piezocatalytic mechanism for CO_2 reduction. DFT calculation results indicated that the CO_2 adsorption and activation process mainly occurred on the (012) surface of BiFeO_3 , with different intermediate products formed mainly through proton-coupled electron transfer as shown in Figure 5B^[116]. The use of ultrasonic vibrations effectively lowered the reaction barriers and favored the production of CO and CH_4 chemicals. These investigations confirm that piezocatalysis can reduce CO_2 into specific high-value-added chemical products, breaking the limitations of traditional perovskite oxides that cannot reduce CO_2 due to their inherent redox potential. Thus, using piezocatalysis to reduce CO_2 into high-value-added chemicals is highly valuable area of exploration.

Despite the ability of piezocatalysis to reduce CO_2 into high-value-added chemicals, its reduction efficiency and selectivity remain relatively low. To address this issue, researchers have employed strategies such as doping, coupling with photocatalytic technique, and constructing heterostructure to enhance the

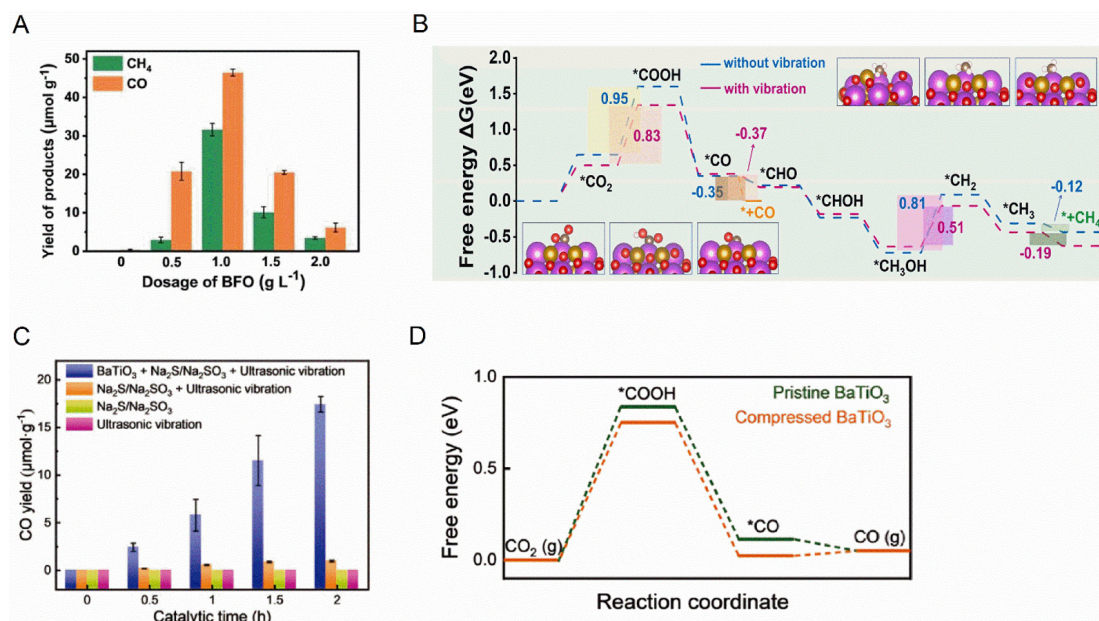


Figure 5. (A) Yield of CO₂ reduction products at different doses of BiFeO₃ and (B) ΔG plots of methane and CO production during catalytic reduction of CO₂. This figure is quoted with permission^[116]. (C) CO yield using BaTiO₃ with the addition of Na₂S/Na₂SO₃ as sacrificial agent and (D) Free energy and structures of CO₂ reduction to CO on the BaO-terminated (001) surface of BaTiO₃ diagram of CO₂ reduction to CO on BaTiO₃ (001) by DFT calculations. This figure is quoted with permission^[118].

performance of piezocatalytic CO₂ reduction, as summarized in Table 2^[115–118]. For example, Zhang *et al.* synthesized niobium-doped lead zirconate titanate piezocatalytic materials, investigating the effects of ultrasound power, particle agglomeration, and Curie temperature on the performance of piezocatalytic CO₂ reduction. Under optimal conditions, the piezocatalytic CO₂ reduction rate reached 789 μmol g⁻¹ h⁻¹^[117]. Additionally, Ma *et al.* utilized piezoelectric-catalytic-electrochemical coupling effect, achieving CO production rate of 63.3 μmol g⁻¹ within 2 h in the absence of sacrificial agents, with a reduction rate of 31.65 μmol g⁻¹ h⁻¹ and near 100% selectivity for CO [Figure 5C]^[118]. They further combined first-principles calculations and COMSOL simulations to confirm the influence of intermediate products, free energy changes, and reaction potentials on the performance of the piezocatalytic CO₂ reduction process as shown in Figure 5D^[118]. These studies provide essential guidance for the application of piezocatalysis in converting CO₂ into high-value-added chemicals. Ni *et al.* constructed the intergrowth ferroelectrics Bi₇Ti₄NbO₂₁ thin-layer nanosheets for piezo-photocatalytic CO₂ reduction^[119]. These nanosheets presented excellent piezo-photocatalytic CO₂ reduction activity with high CO generation rate of 426.97 μmol g⁻¹ h⁻¹. DFT calculations indicate that interlayer lattice mismatch leads to increased tilting and rotation angle of Ti/NbO₆ octahedra on perovskite-like layers, serving as the main reason for increased polarization. Furthermore, the tilting and rotation angle of the interlayer octahedron further increase under stress, suggesting a stronger driving force generated to facilitate charge carrier separation efficiency^[119]. This work offers new perspectives and directions for initiating and investigating the mechanisms of high-performance intergrowth piezo-photocatalysts.

Tribocatalysis also has the potential to convert carbon dioxide into combustible gases such as methane, carbon monoxide, *etc.*^[120–123]. For example, Li *et al.* examined the generation of methane (CH₄) at 2.45 ppm, carbon monoxide (CO) at 22.00 ppm, and hydrogen (H₂) at 1.78 ppm through the use of TiO₂ dispersed in water under magnetic stirring for a duration of 50 h^[120]. For comparison, in the absence of TiO₂ nanoparticles, only 2.17 ppm of CH₄, 1.78 ppm of CO, and 0.33 ppm of H₂ were produced under the same conditions. When the number of stirring rods was increased to four, the production rates significantly

improved. After 50 h, 2.61 ppm of CH_4 , 30.04 ppm of CO , and 8.98 ppm of H_2 were generated. Notably, the production of H_2 and CO increased by 11 times and 36.7%, respectively, compared to the scenario using a single stirring bar^[120]. Moreover, Jia *et al.* enhanced the experimental setup by dispersing Co_3O_4 nanoparticles in water and placing them in a reactor under 1 atm of CO_2 , along with a Teflon magnetic rotary disk^[121]. After 5 h of stirring, concentrations of $0.15 \mu\text{mol L}^{-1}$ CH_4 , $57.41 \mu\text{mol L}^{-1}$ H_2 , and $0.21 \mu\text{mol L}^{-1}$ CO were measured. A significant improvement in CO_2 reduction efficiency was observed when the reactor's bottom was switched from glass to various metal covers (Ni, SUS316, Ti, and Nb), leading to the detection of ethylene (C_2H_4) and ethane (C_2H_6). Particularly, Ti coating increased CH_4 and H_2 concentrations by 26 and 2 times, respectively, compared to the glass substrate. This research not only offers a valuable method to enhance the efficiency of tribocatalysis but also confirms the potential for C_{2+} products to be produced through this process. Furthermore, tribocatalytic materials are not limited to semiconductors; metals also exhibit excellent performance in CO_2 reduction^[121]. Lei *et al.* utilized homemade magnets with a metal Ni bottom along with a glass reactor featuring coatings of various materials on the bottom to convert CO_2 and H_2O into chemical fuels (CO , CH_4 , C_2H_6 , and H_2) through magnetic stirring^[122]. Their findings demonstrated the promising potential of metals in converting H_2O and CO_2 into chemical fuels using mechanical energy. Notably, when Cu replaced Ni and the bottom of the quartz glass reactor was covered with Al_2O_3 , Cu, and Ti disks, tribocatalysis also generated H_2 , CO , CH_4 , C_2H_4 and C_2H_6 ^[122]. The material of the beaker bottom significantly influences the composition of the generated combustible gas, particularly with Ti bottoms yielding much higher concentrations of CO and CH_4 than other materials. The authors proposed a tribocatalysis mechanism in which the elastic deformation of the copper disk applies pressure to water trapped in the micropores of the beaker bottom, resulting in a temporary and substantial pressure increase that enhances the efficiency of tribocatalysis. Recently, Tang *et al.* demonstrated that C-H and C=O bonds are more readily cleaved under a high triboelectric field generated by $\text{Ni}(\text{OH})_2/\text{Ag}_{0.72}\text{Ga}_{0.28}$ and Ga. This facilitates the efficient catalytic conversion of methane and carbon dioxide^[123].

In summary, the reduction of CO_2 to high-value chemical fuels through piezocatalysis and tribocatalysis opens up a new pathway for the development of mechanically driven catalytic technology and holds significant potential for application. However, research on piezocatalytic and tribocatalytic CO_2 reduction remains in its infancy, particularly regarding the microscopic mechanisms behind this process, which require further exploration to achieve more significant breakthroughs. Since the multi-step reduction of CO_2 is more challenging than water splitting and faces certain technical barriers, it is crucial to effectively regulate the reduction activity and selectivity of catalytic materials. This needs to be achieved through a combination of theoretical calculations and advanced characterization techniques such as aberration-corrected microscopy and synchrotron radiation to detect and analyze the evolution of catalytic active sites, electronic states, band structures, and the changes in reaction intermediates. A deeper understanding of the relationship between the reaction mechanisms of piezocatalytic and tribocatalytic CO_2 reduction, energy barrier variations, and performance-enhancing modification strategies is essential. Selecting and designing more suitable catalytic materials and reaction systems remains a key direction needing exploration within the piezocatalytic and tribocatalytic CO_2 reduction process.

Application of piezocatalysis and tribocatalysis for hydrogen peroxide synthesis

Hydrogen peroxide is an emerging energy source and green oxidant widely used in industrial production and everyday life, such as in paper bleaching, wastewater treatment, and organic synthesis. The traditional anthraquinone process for producing H_2O_2 requires high energy consumption and generates toxic by-products, contributing to environmental pollution. Therefore, synthesizing clean H_2O_2 using renewable energy sources has become a focal point of research^[124,125]. Among the current catalytic technologies for synthesizing H_2O_2 , electrocatalytic redox synthesis utilizes O_2 as a reactant and H_2O or H^+ as a proton source, gathering electrons from the cathode to selectively convert O_2 into H_2O_2 through a proton-electron

co-transfer process. This reaction offers advantages such as operation under ambient temperature and pressure, environmental friendliness, and simplicity and controllability, indicating promising prospects. However, electrocatalysts for H_2O_2 synthesis face drawbacks such as low selectivity, low activity, and poor long-term operational stability, limiting their practical applications^[126]. Currently, due to the ability of piezocatalysis to harness vibrational energy from nature, and because the position of energy bands can effectively meet the redox potential requirements of active species (e.g., $\cdot\text{O}_2^-$ and $\cdot\text{OH}$) while the piezoelectric potential promotes the effective separation of charge carriers, piezocatalysis represents a highly promising approach for H_2O_2 synthesis^[127,128].

Recently, although some reports on piezoelectric materials for H_2O_2 synthesis have shown promising results, classical piezocatalysts still exhibit relatively low activity. Consequently, various modification strategies have been employed, including designing novel materials, doping engineering, defect engineering, constructing heterostructures, and integrating with other photocatalysis, as shown in Table 2^[129–137]. Wu *et al.* have rationally designed the $\text{Bi}_{12}\text{O}_{17}\text{C}_{12}$ piezocatalyst, incorporating multiple $[\text{Bi}-\text{O}]_n$ interlayers to achieve highly efficient H_2O_2 production^[128]. The presence of $[\text{Bi}_3\text{O}_{4.25}]$ enhances the electric field, accelerates charge separation, optimizes the band gap structure, and increases the adsorption energy for both O_2 and H_2O , thereby facilitating a higher rate of electron transfer. This is attributed to the availability of sufficient active sites, which enable the simultaneous occurrence of $2e^-$ water oxidation reactions (WOR) and $2e^-$ oxygen reduction reactions (ORR) to produce H_2O_2 . Consequently, $\text{Bi}_{12}\text{O}_{17}\text{C}_{12}$ demonstrates an exceptionally high H_2O_2 generation rate of $7.76 \text{ mM h}^{-1} \text{ g}^{-1}$ in pure water as shown in Figure 6A and B^[128]. Typically, doping or loading certain metal or non-metal elements into the catalyst can effectively modulate the material's energy band structure and electronic states, control the electron transfer pathways, and accelerate the redox reactions involved in piezocatalytic H_2O_2 synthesis, thereby enhancing catalytic performance. For instance, Lin *et al.* prepared $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ nanomaterials and discovered that the piezocatalytic rate for H_2O_2 production was $151.6 \text{ } \mu\text{mol g}^{-1} \text{ h}^{-1}$, significantly exceeding the performance of pure ZnS and CdS^[129]. Additionally, defect engineering is a common approach in the study of efficient piezocatalytic materials, particularly in inducing an appropriate number of vacancies to create more active sites and enhance charge carrier separation efficiency, further boosting piezocatalytic activity. Wang *et al.* synthesized $\text{Bi}_4\text{Ti}_3\text{O}_{12}$ nanosheets with abundant surface oxygen vacancies and achieved a maximum H_2O_2 synthesis rate of $1,611.2 \text{ } \mu\text{mol g}^{-1} \text{ h}^{-1}$ by reducing O_2 in a two-step method, demonstrating good stability^[130]. Furthermore, Fu *et al.* synthesized $\text{C}_3\text{N}_{5-x}\text{-O}$ piezocatalysts, reporting an H_2O_2 synthesis rate of $615 \text{ } \mu\text{mol g}^{-1} \text{ h}^{-1}$, attributed to oxygen doping and nitrogen vacancies exposing more reactive sites and optimizing the energy band structure and charge distribution. The synergistic effects of doping and defects can effectively promote the piezocatalytic synthesis of H_2O_2 , significantly enhancing the catalytic activity^[131]. Moreover, He *et al.* employed *in situ* electron paramagnetic resonance (EPR) spectroscopy [Figure 6C], demonstrating that the piezocatalytic H_2O_2 evolution pathway over BiOBr with abundant oxygen exhibited a similar reaction pathway to that observed in photocatalytic process^[138]. This finding represented solid evidence supporting the notion that piezocatalytic mechanism of ORR was more inclined towards photocatalysis rather than electrocatalysis as shown in Figure 6D. Significantly, this exploratory conclusion provided insight to deepen our understanding of piezocatalysis^[138]. Notably, Zhou *et al.* reported Nb-doped BaTiO_3 -based material, which achieved an H_2O_2 yield of up to $1,360 \text{ } \mu\text{mol g}^{-1} \text{ h}^{-1}$ under the combined action of visible light and ultrasound, with the rate increased by approximately 13 times^[139]. Our group also synthesized $\text{Bi}_4\text{Ti}_3\text{O}_{12}$ piezocatalyst with surface oxygen vacancies (BTO-Ov) to promote *in situ* production of hydrogen peroxide (H_2O_2) and to establish piezocatalytic self-cycling Fenton-like system for the degradation of pollutants. Notably, the H_2O_2 production rate from the BTO-Ov catalyst reached $558.8 \text{ } \mu\text{mol g}^{-1} \text{ h}^{-1}$ when using pure water, significantly surpassing the rate obtained from pure BTO ($274.6 \text{ } \mu\text{mol g}^{-1} \text{ h}^{-1}$). Furthermore, this production rate could be increased to 1,

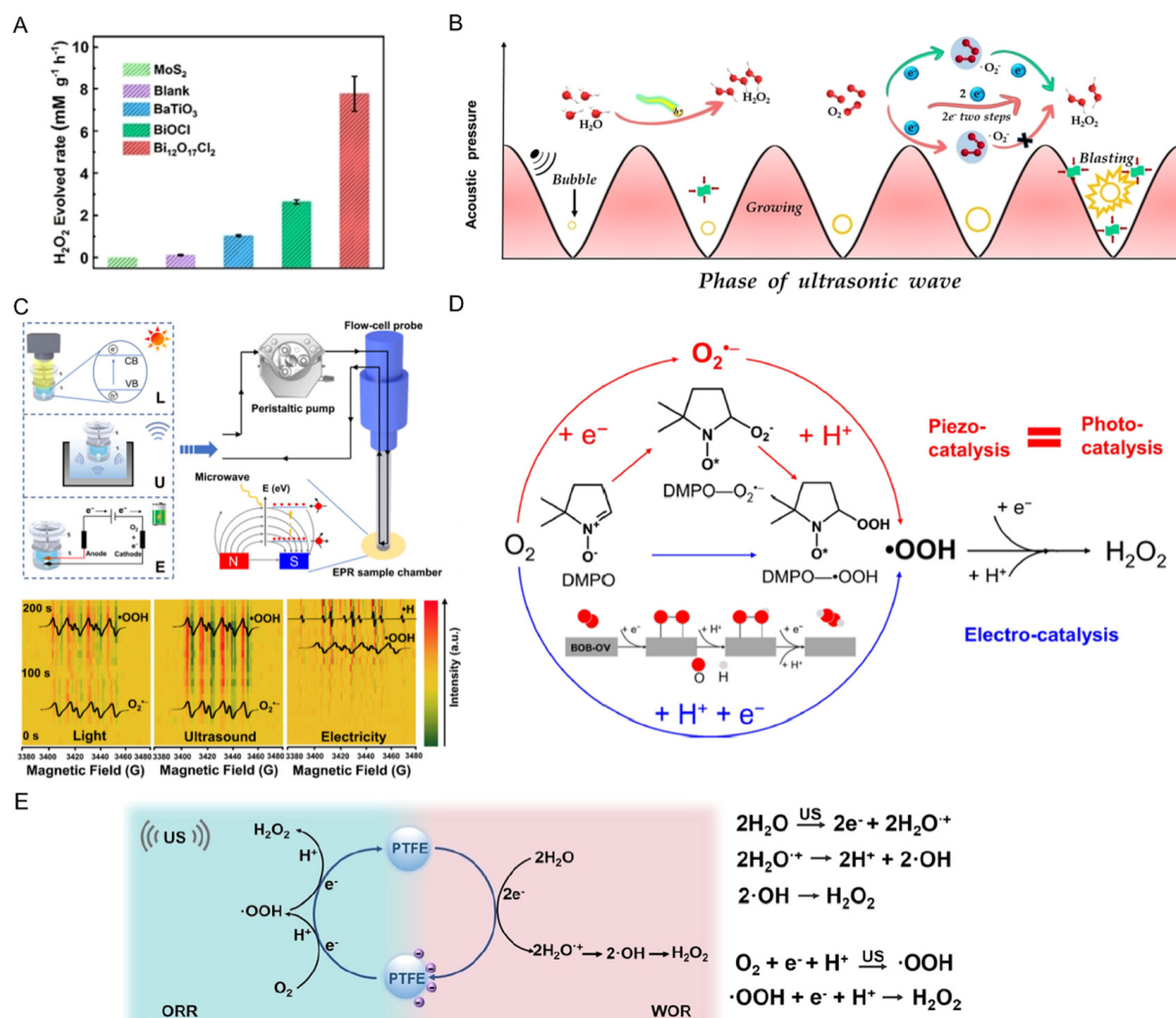


Figure 6. (A) Piezocatalytic H₂O₂ production, time courses of H₂O₂ evolved rate over different piezocatalysts and (B) mechanism of H₂O₂ production process in Bi₁₂O₁₇Cl₂. This figure is quoted with permission^[128]. (C) *In situ* EPR monitoring the ORR pathway of H₂O₂ production and heat-spot imaging maps and (D) of three kinds of catalytic H₂O₂ production by BiOBr-OV. This figure is quoted with permission^[138]. (E) Proposed reaction mechanism of tribocatalysis for H₂O₂ generation. This figure is quoted with permission^[142].

0.916 μmol g⁻¹ h⁻¹ with the addition of ethanol as a sacrificial agent, demonstrating exceptional stability. In the piezocatalytic self-cycling Fenton-like system (BTO-Ov/Fe⁰), the degradation efficiency of the methyl orange dye pollutant reached 91.9% within 20 min, accompanied by a high kinetic coefficient of 0.117 min⁻¹, indicating excellent catalytic activity. Characterization results showed that the introduction of oxygen vacancies enhanced piezoelectric properties, reduced the band gap of BTO, improved charge carrier transfer and separation, and facilitated a dual-channel reaction mechanism, thus resulting in superior piezocatalytic performance. This work not only enabled the *in situ* synthesis of valuable chemicals but also presented a cost-effective and sustainable approach for wastewater purification^[140]. Overall, the combination of piezocatalysis with other technologies can significantly enhance the capability for H₂O₂ synthesis, providing valuable reference for designing high-performance piezocatalysts.

Compared to piezocatalysis, tribocatalysis has the advantages of a wide selection of materials and high triboelectric potential for hydrogen peroxide synthesis^[141,142]. Berbille *et al.* reported that hydrogen peroxide is generated from air and deionized water through ultrasound-driven tribocatalytic conversion, utilizing fluorinated ethylene propylene (FEP) as the catalyst^[141]. With a catalyst-to-solution mass ratio of 1:10,000 at 20 °C, the kinetic rate of H₂O₂ production reaches 58.87 mmol L⁻¹ g⁻¹ h⁻¹. EPR studies indicate that electrons are emitted into the solution by the charged FEP during ultrasonication. Additionally, EPR and isotope labeling experiments demonstrate that H₂O₂ is formed from hydroxyl radicals or two superoxide radicals generated by tribocatalytic process. Traditionally, it has been believed that these radicals migrate in the solution via Brownian diffusion prior to undergoing reactions. Moreover, Ab-initio molecular dynamics calculations reveal that the radicals can react by exchanging protons and electrons through the hydrogen bond network of water, attributed to the Grotthuss mechanism^[141,142]. Fan *et al.* also demonstrated the tribocatalytic H₂O₂ synthesis through a catalytic pathway that involves contact charging at a two-phase interface under room temperature and normal pressure [Figure 6E]^[142]. Notably, mechanical force facilitates electron transfer during the physical interaction between PTFE particles and the deionized water/O₂ interfaces, leading to the generation of reactive free radicals ($\cdot\text{OH}$ and $\cdot\text{O}_2^-$). These free radicals can subsequently react to form H₂O₂, achieving a production rate of up to 313 $\mu\text{mol L}^{-1} \text{h}^{-1}$. Furthermore, the novel reaction device demonstrates long-term stability in H₂O₂ production^[142]. This work presents an innovative method for the efficient synthesis of H₂O₂ and may inspire further investigations into tribocatalytic induced chemical processes. Overall, the synthesis of high-value-added chemicals such as H₂O₂ using piezocatalysis and tribocatalysis holds great potential for application. However, the current efficiency of H₂O₂ synthesis remains low and the reaction pathways are not clearly defined, necessitating further exploration and resolution.

CONCLUSIONS

This review briefly summarises the research development of piezocatalysis and tribocatalysis, focusing on the latest advances in energy conversion applications. Effective strategies for enhancing the catalyst performance and exploring the microscopic mechanisms are discussed. This provides necessary guidance for the design and performance optimization of novel catalysts and enhances the understanding of the microscopic catalytic mechanisms, which can lead to new applications. Overall, piezocatalysis and tribocatalysis hold considerable potential for energy conversion applications to address energy shortage issues. However, further advances are still required to realise practical applications. Continuous contributions from the scientific community are essential for the development and maturation of this research field. Figure 7 depicts the development roadmap of piezocatalysis and tribocatalysis, including future research directions aligning with the objectives of carbon peaking and carbon neutrality in industry and society.

Despite the remarkable progress made in the fields of piezocatalysis and tribocatalysis, several issues remain to be addressed for obtaining high-performance catalysts:

- (1) There is still a lack of understanding of the microscopic mechanisms of piezocatalysis and tribocatalysis and their coupling with other catalytic technologies. In particular, the evolution and mechanisms of action of the active sites during the catalytic process have not been adequately studied. Furthermore, the contributions of charges and carriers remain unclear, leading to a lack of theoretical guidance for the exploration of new catalysts.
- (2) The efficiency of piezocatalysts and tribocatalysts remains relatively low, with the catalytic reaction kinetics being relatively slow. Moreover, catalytic processes often require high-frequency and power vibrations for smooth operation, limiting their practical applications. To accelerate the development and application of piezocatalysis and tribocatalysis, the following efforts should be prioritized:

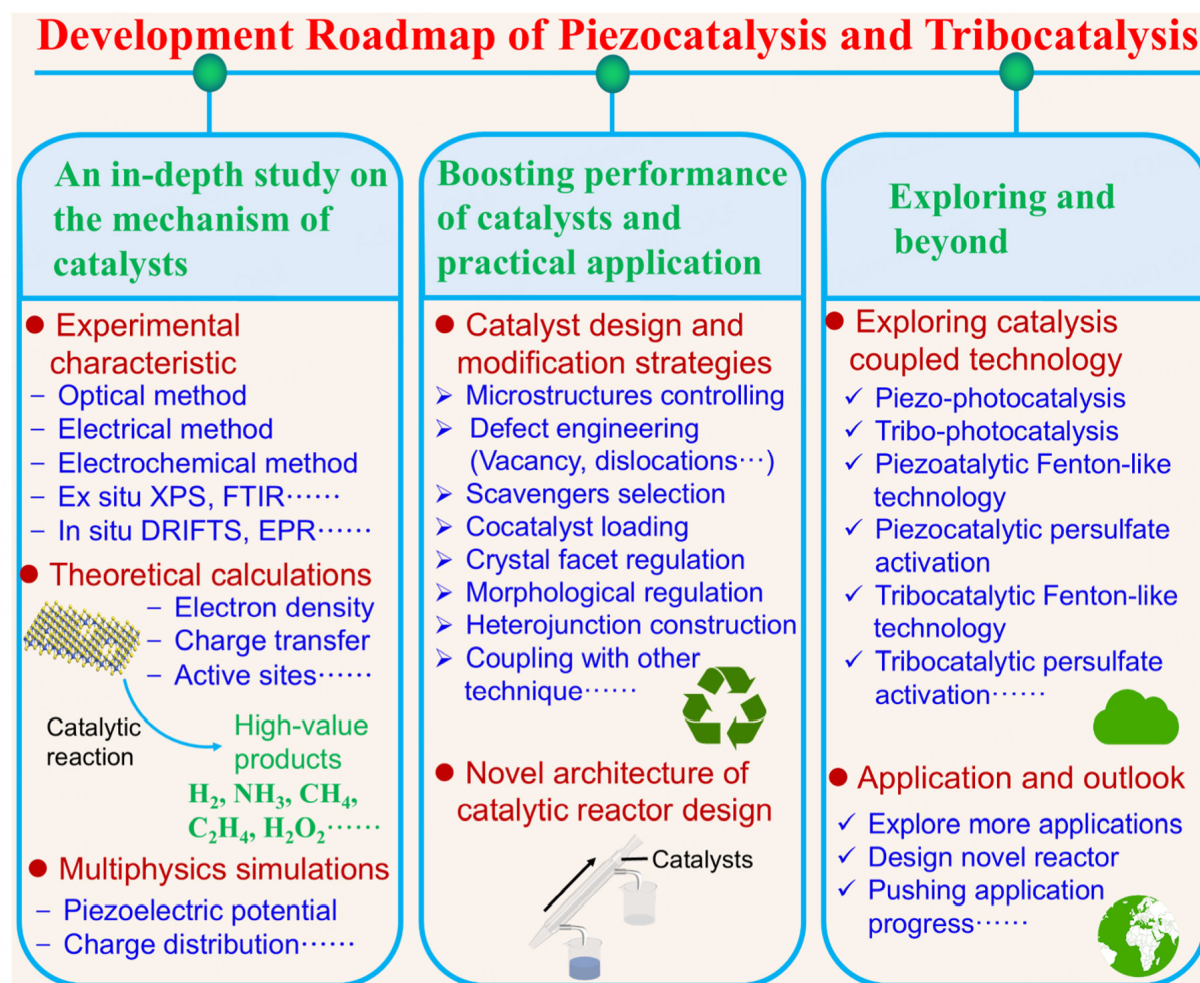


Figure 7. The development roadmap of piezocatalysis and tribocatalysis.

Advanced characterization techniques such as aberration-corrected microscopy, synchrotron radiation technology and *in situ* Fourier transform infrared spectroscopy should be utilized to identify and analyse key factors such as the evolution of catalytic active sites, electronic states, energy band structures, and reaction intermediates, which will deepen the understanding of the catalytic reaction mechanisms. A systematic investigation of the separation and migration of charges and carriers should be conducted to elucidate these mechanisms and guide the development of high-performance catalytic materials. Moreover, theoretical calculations would help clarify aspects such as electronic structures, charge separation and transfer, and the thermodynamics and kinetics of catalytic reactions. The use of machine learning algorithms and genome technologies to establish predictive models would facilitate the identification of high-performance materials, further promoting the development and application of piezocatalysis and tribocatalysis.

The transition from laboratory-scale to industrial-scale applications still presents notable challenges, particularly concerning energy efficiency, cost, and safety in catalytic processes. Although ultrasonic-driven catalysis is suitable for small-scale applications, its high energy consumption and equipment costs render it impractical for large-scale, continuous operations. Thus, research should focus on alternative catalytic processes with lower energy requirements. In addition, the integration of piezocatalysis and tribocatalysis with other innovative technologies could enhance the overall effectiveness and economic viability. Thorough assessments of their environmental impact and sustainability are also required. To guide the future

development of more environmentally friendly materials and methods. Finally, strengthening the collaboration between industry and academia would help realise the industrialization of piezocatalysis and tribocatalysis.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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REFERENCES

1. Yi, H.; Huang, D.; Qin, L.; et al. Selective prepared carbon nanomaterials for advanced photocatalytic application in environmental pollutant treatment and hydrogen production. *Appl. Catal. B. Environ.* **2018**, *239*, 408-24. [DOI](#)
2. Dong, W.; Xiao, H.; Jia, Y.; et al. Engineering the defects and microstructures in ferroelectrics for enhanced/novel properties: an emerging way to cope with energy crisis and environmental pollution. *Adv. Sci.* **2022**, *9*, e2105368. [DOI](#) [PubMed](#) [PMC](#)
3. Xia, M.; Zhang, Y.; Xiao, J.; et al. Magnetic field induced synthesis of (Ni, Zn)Fe₂O₄ spinel nanorod for enhanced alkaline hydrogen evolution reaction. *Prog. Nat. Sci. Mater. Int.* **2023**, *33*, 172-7. [DOI](#)
4. Wang, S.; Li, Y.; Liu, Q.; et al. Photo-/electro-/piezo-catalytic elimination of environmental pollutants. *J. Photochem. Photobiol. A. Chem.* **2023**, *437*, 114435. [DOI](#)
5. Zhang, X.; Wu, X.; Zhang, J.; Xu, H.; Yu, X. Recent progress in graphitic carbon nitride-based materials for antibacterial applications: synthesis, mechanistic insights, and utilization. *Microstructures* **2024**, *4*, 2024017. [DOI](#)
6. Pyser, J. B.; Chakrabarty, S.; Romero, E. O.; Narayan, A. R. H. State-of-the-art biocatalysis. *ACS. Cent. Sci.* **2021**, *7*, 1105-16. [DOI](#) [PubMed](#) [PMC](#)
7. Li, J.; Liu, X.; Zhao, G.; et al. Piezoelectric materials and techniques for environmental pollution remediation. *Sci. Total. Environ.* **2023**, *869*, 161767. [DOI](#)

-
8. Hao, A.; Ning, X.; Liu, X.; Zhan, L.; Qiu, X. Phosphorus heteroatom doped BiOCl as efficient catalyst for photo-piezocatalytic degradation of organic pollutant and unveiling the mechanism: experiment and DFT calculation. *Chem. Eng. J.* **2024**, *499*, 155823. DOI
 9. Xu, Y.; Meng, Y.; Xiang, X.; et al. Modulating low-frequency tribocatalytic performance through defects in uni-doped and bi-doped SrTiO₃. *J. Adv. Ceram.* **2024**, *13*, 1153-63. DOI
 10. Liang, Z.; Yan, C.; Rtimi, S.; Bandara, J. Piezoelectric materials for catalytic/photocatalytic removal of pollutants: recent advances and outlook. *Appl. Catal. B. Environ.* **2019**, *241*, 256-69. DOI
 11. Dai, J.; Fan, Z.; Xie, H.; et al. Versatile BiFeO₃ shining in piezocatalysis: from materials engineering to diverse applications. *J. Adv. Ceram.* **2025**, *14*, 9221046. DOI
 12. Liu, N.; Wang, R.; Zhao, J.; Jiang, J.; Fan, F. R. Piezoelectricity and triboelectricity enhanced catalysis. *Nano. Res. Energy.* **2024**, *3*, e9120137. DOI
 13. Tu, S.; Guo, Y.; Zhang, Y.; et al. Piezocatalysis and piezo-photocatalysis: catalysts classification and modification strategy, reaction mechanism, and practical application. *Adv. Funct. Mater.* **2020**, *30*, 2005158. DOI
 14. Liu, J.; Qi, W.; Xu, M.; Thomas, T.; Liu, S.; Yang, M. Piezocatalytic techniques in environmental remediation. *Angew. Chem. Int. Ed.* **2023**, *62*, e202213927. DOI
 15. Sudrajat, H.; Rossetti, I.; Carra, I.; Colmenares, J. C. Piezocatalytic reduction: an emerging research direction with bright prospects. *Curr. Opin. Chem. Eng.* **2024**, *45*, 101043. DOI
 16. Wang, C.; Hu, C.; Chen, F.; Ma, T.; Zhang, Y.; Huang, H. Design strategies and effect comparisons toward efficient piezocatalytic system. *Nano. Energy.* **2023**, *107*, 108093. DOI
 17. Starr, M. B.; Wang, X. Coupling of piezoelectric effect with electrochemical processes. *Nano. Energy.* **2015**, *14*, 296-311. DOI
 18. Su, C.; Li, C.; Wang, W. Efficient piezocatalytic activation of peroxydisulfate over Bi₂Fe₄O₉: thickness-dependent synergy effect between peroxydisulfate activation and piezocatalysis. *Rare. Met.* **2023**, *42*, 4005-14. DOI
 19. Hong, K.; Xu, H.; Konishi, H.; Li, X. Direct water splitting through vibrating piezoelectric microfibers in water. *J. Phys. Chem. Lett.* **2010**, *1*, 997-1002. DOI
 20. Hong, K.; Xu, H.; Konishi, H.; Li, X. Piezoelectrochemical effect: a new mechanism for azo dye decolorization in aqueous solution through vibrating piezoelectric microfibers. *J. Phys. Chem. C.* **2012**, *116*, 13045-51. DOI
 21. Ali, A.; Chen, L.; Nasir, M. S.; Wu, C.; Guo, B.; Yang, Y. Piezocatalytic removal of water bacteria and organic compounds: a review. *Environ. Chem. Lett.* **2023**, *21*, 1075-92. DOI
 22. Zhou, L. L.; Yang, T.; Wang, K.; et al. Efficient piezo-catalytic dye degradation using piezoelectric 6H-SiC under harsh conditions. *Rare. Met.* **2024**, *43*, 3173-84. DOI
 23. Karmakar, S.; Pramanik, A.; Kole, A. K.; Chatterjee, U.; Kumbhakar, P. Syntheses of flower and tube-like MoSe₂ nanostructures for ultrafast piezocatalytic degradation of organic dyes on cotton fabrics. *J. Hazard. Mater.* **2022**, *424*, 127702. DOI PubMed
 24. Chen, L.; Dai, X.; Li, X.; et al. A novel Bi₂S₃/KTA_{0.75}Nb_{0.25}O₃ nanocomposite with high efficiency for photocatalytic and piezocatalytic N₂ fixation. *J. Mater. Chem. A.* **2021**, *9*, 13344-54. DOI
 25. Hu, J.; Zhao, R.; Ni, J.; et al. Enhanced ferroelectric polarization in Au@BaTiO₃ yolk-in-shell nanostructure for synergistic boosting visible-light- piezocatalytic CO₂ reduction. *Adv. Sci.* **2024**, *11*, e2410357. DOI PubMed PMC
 26. Fan, F.; Xie, S.; Wang, G.; Tian, Z. Tribocatalysis: challenges and perspectives. *Sci. China. Chem.* **2021**, *64*, 1609-13. DOI
 27. Che, J.; Gao, Y.; Wu, Z.; et al. Review on tribocatalysis through harvesting friction energy for mechanically-driven dye decomposition. *J. Alloys. Compd.* **2024**, *1002*, 175413. DOI
 28. Zhao, B.; Chen, N.; Xue, Y.; et al. Challenges and perspectives of tribocatalysis in the treatment for dye wastewater. *J. Water. Proc. Eng.* **2024**, *63*, 105455. DOI
 29. Trinh, Q. T.; Golio, N.; Cheng, Y.; et al. Sonochemistry and sonocatalysis: current progress, existing limitations, and future opportunities in green and sustainable chemistry. *Green. Chem.* **2025**, *27*, 4926-58. DOI
 30. Pickhardt, W.; Grätz, S.; Borchardt, L. Direct mechanocatalysis: using milling balls as catalysts. *Chemistry* **2020**, *26*, 12903-11. DOI PubMed PMC
 31. Jia, P.; Li, J.; Huang, H. Piezocatalysts and piezo-photocatalysts: from material design to diverse applications. *Adv. Funct. Mater.* **2024**, *34*, 2407309. DOI
 32. Wang, K.; Han, C.; Li, J.; Qiu, J.; Sunarso, J.; Liu, S. The mechanism of piezocatalysis: energy band theory or screening charge effect? *Angew. Chem. Int. Ed.* **2022**, *61*, e202110429. DOI
 33. Xu, X.; Wang, Y.; Cheng, W.; et al. Recent advances in piezocatalytic hydrogen production and prospects. *Surf. Interfaces.* **2024**, *54*, 105245. DOI
 34. Liu, Y.; Zhang, Y.; Yang, Q.; Niu, S.; Wang, Z. Fundamental theories of piezotronics and piezo-phototronics. *Nano. Energy.* **2015**, *14*, 257-75. DOI

35. Tu, S.; Huang, H.; Zhang, T.; Zhang, Y. Controllable synthesis of multi-responsive ferroelectric layered perovskite-like $\text{Bi}_4\text{Ti}_3\text{O}_{12}$: photocatalysis and piezoelectric-catalysis and mechanism insight. *Appl. Catal. B. Environ.* **2017**, *219*, 550–62. DOI
36. Tian, W.; Qiu, J.; Li, N.; et al. Efficient piezocatalytic removal of BPA and Cr(VI) with SnS_2/CNFs membrane by harvesting vibration energy. *Nano. Energy*. **2021**, *86*, 106036. DOI
37. Jiang, Y.; Liang, J.; Zhuo, F.; et al. Unveiling mechanically driven catalytic processes: beyond piezocatalysis to synergetic effects. *ACS. Nano*. **2025**, *19*, 18037–74. DOI
38. Du, Y.; Sun, W.; Li, X.; et al. Mechanocatalytic hydrogen generation in centrosymmetric barium dititanate. *Adv. Sci.* **2024**, *11*, e2404483. DOI PubMed PMC
39. Li, X.; Tong, W.; Shi, J.; Chen, Y.; Zhang, Y.; An, Q. Tribocatalysis mechanisms: electron transfer and transition. *J. Mater. Chem. A*. **2023**, *11*, 4458–72. DOI
40. Kajdas, C. K. Importance of the triboemission process for tribochemical reaction. *Tribol. Int.* **2005**, *38*, 337–53. DOI
41. Hu, C.; Huang, H. Advances in piezoelectric polarization enhanced photocatalytic energy conversion. *Acta. Phys. Chim. Sin.* **2023**, *2212048*. DOI
42. Li, L.; Kang, P.; Feng, D.; et al. High temperature liquid shock manufacturing of RuNi catalysts for hydrogen evolution reaction. *Prog. Nat. Sci. Mater. Int.* **2024**, *34*, 985–9. DOI
43. Zhang, B.; Sun, B.; Liu, F.; Gao, T.; Zhou, G. TiO_2 -based S-scheme photocatalysts for solar energy conversion and environmental remediation. *Sci. China. Mater.* **2024**, *67*, 424–43. DOI
44. Brereton, K. R.; Bonn, A. G.; Miller, A. J. M. Molecular photoelectrocatalysts for light-driven hydrogen production. *ACS. Energy. Lett.* **2018**, *3*, 1128–36. DOI
45. Sun, Y.; Li, X.; Vijayakumar, A.; et al. Hydrogen generation and degradation of organic dyes by new piezocatalytic $0.7\text{BiFeO}_3\text{-}0.3\text{BaTiO}_3$ nanoparticles with proper band alignment. *ACS. Appl. Mater. Interfaces*. **2021**, *13*, 11050–7. DOI
46. Chen, Z.; Liu, W.; Zheng, L.; et al. Enhancing production of hydrogen and simultaneous degradation of ciprofloxacin over Sn doped SrTiO_3 piezocatalyst. *Sep. Purif. Technol.* **2025**, *353*, 128307. DOI
47. You, H.; Wu, Z.; Zhang, L.; et al. Harvesting the vibration energy of BiFeO_3 nanosheets for hydrogen evolution. *Angew. Chem. Int. Ed.* **2019**, *58*, 11779–84. DOI
48. Xu, X.; Xiao, L.; Wu, Z.; et al. Harvesting vibration energy to piezo-catalytically generate hydrogen through Bi_2WO_6 layered-perovskite. *Nano. Energy*. **2020**, *78*, 105351. DOI
49. Ning, X.; Jia, D.; Li, S.; Khan, M. F.; Hao, A. Oxygen-incorporated MoS_2 catalyst for remarkable enhancing piezocatalytic H_2 evolution and degradation of organic pollutant. *Rare. Met.* **2023**, *42*, 3034–45. DOI
50. Mondal, S.; Dilly Rajan, K.; Patra, L.; Rathinam, M.; Ganesh, V. Sulfur vacancy-induced enhancement of piezocatalytic H_2 production in MoS_2 . *Small* **2025**, *21*, e2411828. DOI PubMed
51. Chou, T.; Chan, S.; Lin, Y.; et al. A highly efficient Au- MoS_2 nanocatalyst for tunable piezocatalytic and photocatalytic water disinfection. *Nano. Energy*. **2019**, *57*, 14–21. DOI
52. Zhao, S.; Liu, M.; Zhang, Y.; et al. Harvesting mechanical energy for hydrogen generation by piezoelectric metal-organic frameworks. *Mater. Horiz.* **2022**, *9*, 1978–83. DOI
53. Su, P.; Kong, D.; Zhao, H.; et al. $\text{SnFe}_2\text{O}_4/\text{ZnIn}_2\text{S}_4/\text{PVDF}$ piezophotocatalyst with improved photocatalytic hydrogen production by synergetic effects of heterojunction and piezoelectricity. *J. Adv. Ceram.* **2023**, *12*, 1685–700. DOI
54. Wang, J.; Hu, C.; Zhang, Y.; Huang, H. Engineering piezoelectricity and strain sensitivity in CdS to promote piezocatalytic hydrogen evolution. *Chin. J. Catal.* **2022**, *43*, 1277–85. DOI
55. Zhan, L.; Hu, J.; Cao, Y.; et al. Ce-regulating defect and morphology engineering for efficiently enhancing the piezocatalytic performances of BiOBr . *Chem. Commun.* **2024**, *60*, 1892–5. DOI
56. Qiu, X.; Xie, J.; Ning, X.; et al. Enhancing the piezocatalytic performance for H_2 evolution by constructing $\text{BiOCl}/\text{UiO-66}$ heterostructure. *Appl. Surf. Sci.* **2024**, *670*, 160694. DOI
57. Du, Y.; Lu, T.; Li, X.; et al. High-efficient piezocatalytic hydrogen evolution by centrosymmetric $\text{Bi}_2\text{Fe}_4\text{O}_9$ nanoplates. *Nano. Energy*. **2022**, *104*, 107919. DOI
58. Lei, R.; Gao, F.; Yuan, J.; et al. Free layer-dependent piezoelectricity of oxygen-doped MoS_2 for the enhanced piezocatalytic hydrogen evolution from pure water. *Appl. Surf. Sci.* **2022**, *576*, 151851. DOI
59. Li, Y.; Li, L.; Liu, F.; et al. Robust route to H_2O_2 and H_2 via intermediate water splitting enabled by capitalizing on minimum vanadium-doped piezocatalysts. *Nano. Res.* **2022**, *15*, 7986–93. DOI PubMed PMC
60. Lei, R.; Fu, X.; Chen, N.; Chen, Y.; Feng, W.; Liu, P. Cocatalyst engineering to weaken the charge screening effect over $\text{Au-Bi}_4\text{Ti}_3\text{O}_{12}$ for piezocatalytic pure water splitting. *Catal. Sci. Technol.* **2022**, *12*, 7361–8. DOI

-
61. Ma, Y.; Wang, B.; Zhong, Y.; et al. Bifunctional $\text{RbBiNb}_2\text{O}_7/\text{poly}(\text{tetrafluoroethylene})$ for high-efficiency piezocatalytic hydrogen and hydrogen peroxide production from pure water. *Chem. Eng. J.* **2022**, *446*, 136958. DOI
62. He, Y.; Tian, N.; An, Y.; Sun, R.; Zhang, Y.; Huang, H. Morphology regulation and oxygen vacancy construction synergistically boosting the piezocatalytic degradation and pure water splitting of SrTiO_3 . *Small* **2024**, *20*, e2407624. DOI
63. Ma, X.; Gao, Y.; Yang, B.; et al. Enhanced charge separation in La_2NiO_4 nanoplates by coupled piezocatalysis and photocatalysis for efficient H_2 evolution. *Nanoscale* **2022**, *14*, 7083–95. DOI
64. Hu, C.; Chen, F.; Wang, Y.; et al. Exceptional cocatalyst-free photo-enhanced piezocatalytic hydrogen evolution of carbon nitride nanosheets from strong in-plane polarization. *Adv. Mater.* **2021**, *33*, e2101751. DOI
65. Wang, M.; Zuo, Y.; Wang, J.; et al. Remarkably enhanced hydrogen generation of organolead halide perovskites via piezocatalysis and photocatalysis. *Adv. Energy. Mater.* **2019**, *9*, 1901801. DOI
66. Zhao, Q.; Xiao, H.; Huangfu, G.; et al. Highly-efficient piezocatalytic performance of nanocrystalline $\text{BaTi}_{0.89}\text{Sn}_{0.11}\text{O}_3$ catalyst with Tc near room temperature. *Nano. Energy.* **2021**, *85*, 106028. DOI
67. Yu, C.; He, J.; Tan, M.; et al. Selective enhancement of photo-piezocatalytic performance in BaTiO_3 via heterovalent ion doping. *Adv. Funct. Mater.* **2022**, *32*, 2209365. DOI
68. Zhou, H.; Cao, J.; Ji, Y.; Xia, M.; Yao, W. Twin boundaries-induced centrosymmetric breaking of hollow CaTiO_3 nanocuboids for piezocatalytic hydrogen evolution. *Small* **2024**, *20*, e2402679. DOI
69. Tang, Q.; Wu, J.; Kim, D.; et al. Enhanced piezocatalytic performance of BaTiO_3 nanosheets with highly exposed {001} facets. *Adv. Funct. Mater.* **2022**, *32*, 2202180. DOI
70. Wang, Y.; Wu, J. M. Effect of controlled oxygen vacancy on H_2 -production through the piezocatalysis and piezophotonics of ferroelectric R3C ZnSnO_3 nanowires. *Adv. Funct. Mater.* **2020**, *30*, 1907619. DOI
71. Ma, J.; Xia, L.; Ruan, L.; et al. Sacrificial agent effect in piezo-electrocatalytic hydrogen evolution. *Appl. Phys. Lett.* **2023**, *122*, 203902. DOI
72. Su, R.; Hsain, H. A.; Wu, M.; et al. Nano-ferroelectric for high efficiency overall water splitting under ultrasonic vibration. *Angew. Chem. Int. Ed.* **2019**, *58*, 15076–81. DOI
73. Feng, W.; Yuan, J.; Zhang, L.; et al. Atomically thin ZnS nanosheets: facile synthesis and superior piezocatalytic H_2 production from pure H_2O . *Appl. Catal. B. Environ.* **2020**, *277*, 119250. DOI
74. Feng, W.; Yuan, J.; Gao, F.; et al. Piezopotential-driven simulated electrocatalytic nanosystem of ultrasmall MoC quantum dots encapsulated in ultrathin N-doped graphene vesicles for superhigh H_2 production from pure water. *Nano. Energy.* **2020**, *75*, 104990. DOI
75. Tian, J.; Li, J.; Guo, Y.; Liu, Z.; Liu, B.; Li, J. Oxygen vacancy mediated bismuth-based photocatalysts. *Adv. Powder. Mater.* **2024**, *3*, 100201. DOI
76. Zhang, Y.; Feng, K.; Song, M.; et al. Dislocation-engineered piezocatalytic water splitting in single-crystal BaTiO_3 . *Energy. Environ. Sci.* **2025**, *18*, 602–12. DOI
77. Ning, X.; Hao, A.; Cao, Y.; et al. Construction of $\text{MXene}/\text{Bi}_2\text{WO}_6$ schottky junction for highly efficient piezocatalytic hydrogen evolution and unraveling mechanism. *Nano. Lett.* **2024**, *24*, 3361–8. DOI
78. Low, J.; Yu, J.; Jaroniec, M.; Wageh, S.; Al-Ghamdi, A. A. Heterojunction photocatalysts. *Adv. Mater.* **2017**, *29*, 1601694. DOI PubMed
79. Zhang, K.; Sun, X.; Wang, H.; Ma, Y.; Huang, H.; Ma, T. Interfacial engineering of Bi_2MoO_6 - BaTiO_3 type-I heterojunction promotes cocatalyst-free piezocatalytic H_2 production. *Nano. Energy.* **2024**, *121*, 109206. DOI
80. Shi, M.; Wu, X.; Zhao, Y.; Li, R.; Li, C. Unlocking the key to photocatalytic hydrogen production using electronic mediators for Z-scheme water splitting. *J. Am. Chem. Soc.* **2025**, *147*, 3641–9. DOI
81. Zhang, L.; Zhang, J.; Yu, H.; Yu, J. Emerging S-scheme photocatalyst. *Adv. Mater.* **2022**, *34*, e2107668. DOI
82. Wang, Y.; Chen, Y.; Cheng, J.; et al. Acid-engineering combined heterojunction formation for high efficient piezo-catalytic $\text{FeCo-LDH}/\text{ZnO}$. *Nano. Energy.* **2025**, *144*, 111333. DOI
83. Lee, G.; Lyu, L.; Hsiao, K.; et al. Induction of a piezo-potential improves photocatalytic hydrogen production over $\text{ZnO}/\text{ZnS}/\text{MoS}_2$ heterostructures. *Nano. Energy.* **2022**, *93*, 106867. DOI
84. Fu, Y.; Wang, Y.; Zhao, H.; et al. Synthesis of ternary $\text{ZnO}/\text{ZnS}/\text{MoS}_2$ piezoelectric nanoarrays for enhanced photocatalytic performance by conversion of dual heterojunctions. *Appl. Surf. Sci.* **2021**, *556*, 149695. DOI
85. Kuru, T.; Sarilmaz, A.; Aslan, E.; Ozel, F.; Hatay Patir, I. Rational design of $\text{ZnO}/\text{SrTiO}_3$ S-scheme heterojunction for photo-enhanced piezocatalytic hydrogen production. *Appl. Surf. Sci.* **2025**, *682*, 161704. DOI
86. Xu, M. L.; Lu, M.; Qin, G. Y.; et al. Piezo-photocatalytic synergy in $\text{BiFeO}_3/\text{COF}$ Z-scheme heterostructures for high-efficiency overall water splitting. *Angew. Chem. Int. Ed.* **2022**, *61*, e202210700. DOI

87. Hao, P.; Cao, Y.; Ning, X.; et al. Rational design of CdS/BiOCl S-scheme heterojunction for effective boosting piezocatalytic H₂ evolution and pollutants degradation performances. *J. Colloid. Interface. Sci.* **2023**, *639*, 343-54. DOI
88. Yang, G.; Chen, Q.; Wang, W.; et al. Cocatalyst engineering in piezocatalysis: a promising strategy for boosting hydrogen evolution. *ACS. Appl. Mater. Interfaces.* **2021**, *13*, 15305-14. DOI
89. Shan, B.; Yuan, N.; Li, F.; et al. Plasmonic enhanced piezoelectric photocatalytic performance with PVDF@BT/MoS₂/Au by strong piezoelectric functional particle doping. *J. Alloys. Compd.* **2022**, *925*, 166695. DOI
90. Xiang, D.; Liu, Z.; Wu, M.; et al. Enhanced piezo-photoelectric catalysis with oriented carrier migration in asymmetric Au-ZnO nanorod array. *Small* **2020**, *16*, e1907603. DOI
91. Liu, W.; Fu, P.; Zhang, Y.; Xu, H.; Wang, H.; Xing, M. Efficient hydrogen production from wastewater remediation by piezoelectricity coupling advanced oxidation processes. *Proc. Natl. Acad. Sci. USA.* **2023**, *120*, e2218813120. DOI PubMed PMC
92. Zhu, Z.; Jin, Z.; Jiang, C.; et al. Ferroelectric field enhanced tribocatalytic hydrogen production and RhB dye degradation by tungsten bronze ferroelectrics. *Nanoscale* **2024**, *16*, 10597-606. DOI
93. Chen, S.; Liu, D.; Peng, T. Fundamentals and recent progress of photocatalytic nitrogen-fixation reaction over semiconductors. *Solar. RRL.* **2021**, *5*, 2000487. DOI
94. Dong, G.; Huang, C.; Chen, F.; et al. Construction of electron rich Fe active sites by FeCu alloy anchoring on carbon nitride for photocatalytic nitrogen reduction. *Rare. Met.* **2024**, *43*, 1570-9. DOI
95. Yuan, J.; Chen, F.; Feng, W.; et al. Dynamic switching spin state of Fe single atoms for piezoelectric-mediated overall nitrogen fixation photosynthesis. *Adv. Mater.* **2025**, *37*, e2504015. DOI
96. Xia, Y.; Xu, Y.; Yu, X.; et al. Structural design and control of photocatalytic nitrogen-fixing catalysts. *J. Mater. Chem. A.* **2022**, *10*, 17377-94. DOI
97. Li, M.; Huang, H.; Low, J.; Gao, C.; Long, R.; Xiong, Y. Recent progress on electrocatalyst and photocatalyst design for nitrogen reduction. *Small. Methods.* **2019**, *3*, 1800388. DOI
98. Zhang, Y.; Wang, D.; Wang, S. High-entropy alloys for electrocatalysis: design, characterization, and applications. *Small* **2022**, *18*, e2104339. DOI
99. Zhao, C.; Cai, L.; Wang, K.; et al. Novel Bi₂WO₆/ZnSnO₃ heterojunction for the ultrasonic-vibration-driven piezocatalytic degradation of RhB. *Environ. Pollut.* **2023**, *319*, 120982. DOI
100. Peng, F.; Lin, J.; Li, H.; et al. Design of piezoelectric ZnO based catalysts for ammonia production from N₂ and H₂O under ultrasound sonication. *Nano. Energy.* **2022**, *95*, 107020. DOI
101. Dai, X.; Chen, L.; Li, Z.; et al. CuS/KTa_{0.75}Nb_{0.25}O₃ nanocomposite utilizing solar and mechanical energy for catalytic N₂ fixation. *J. Colloid. Interface. Sci.* **2021**, *603*, 220-32. DOI
102. Chen, L.; Zhang, W.; Wang, J.; et al. High piezo/photocatalytic efficiency of Ag/Bi₅O₇I nanocomposite using mechanical and solar energy for N₂ fixation and methyl orange degradation. *Green. Energy. Environ.* **2023**, *8*, 283-95. DOI
103. Ning, X.; Hao, A.; Qiu, X. S-scheme heterojunction engineering of CdS/Bi₂WO₆ in breakthrough piezocatalytic nitrogen reduction and hydrogen evolution: performance, mechanism, and DFT calculations. *Adv. Funct. Mater.* **2025**, *35*, 2413217. DOI
104. Chen, L.; Wang, J.; Li, X.; et al. Facile preparation of Ag₂S/KTa_{0.5}Nb_{0.5}O₃ heterojunction for enhanced performance in catalytic nitrogen fixation via photocatalysis and piezo-photocatalysis. *Green. Energy. Environ.* **2023**, *8*, 1630-43. DOI
105. Yuan, J.; Feng, W.; Zhang, Y.; et al. Unraveling synergistic effect of defects and piezoelectric field in breakthrough piezo-photocatalytic N₂ reduction. *Adv. Mater.* **2024**, *36*, e2303845. DOI
106. Wu, Z.; Xu, T.; Ruan, L.; et al. Strong tribocatalytic nitrogen fixation of graphite carbon nitride g-C₃N₄ through harvesting friction energy. *Nanomaterials* **2022**, *12*, 1981. DOI PubMed PMC
107. Zhang, S.; Xiao, D.; Song, L.; Cui, T. Tribocatalytic nitrogen fixation assisted by active nitrogen atoms on the surface of Si₃N₄ at room temperature. *J. Phys. Chem. C.* **2024**, *128*, 19153-65. DOI
108. Yu, H.; Wei, X.; Wang, M.; et al. Macroscopic polarization enhancement boosting piezo-photocatalytic performance via Nb-doping on B-site of Bi₄Ti₃O₁₂ nanosheets. *J. Adv. Ceram.* **2024**, *13*, 437-46. DOI
109. Huang, B.; Fu, X.; Wang, K.; et al. Chemically bonded BiVO₄/Bi₁₉Cl₃S₂₇ heterojunction with fast hole extraction dynamics for continuous CO₂ photoreduction. *Adv. Powder. Mater.* **2024**, *3*, 100140. DOI
110. Li, H.; Du, H.; Luo, H.; Wang, H.; Zhu, W.; Zhou, Y. Recent developments in metal nanocluster-based catalysts for improving photocatalytic CO₂ reduction performance. *Microstructures* **2023**, *3*, 2023024. DOI
111. Liang, X.; Tian, N.; Hu, S.; Zhou, Z.; Sun, S. Recent advances of bismuth-based electrocatalysts for CO₂ reduction: strategies, mechanism and applications. *Mater. Rep. Energy.* **2023**, *3*, 100191. DOI

-
112. Lu, S.; Zhang, S.; Liu, Q.; et al. Recent advances in novel materials for photocatalytic carbon dioxide reduction. *Carbon. Neutral.* **2024**, *3*, 142–68. DOI
113. Li, Y.; Hou, Z.; Wan, X.; Liu, J.; Zhang, J. Halide perovskite-based heterostructures for photocatalytic CO₂ conversion. *Rare. Met.* **2024**, *43*, 5453–72. DOI
114. Vuong, H.; Nguyen, D.; Phuong, L. P.; Minh, P. P. D.; Ho, B. N.; Nguyen, H. A. Nitrogen-rich graphitic carbon nitride (g-C₃N₅): emerging low-bandgap materials for photocatalysis. *Carbon. Neutral.* **2023**, *2*, 425–57. DOI
115. Phuong, P. T. T.; Vo, D. N.; Duy, N. P. H.; et al. Piezoelectric catalysis for efficient reduction of CO₂ using lead-free ferroelectric particulates. *Nano. Energy.* **2022**, *95*, 107032. DOI
116. He, J.; Wang, X.; Lan, S.; et al. Breaking the intrinsic activity barriers of perovskite oxides photocatalysts for catalytic CO₂ reduction via piezoelectric polarization. *Appl. Catal. B. Environ.* **2022**, *317*, 121747. DOI
117. Zhang, Y.; Thuy Phuong, P. T.; Hoang Duy, N. P.; et al. Polarisation tuneable piezo-catalytic activity of Nb-doped PZT with low Curie temperature for efficient CO₂ reduction and H₂ generation. *Nanoscale. Adv.* **2021**, *3*, 1362–74. DOI PubMed PMC
118. Ma, J.; Jing, S.; Wang, Y.; et al. Piezo-electrocatalysis for CO₂ reduction driven by vibration. *Adv. Energy. Mater.* **2022**, *12*, 2200253. DOI
119. Ni, J.; Zhao, R.; Shi, C.; et al. Structure-tailored superlattice Bi₇Ti₄NbO₂₁: coupling octahedral tilting and rotation induced high ferroelectric polarization for efficient piezo-photocatalytic CO₂ reduction. *Adv. Powder. Mater.* **2025**, *4*, 100265. DOI
120. Li, P.; Tang, C.; Xiao, X.; Jia, Y.; Chen, W. Flammable gases produced by TiO₂ nanoparticles under magnetic stirring in water. *Friction* **2022**, *10*, 1127–33. DOI
121. Jia, X.; Wang, H.; Lei, H.; et al. Boosting tribo-catalytic conversion of H₂O and CO₂ by Co₃O₄ nanoparticles through metallic coatings in reactors. *J. Adv. Ceram.* **2023**, *12*, 1833–43. DOI
122. Lei, H.; Wu, Z.; Wang, H.; et al. Converting H₂O and CO₂ into chemical fuels by nickel via friction. *Surf. Interfaces.* **2024**, *46*, 104203. DOI
123. Tang, J.; Kumar, P. V.; Scott, J. A.; et al. Low temperature nano mechano-electrocatalytic CH₄ conversion. *ACS. Nano.* **2022**, *16*, 8684–93. DOI
124. Tang, Y.; Hao, J.; Qu, J.; et al. Robust synergistic effects of doping and defect engineering in photocatalytic H₂O₂ production. *Mater. Rep. Energy.* **2025**, *5*, 100325. DOI
125. Huang, J.; Dong, H.; An, L.; Zhu, M.; Qin, J. Al-based metal-organic framework for piezocatalytic hydrogen peroxide production: efficiency, pathway, and mechanism. *Chem. Eng. J.* **2025**, *504*, 158555. DOI
126. Wang, Y.; Waterhouse, G. I. N.; Shang, L.; Zhang, T. Electrocatalytic oxygen reduction to hydrogen peroxide: from homogeneous to heterogeneous electrocatalysis. *Adv. Energy. Mater.* **2021**, *11*, 2003323. DOI
127. Zhang, B.; Zhao, M.; Cheng, K.; et al. Piezoelectric effect coupled advanced oxidation processes for environmental catalysis application. *Coord. Chem. Rev.* **2025**, *523*, 216234. DOI
128. Wu, Y.; Wang, P.; Che, H.; Liu, W.; Tang, C.; Ao, Y. Triggering dual two-electron Pathway for H₂O₂ generation by multiple [Bi-O]_n interlayers in ultrathin Bi₁₂O₁₇Cl₂ towards efficient piezo-self-fenton catalysis. *Angew. Chem. Int. Ed.* **2024**, *63*, e202316410. DOI
129. Lin, S.; Wang, Q.; Huang, H.; Zhang, Y. Piezocatalytic and photocatalytic hydrogen peroxide evolution of sulfide solid solution nano-branches from pure water and air. *Small* **2022**, *18*, e2200914. DOI
130. Wang, C.; Chen, F.; Hu, C.; Ma, T.; Zhang, Y.; Huang, H. Efficient piezocatalytic H₂O₂ production of atomic-level thickness Bi₄Ti₃O₁₂ nanosheets with surface oxygen vacancy. *Chem. Eng. J.* **2022**, *431*, 133930. DOI
131. Fu, C.; Wu, T.; Sun, G.; et al. Dual-defect enhanced piezocatalytic performance of C₃N₅ for multifunctional applications. *Appl. Catal. B. Environ.* **2023**, *323*, 122196. DOI
132. Banoo, M.; Samanta, K.; Sah, A. K.; et al. Bi off-centering in centrosymmetric BiOBr leading to ultrahigh bifunctional piezocatalytic fuel generation efficiencies in seawater. *Adv. Funct. Mater.* **2024**, *34*, 2411464. DOI
133. Shao, D.; Zhang, L.; Sun, S.; Wang, W. Oxygen reduction reaction for generating H₂O₂ through a piezo-catalytic process over bismuth oxychloride. *ChemSusChem* **2018**, *11*, 527–31. DOI
134. Wang, K.; Zhang, M.; Li, D.; et al. Ternary BaCaZrTi perovskite oxide piezocatalysts dancing for efficient hydrogen peroxide generation. *Nano. Energy.* **2022**, *98*, 107251. DOI
135. Zhang, Y.; Lin, Y.; Li, R.; et al. Enhanced piezo-catalytic H₂O₂ production over Bi_{0.5}Na_{0.5}TiO₃ via piezoelectricity enhancement and surface engineering. *Chem. Eng. J.* **2023**, *465*, 143043. DOI
136. Wang, K.; Shao, D.; Zhang, L.; Zhou, Y.; Wang, H.; Wang, W. Efficient piezo-catalytic hydrogen peroxide production from water and oxygen over graphitic carbon nitride. *J. Mater. Chem. A.* **2019**, *7*, 20383–9. DOI

137. Cui, Y.; Wang, F.; Yuan, P.; et al. Harvesting vibration energy to produce hydrogen peroxide with Bi₃TiNbO₉ nanosheets through a water oxidation dominated dual-channel pathway. *ACS. Sustain. Chem. Eng.* **2024**, *12*, 3595-607. DOI
138. He, J.; Li, Z.; Feng, P.; et al. Piezo-catalysis mechanism elucidation by tracking oxygen reduction to hydrogen peroxide with in situ EPR spectroscopy. *Angew. Chem. Int. Ed.* **2024**, *63*, e202410381. DOI
139. Zhou, X.; Yan, F.; Lyubartsev, A.; et al. Efficient production of solar hydrogen peroxide using piezoelectric polarization and photoinduced charge transfer of nanopiezoelectrics sensitized by carbon quantum dots. *Adv. Sci.* **2022**, *9*, e2105792. DOI PubMed PMC
140. Qiu, X.; Hao, A.; Hu, S.; et al. Oxygen vacancy engineering of Bi₄Ti₃O₁₂ piezocatalyst driving in situ H₂O₂ evolution for self-cycled Fenton-like degradation of pollutants. *Inorg. Chem.* **2025**, *64*, 6172-82. DOI
141. Berbille, A.; Li, X. F.; Su, Y.; et al. Mechanism for generating H₂O₂ at water-solid interface by contact-electrification. *Adv. Mater.* **2023**, *35*, e2304387. DOI
142. Zhao, J.; Zhang, X.; Xu, J.; Tang, W.; Lin, Wang. Z.; Fan, F. R. Contact-electro-catalysis for direct synthesis of H₂O₂ under ambient conditions. *Angew. Chem. Int. Ed.* **2023**, *62*, e202300604. DOI

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