Peroxymonosulfate Activation by BaTiO$_3$ Piezocatalyst

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Abstract: Peroxymonosulfate (PMS) plays an important role in the advanced oxidation process for environmental remediation. In this study, barium titanate (BTO) piezocatalyst was selected for the activation of PMS driven by ultrasonic power. The degradation of Rhodamine B (RhB) by BTO single component, PMS single component, and BTO/PMS double components were investigated. The results indicated that PMS can be efficiently activated by BTO under an ultrasound with an RhB degradation rate of 98% within 20 min. The ultrasound not only promoted the activation of the PMS itself, but the surface charge carriers of BTO induced by the ultrasound also contributed to the activation of PMS. $\cdot$O$_2^-$, $\cdot$OH, and $\cdot$SO$_4^-$ radicals were found to be the main active species that participated in the reaction. In order to verify the reaction’s environmental applicability, amoxicillin (AMX) as a typical environmental pollutant was studied. BTO/PMS displayed 80% removal efficiency of AMX, and the products generated were less toxic as demonstrated by eco-toxicity comparison. This work provides a promising strategy to improve the utilization of ultrasonic energy and apply it to the field of environmental pollutants treatment.

Keywords: barium titanate; ultrasonic; peroxymonosulfate; piezocatalyst

1. Introduction

In recent years, some researchers have paid special attention to the degradation of refractory organic pollutants by peroxymonosulfate (PMS) systems [1–3]. PMS can react directly with organic pollutants, but this reaction rate is limited [4–6]. To locally produce more oxidizing active species, the PMS must be properly activated [7–9]. The active species generated from PMS are mainly $\cdot$SO$_4^-$ and $\cdot$OH [10,11]. The redox potentials of $\cdot$SO$_4^-$ and $\cdot$OH radicals are relatively high, and thus they can degrade a variety of organic pollutants quickly and efficiently [12–14]. At present, the main activation methods of PMS mainly include ultraviolet activation, ultrasonic activation, metal/metal oxide activation, and carbon-based material activation [15–17]. Physical activation processes such as light or vibration activation provide very limited PMS activation efficiency [18–20]. Catalytic approaches, whatever homogeneous or heterogeneous ones, provide more efficient PMS activation processes.

Photocatalysts [21–28] and piezocatalysts [29–35] both demonstrate excellent PMS activation efficiencies. For example, the $g$-C$_3$N$_4$-based photocatalyst exhibits excellent PMS activation. Photo-generated electrons can interact with PMS and facilitate its activation. Jiang et al. [36] propose that the facile static interactions between host $g$-C$_3$N$_4$ and negatively charged PMS influence the degradation efficiency of acidic orange 7. However, direct PMS activation needs UV light, which restricts its application. Piezocatalysis has the advantage of converting mechanical energy into chemical energy by exploiting abundant low-frequency vibration energy sources. For example, Cao et al. [37] report that PMS can be activated by the MoS$_2$ piezocatalyst with sulfur vacancies. The O–O bond length in PMS is prolonged, which results in the generation of more abundant $\cdot$OH and $\cdot$SO$_4^-$ radicals. On one hand, PMS can be directly activated by ultrasound. On the other hand, the coupling of PMS and
carriers generated by a piezocatalyst also promotes PMS activation. Until now, few studies have combined PMS activation with varieties of piezocatalysts.

Barium titanate (BTO) has been used as piezocatalyst due to its facile preparation and stability [38–42]. Herein, BTO catalysts with different morphologies were synthesized by hydrothermal method and used for PMS activation. Rhodamine B (RhB) was taken as the characteristic pollutant to study the synergetic effect between PMS and BTO. Furthermore, parameters such as catalyst dosage, PMS concentration, ultrasonic power, and the presence of inorganic anions on the removal efficiency of RhB were investigated. Finally, amoxicillin (AMX), a widely used drug, was selected to investigate the application of this synergetic system. The possible degradation intermediates of amoxicillin and the toxicity of the products in the reaction process were also provided.

2. Results and Discussion
2.1. Characterizations

BTO-180, BTO-210, and BTO-240 samples with different morphologies were prepared (Figure 1a–c). BTO-180 catalyst presented a fine and smooth linear structure. The average length of the nanowires structure exceeded 10 µm. BTO-210 catalyst has a mixed linear and rod-like structure. When the reaction temperature reached 240 °C, the morphology of BTO-240 changed into a short rod-like structure. Figure 1d shows the XRD patterns of different samples. The diffraction peaks of BTO samples at 21.99°, 31.56°, 38.87°, 45.20°, 50.89°, 56.09°, and 65.77° corresponded well to (100), (110), (111), (200), (210), (211), and (220) of standard card, respectively (JCPDS: 05-0626; tetragonal barium titanate) [42]. No other miscellaneous peaks appeared on the XRD patterns, indicating good crystallinity of the materials. Since the deformation of the samples affects the corresponding piezoelectric properties, the finite element method (FEM) of COMSOL software was used to simulate the distribution of piezoelectric potential (Figure 1e). The length of the BTO model was set to 200, 600, and 1000 nm to simulate the effect of morphology on the piezoelectric effect. In the simulation of the piezoelectric potential, the polar axis of BTO was oriented along the Z-axis, and the piezoelectric potential in the BTO nanowire was mainly distributed at the bottom, so the piezoelectric potential in the nanowire was continuously distributed along the polar axis. When 10^8 Pa pressure was applied, it produced a maximum potential difference of 128 mV for a model of length of 200 nm; the maximum potential difference was 356 mV for the model with a length of 600 nm, and 530 mV for the model with a length of 1000 nm. The results indicated that longer nanostructures were more likely to induce piezoelectric effects. Related studies also proved the correlations between morphologies and piezoelectric properties; easier deformation corresponded to higher piezopotential [3,10,12].

To further confirm the piezocatalytic activity of different BTO catalysts, the dye degradation experiments were conducted. In Figure 1f, the degradation rate of BTO-180 catalyst reached 70% when the ultrasonic reaction was carried out for 40 min. As for BTO-210 catalyst, the degradation efficiency was slightly lower than that of BTO-180 catalyst, but significantly higher than that of BTO-240 catalyst. Combined with the COMSOL analysis, BTO-180 was selected for the PMS activation test.

To further investigate the structure of the BTO-180 catalyst, some other characterizations were carried out. BTO-180 presented a rod-like structure via TEM, consistent with the results obtained via SEM (Figure 2a). Clear lattice stripes with 0.41 nm spacing were observed (Figure 2b), which corresponded to the (100) crystal surface. The SEAD diagram showed a large number of diffraction spots with a parallel regular arrangement, indicating that the BTO catalyst was a single crystal structure. The N2 adsorption-desorption isotherm of the catalyst complied with the type III isotherm. A rapid rise near P/P0 = 1 demonstrated the presence of large holes (Figure 2c), which was due to the overlapping of nanorods. The specific surface area of BTO-180 was 7.1 m²/g, calculated using the BET method. The topography image on the left shows the morphology of the polycrystalline material. The PFM phase signal is shown on the right, revealing the ferroelectric domains in this sample. Figure 2d shows a rod-like BTO-180 PFM phase image. Under the ±10 V DC
bias electric field, the typical butterfly curve (Figure 2e) and the reverse of the piezoelectric hysteresis loop (Figure 2f) were measured. The test results revealed the catalyst with a large displacement and a phase change of 180, which showed that the BTO-180 demonstrates a good piezoelectric response.

Figure 1. (a–c) SEM images of BTO-180, BTO-210, and BTO-240. (d) XRD patterns of various samples. (e) The influence of deformation on piezoelectric potential. (f) The performance of RhB degradation (5 mg/L) on different samples.

Figure 2. (a,b) TEM images and the corresponding SEAD pattern of BTO-180. (c) The N₂ adsorption curve of BTO-180. (d) PFM images of BTO-180. (e,f) The butterfly curves and a reverse piezoelectric hysteresis loop of BTO-180.
2.2. Performances

As shown in Figure 3a, the degradation efficiency of RhB under ultrasound with PMS was about 25%. The activation of PMS by ultrasound with the generation of active radicals facilitated the degradation of RhB. In the absence of PMS, BTO-180 can also decompose RhB, and the removal efficiency was about 37%, which was still not enough for the decomposition of RhB. Nevertheless, the degradation efficiency of RhB gradually increased under the synergistic effects of BTO and PMS. When the PMS dosage was 0.2 g/L, the degradation rate of RhB reached 98%, indicating that the activation of PMS could indeed assist the catalytic degradation of pollutants. Under ultrasonic conditions, the activation of PMS by BTO-180 generated more active species, which promoted the degradation of RhB. However, when the dosage of PMS increased to 0.3 g/L, the activation of PMS by the catalyst reached saturation, and the excess PMS in the system did not react with the catalyst. Moreover, the kinetic analysis was conducted (Figure 3b). The degradation of RhB followed a quasi-first-order kinetic reaction. The reaction rate constant \( k \) for pure PMS (0.2 g/L) and BTO-180 was 0.002 and 0.003 min\(^{-1}\), respectively. For the PMS/BTO-180 (0.2 g/L), the reaction rate constant \( k \) reached as high as 0.032 min\(^{-1}\), which was 10 times those of pure PMS and BTO-180. In addition, we also investigated the effect of the ultrasound power on the degradation of RhB by the BTO/PMS system. As shown in Figure 3c, RhB was barely degraded in the absence of ultrasound, but was degraded by about 50% at 120 min at 100 W, and by about 80% at 200 W and 400 W, with the best effect at 300 W, and with faster degradation rates. Considering the removal efficiency and economic benefits, 300 W was finally used.

![Figure 3. (a) The effect of PMS concentration on RhB degradation. (b) Reaction kinetics. (c) The effect of ultrasound power on RhB degradation.](image-url)

To optimize the reaction conditions, the effects of BTO-180 dosage, reaction pH, RhB concentration, and various anions on PMS activation were investigated. In Figure 4a, when the BTO-180 dosage was 0.08 g/L, the RhB removal efficiency was 51.5% within 120 min. With the increase of catalyst dosage (0.1 g/L), the removal efficiency of RhB increased to 96%. However, a further increase of BTO dosage did not promote the reaction. For example, when the catalyst dosage increased to 0.2 g/L, the RhB removal efficiency declined to 61.2%. Piezoelectric potential was generated at the ends of the rod-like BTO, as demonstrated by COMSOL simulation. Excess BTO might inhibit the activation of PMS due to the surface competitive adsorption [43]. The influence of pH on PMS activation was also investigated (Figure 4b). At pH = 1, the removal efficiency of RhB reached 98% after 20 min of reaction, which indicated that the active species were conducive to the reaction under the condition of strong acid [44]. However, under neutral or alkaline conditions, the degradation of RhB decreased by at least 40%; this decline was attributed to the poor stability of PMS under neutral or alkaline conditions. Under this condition, the \(-SO_4^-\) in the solution was converted to \(-OH\), and \(-OH\) has a lower redox potential and a shorter half-life than \(-SO_4^-\). It is more easily quenched, which leads to the reduction of RhB removal efficiency [44]. The effect of RhB concentration was also investigated. In Figure 4c, RhB...
could be completely degraded within 120 min when its concentration was below 10 mg/L. However, its degradation was limited due to the restriction of PMS dosage.

![Figure 4](image-url)

**Figure 4.** (a) The influence of catalyst concentration on RhB degradation. (b) The influence of pH on RhB degradation. (c) The influence of RhB concentration on its degradation performance. (d) The influence of Cl\(^{-}\) on RhB degradation. (e) The influence of HCO\(_3\)\(^{-}\) on RhB degradation. (f) The influence of NO\(_3\)\(^{-}\) on RhB degradation. Test conditions if there is no special statement: 0.1 g/L BTO-180; 10 mg/L RhB; 0.2 g/L PMS.

Moreover, natural water is not a single component; it contains many inorganic anions. The degradation of RhB in the presences of Cl\(^{-}\) (NaCl), HCO\(_3\)\(^{-}\) (NaHCO\(_3\)), and NO\(_3\)\(^{-}\) (NaNO\(_3\)) were explored. In Figure 4d, the removal efficiency of RhB decreased with the introduction of Cl\(^{-}\), which was due to the scavenging effect of Cl\(^{-}\) on the active species [45,46]. The equations are shown as follows (Equations (1)–(4)):

\[
\text{SO}_4^{2-} + \text{Cl}^- \rightarrow \text{SO}_4^{2-} + \cdot\text{Cl} \\
\cdot\text{Cl} + \text{H}_2\text{O} \rightarrow \text{ClO}^- + \text{H}^+ \\
\text{ClO}^- + \cdot\text{Cl} \rightarrow \text{Cl}_2^- + \text{OH}^- \\
\cdot\text{Cl}_2^- + \cdot\text{Cl} \rightarrow \text{Cl}_2 + \text{Cl}^- 
\]

In Figure 4e, similar phenomena were also observed in the existing HCO\(_3\)\(^{-}\) system. HCO\(_3\)\(^{-}\) could also react with \cdotSO\(_4\)\(^{-}\) species with the generation of less active \cdotOH or \cdotCO\(_3\)\(^{-}\), which resulted in the decline of the RhB degradation rate (Equations (5) and (6)) [47].

\[
\text{HCO}_3^- + \cdot\text{SO}_4^{2-} \rightarrow \text{SO}_4^{2-} + \cdot\text{HCO}_3^- \\
\text{HCO}_3^- + \cdot\text{OH} \rightarrow \text{H}_2\text{O} + \cdot\text{CO}_3^- 
\]

The presence of NO\(_3\)\(^{-}\) in PMS/BTO system also inhibited the degradation of RhB (Figure 4f). This was because the negative reaction was caused by the increase of ionic strength [48]. When the pH value of the solution was lower than 7.2, the NO\(_3\)\(^{-}\) anion competed with HSO\(_3\)\(^{-}\) for the adsorption site on BTO, which interfered with the interaction...
between HSO$_4^-$ ions and the catalytic site on the catalyst surface, and thus the PMS activation efficiency was affected.

To meet the standard for good practical application, the catalyst must have good stability. In this study, the stability of the catalyst was verified by cycle experimentation. The methods and steps of the cycle experiment were consistent with the methods mentioned above. As shown in Figure 5a, the removal efficiency of RhB decreased from 95.8% to 83.5% after the reaction was repeated seven times. No obvious changes were observed on the crystal structure of BTO-180 before or after reaction (Figure 5b). The decline of the activity was due to the inevitable loss during the catalyst cycling experiment.

![Figure 5](image)

**Figure 5.** (a) The reusability of the BTO-180 piezocatalyst for the treatment of RhB. (b) XRD patterns of the BTO-180 sample before and after use.

2.3. **Mechanism Discussion**

To study the valence state change of the catalyst before and after the reaction, experiments under three conditions were designed. In Figure 6b of Ti 2p XPS, the BTO binding energies of Ti 2p3/2 were 458.5 eV for BTO. When PMS was activated by ultrasonic power, the Ti 2p3/2 XPS shifted to higher binding energy (458.7 eV), indicating that electron transfer occurred from Ti (BTO) to O (PMS), which was strong evidence that electron coupling existed between BTO and PMS. However, for pure PMS/BTO, no obvious binding energy shift was observed, indicating that ultrasound was essential for PMS activation. The S 2p XPS was shown in Figure 6c. Due to the strong noise or traces of S element contents, we did not observe any S species in PMS/BTO. A sharp peak at 167 eV appeared, which was located around the S 2p3/2 XPS peak. The strong interaction between PMS and BTO under ultrasound conditions might facilitate the generation of adsorbed species [37].
Electron spin-resonance spectroscopy experiments allowed the accurate detection of free radicals in the reaction. In Figure 6d, \( \cdot O_2^- \) and \( \cdot OH \) free radicals [49] were detected in BTO solution under ultrasound conditions. This result indicated that charge-hole pairs were generated under ultrasound conditions as well as the charge-hole pairs used to activate oxygen and water into superoxide and hydroxyl groups. In addition, \( \cdot OH \) free radicals were detected in the BTO system, while both \( \cdot OH \) and \( \cdot SO_4^- \) radicals were detected in the BTO/PMS system, indicating that PMS was successfully activated.

Based on the above results, the PMS activation mechanism by BTO piezocatalyst was proposed (Figure 6e). With the assistance of ultrasonic vibration, the deformation of BTO piezocatalyst generated the polarization potential. The formed built-in electric field drove the separation of the polarization charges, causing the oxygen molecules and water molecules adsorbed to generate \( \cdot O_2^- \) and \( \cdot OH \) radicals. The activation of PMS under ultrasound conditions generated \( \cdot SO_4^- \) and \( \cdot OH \) radicals. Furthermore, the coupling of piezoelectrons and PMS facilitated its activation. The electrons generated by BTO transferred to PMS, and the obtained electrons were used to generate more \( \cdot SO_4^- \) and \( \cdot OH \) radicals.

2.4. Environmental Implication

As the most common β-lactam antibiotic, amoxicillin is difficult to degrade due to its high toxicity, stable chemical properties, and low biodegradation rate. Therefore, it is of great practical significance to explore an efficient and economical material for the...
treatment of amoxicillin (AMX) wastewater. The degradation of AMX was performed to check the application of this PMS/BTO piezocatalysis technique. As shown in Figure 7a, PMS/BTO-180 demonstrated a much higher AMX degradation rate (80%) than those of pure PMS and pure BTO systems, following the similar orders as observed in the RhB degradation system. Five degradation byproducts (DPs) were detected via UPLC-MS analysis (Figure 7b). The resulting DPs can be attributed to the radical attacks since -SO₄⁻ and ·OH free radicals attacked AMX through their additions to unsaturated bonds, electron transfer, and hydrogen abstraction [50,51]. DP1 was formed by adding OH on an –NH₂ group. DP2 was formed by the dehydrogenation and subsequent loss of oxygen. The formation of DP3 involved ring cleavage. DP4 exhibited the loss of an NH₂ group. Acetic acid (DP5) was also detected, further demonstrating the destruction of the AMX.

Figure 7. (a) The degradation of AMX by PMS, BTO-180, and PMS/BTO-180. (b) The detected DPs during the reaction.

Table 1 depicts the acute and chronic toxicities of AMX and its DPs towards fish, daphnia, and green algae. The guidelines proposed by the European Union and the Chinese hazard evaluation for new chemical substances, i.e., a pollutant having low acute and chronic toxicity value (mg/L), show that high risks were followed to assess the toxicity level of AMS and its DPs [52–55]. All the detected DPs showed higher values of acute toxicities (represented as LC₅₀ (towards fish and daphnia) and EC₅₀ (towards green algae)) and chronic toxicities (represented as ChV (towards fish, daphnia, and green algae)), as compared to AMX, which suggested that these DPs showed lower risks. For the nontoxic DP5, the suggested final product from the degradation of AMX divulged the effectiveness of the PMS/BTO piezocatalysis for the efficient treatment and detoxification of emerging water pollutants.

| Compound | Acute Toxicity | Chronic Toxicity |
|----------|----------------|------------------|
|          | Fish (LC₅₀) | Daphnia (EC₅₀) | Green Algae (ChV) | Fish (ChV) | Daphnia (ChV) | Green Algae (ChV) |
| AMX      | 184          | 15.3            | 30.3               | 1.73       | 3.19           | 5.12             |
| DP1      | 281          | 19.0            | 42.9               | 2.43       | 4.04           | 7.03             |
| DP2      | 3.73 × 10³  | 4.05 × 10³      | 1.73 × 10³         | 2.02 × 10³ | 26.2           | 430              |
| DP3      | 1.63 × 10⁴  | 1.13 × 10³      | 58.3               | 31.1       | 129            |                  |
| DP4      | 5.39 × 10⁴  | 2.64 × 10⁴      | 1.28 × 10⁵         | 320        | 4.23 × 10⁵     |                  |
| DP5      | 2.58 × 10⁴  | 4.40 × 10³      | 2.05 × 10³         | 732        | 778            |                  |

LC₅₀ or EC₅₀ > 100 (harmless); 10 < LC₅₀ or EC₅₀ < 100 (harmful); 1 < LC₅₀ or EC₅₀ < 10 (toxic); LC₅₀ or EC₅₀ < 1 (poisonous); ChV > 10 (harmless); 1 < ChV < 10 (harmful); 0.1 < ChV < 1 (toxic); ChV < 0.1 (poisonous) (Toxicity analysis indexes refer to HJ/T154-2004).
3. Materials and Methods

TiO\(_2\), NaOH, HCl, Ba(OH)\(_2\)-8H\(_2\)O, RhB were purchased from Sinopharm Chemical Reagent Co., Ltd (Shanghai, China). PMS (KHSO\(_5\)), Amoxicillin and DMPO were purchased from Sigma-Aldrich (St. Louis, MO, USA). Chemicals and reagents were of analytical grade and used without further purification.

3.1. Catalyst Preparation

TiO\(_2\) (1.6 g) was dissolved in NaOH (70 mL, 10 M) solution and stirred for 30 min. Then, the solution was transferred to a polytetrafluoron reactor and heated at 240 °C for 24 h. After the hydrothermal reaction, all NaTi\(_3\)O\(_7\) precipitates obtained by centrifugation were transferred to a beaker containing HCl (100 mL, 0.2 M) and stirred slowly for 4 h. Finally, the precipitates (donated as H\(_2\)Ti\(_3\)O\(_7\)) were collected and washed several times with deionized water to remove possible impurities.

For the BTO-180 sample, H\(_2\)Ti\(_3\)O\(_7\) (0.15 g) and Ba(OH)\(_2\)-8H\(_2\)O (0.55 g) were dissolved in 80 mL deionized water; then, the solution was transferred to a polytetrafluoron reactor and heated at 180 °C for 24 h. Next, the precipitates were collected and washed several times with deionized water to remove possible impurities. The synthetic procedures were the same for BTO-210 and BTO-240 with the exception of the reaction temperature.

3.2. Characterizations

The X-ray diffraction (XRD, Regaku Smartlab, Tokyo, Japan) patterns of the samples were recorded with a D/MAX-RB X-ray diffractometer; the operating voltage and current were 40 kV and 50 mA, respectively. The morphology of the catalysts was studied by a field emission scanning electron microscope (FESEM, JEOL 6490, Tokyo, Japan) at 200 kV. A high-resolution transmission electron microscope (HRTEM, JEM-2100F, Tokyo, Japan) was used to study the morphology and microstructure of the samples. Surface properties of the samples were studied by an N\(_2\) adsorption instrument (ASAP2020, Micromeritics, Atlanta, GA, USA). The chemical states of the samples were analyzed by X-ray photoelectron spectroscopy (XPS, Kratos Ultra DLD, Warwick, UK). A piezoelectric force microscope (PFM, Cypher ES, Oxford, UK) was used to study the piezoelectric phenomena of materials on the nanoscale. An electron paramagnetic resonance (EPR, EPR 200M, Bremen, Germany) spectrometer was used to detect the free radicals produced by the samples. The COMSOL Multiphysics (6.1 v., COMSOL, Burlington, MA, USA) was used to simulate the distribution of the piezoelectric potential. The pressure applied perpendicular to the plane was set to 10\(^8\) Pa.

3.3. Experimental Conditions and Analysis Methods

BTO (10 mg) was precisely weighed and dispersed in RhB solution (100 mL). The solution was stirred vigorously for 20 min under dark conditions to achieve an adsorption-desorption equilibrium. Then, a certain amount of PMS was added to the suspension and transferred to the ultrasonic instrument (40 kHz, 300 W) to start the reaction. Mixed suspension (5 mL) was collected every 20 min. Methanol (1 mL) was quickly added into the centrifuge tube and shaken well to fully quench the reaction. The concentration of RhB was determined by a UV-vis spectrophotometer at 554 nm.

BTO-180 (25 mg) was added into the amoxicillin solution (5 mg/L, 50 mL). The frequency of the ultrasonic instrument was 40 kHz and the power was 300 W. Quantitative analyses of AMX samples were performed by HPLC equipped with a quaternary pump, a stationary phase, and a variable wavelength detector at 228 nm. Methanol, acetonitrile, and acetic acid were mixed and used as mobile phases at a flow rate of 1 mL/min. A membrane filter of 0.22 µm was passed before injection.

Ultraperformance liquid chromatography-tandem mass spectrometry (UPLC-MS, Waters Corp., Pleasanton, CA, USA) was used to identify the degradation byproducts of AMX. The C18 column (150 mm × 4.6 mm; particle size of 1.7 µm) was equipped with a Quattro Premier XE tandem quadrupole mass spectrometer using an electrospray ionization source.
To test whether the applied AOP technology was clean or green, ecological structural activity relationships were used to estimate the ecotoxicity of AMX and its degradation byproducts from their acute and chronic toxicities to fish, daphnia, and green algae.

4. Conclusions

In summary, barium titanate piezocatalyst was used to activate peroxymonosulfate for the degradation of Rhodamine B. The direct activation of peroxymonosulfate by ultrasound, the formed free radicals by the barium titanate piezocatalyst, and the strong interactions between PMS and the deformed barium titanate together contributed to the degradation of Rhodamine B. ·O$_2^-$, OH, and ·SO$_4^-$ radicals were found to be the main active species that participated in the reaction. Finally, the system was used for the degradation of amoxicillin. The harmless or low-toxicity substances after reaction demonstrated the potential application of the piezocatalyst-based peroxymonosulfate activation system in pharmacy wastewater remediation. This study provides some guidance for the efficient activation of PMS. Further efforts are still needed to explore the state-of-the-art piezocatalysts.

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