**KNbO$_3$/ZnO heterojunction harvesting ultrasonic mechanical energy and solar energy to efficiently degrade methyl orange**

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**Abstract**

In this paper, KNbO$_3$/ZnO nanocomposite was synthesized and used in piezophotocatalytic degradation of methyl orange (MO) under simulated sunlight and ultrasonic vibration. Under simulated solar light, the optimal KNbO$_3$/ZnO sample presented a MO degradation rate of 0.047 min$^{-1}$, which is 2.47 times higher than that of ZnO. The promotion effect of KNbO$_3$ on ZnO was also observed in the piezoelectric catalytic reaction. In addition, the co-utilization of solar and mechanical energy can further increase the MO degradation rate. Piezoelectric property and photoresponse capability are the origins of the piezo/photo catalytic behavior of the KNbO$_3$/ZnO composite. Owing to the different band potentials of KNbO$_3$ and ZnO, the electric potential field at their interface can drive the second distribution of the photo/piezoinduced charge carriers and hence promote the photo/piezocatalytic activity. This phenomenon was verified by the analysis on transient photocurrent and piezocurrent response. Trapping experiments on reactive species were also conducted. Superoxide radicals, holes, and hydroxyl radicals were found to be the main reactive species during the photo/piezocatalytic reaction. Recycling test showed that the KNbO$_3$/ZnO composite exhibited good catalytic stability during six consecutive uses. Given its advantages of good catalytic activity and stability, the synthesized KNbO$_3$/ZnO nanocomposite material has great potential in the further use of solar and mechanical energy to develop new water purification technologies.

**1. Introduction**

With the rapid development of the economy, environmental pollution has become a huge problem for humans. Photocatalysis can decompose organic compounds in wastewater into non-toxic inorganic substances by using solar energy, thus providing a green approach for wastewater treatment [1]. Piezocatalysis is another new green technology that uses mechanical vibration to enrich heat-excited free electrons and holes on the surface of piezocatalyst particles, thus generating active free radicals with strong oxidation ability to decompose organic pollutants [2]. The abundant low-frequency mechanical energy source in nature guarantees the wide application prospective of this technique. Given that piezocatalysis can realize the effective degradation of dye molecules in the absence of light or weak light, this method can effectively compensate for the shortage of photocatalysis.

ZnO nanostructures have been widely used in organic pollutant degradation due to their high photocatalytic efficiency, low cost, and environmental friendliness [3–7]. When the light energy is equal to or exceeds the band gap energy of zinc oxide, the electrons are excited from the valence band (VB) to the conduction band (CB) and leave the same number of holes. The photogenerated charge carriers then migrate to the surface and induces photocatalysis. In addition, ZnO has good piezoelectric properties and can trigger the piezocatalytic reaction [8]. Nevertheless, the piezocatalytic activity of pure ZnO is still limited. Various methods, such as morphology modification, oxygen vacancy introduction, noble metal loading, and semiconductor coupling, have been used to improve the piezocatalytic performance of ZnO. Ning et al. synthesized ZnO nanorods (NRs) and nanoparticles (NPs) via a solid-state chemical method [9]. ZnO NRs exhibit 5–18 times higher piezoelectric potential and thus have higher piezoelectric activity than ZnO NPs in MB degradation. Bai et al. introduced oxygen vacancy into ZnO via heating the ZnO powders in the H$_2$Ar atmosphere [10]. The introduced oxygen vacancies increase the content of free charge carriers and hence enhance the catalytic activity of ZnO in piezocatalytic RhB degradation. Xiang et al. reported that the loading of Ag nanoparticles improves the separation of charge carriers via trapping the heat-excited free electrons, thereby enhancing the piezo/photo catalytic activity of ZnO [11]. Zhang et al. reported that decorating BiOI on ZnO nanorod...
arrays greatly improves the activity in the piezo/photo-catalytic degradation of organic pollutants [12] because of the enhanced charge separation due to the coupling effect of ZnO nanorod and BiOI. Ren et al. found that ZnS coupling presents a similar promotion effect on ZnO nanorods as that of ZnO [14]. Hence, ZnS/ZnO composite materials were also employed in the present work.

2. Experimental

2.1. Preparation of catalyst

All chemicals used in the manuscript are analytical pure, and were purchased from the Sinopharm Chemical Reagent Co., Ltd. (China). ZnO nanorods were prepared using a hydrothermal method. In brief, 1.222 g (4.6 mmol) of Nb2O5 was added to 70 mL of KOH solution (10 mol/L) and stirred for 1 h. The obtained mixture was then hydrothermally treated at 160 °C for 18 h to obtain white KNbO3 powders.

KNbO3/ZnO catalyst was also synthesized by the hydrothermal method. ZnCl2 solution was prepared via dissolving 0.02 mol (2.7260 g) ZnCl2 in 70 mL of deionized water. A certain amount (0.5%, 1%, and 1.5%) of KNbO3 nanorods was uniformly dispersed in the solution by ultrasonic treatment for 0.2 h. The NaOH solution (5 mol/L, 8 mL) was then added under stirring. After the mixture was treated hydrothermally (100 ml kettle) at 160 °C for 18 h, the KNbO3/ZnO sample was obtained via centrifugation, washing with deionized water and ethanol, and drying at 80 °C for 12 h. In the absence of KNbO3 powders, pristine ZnO was prepared by a similar method.

2.2. Piezocatalytic and photocatalytic experiments

The piezoelectric catalytic activity of different KNbO3/ZnO catalysts was examined by measuring the degradation rate of MO dye under ultrasonic vibration at room temperature. An ultrasonic generator (Jie-meng JP030, 40 kHz, 120 W) was used as the vibration source. In brief, 100 mL of MO solution (10 ppm) was used as the reaction solution, and the catalyst dosage was 0.1 g during each test. Prior to the test, an adsorption-desorption equilibrium between the catalyst and MO solution was established via continuous stirring for 1 h. During the reaction, 3 mL of the solution was collected at every 15 min interval, and the MO concentration was measured with a UV–vis spectrophotometer (Beijing Purkinje, TU-1950). Piezocatalytic experiments with different scavengers were also implemented in the same way, and the scavenger concentration is 0.001 mol/L.

The photocatalytic activity of the KNbO3/ZnO composites was investigated by conducting the photocatalytic degradation of MO under simulated sunlight. The catalytic test is the same as that of the piezocatalytic procedure, except for the vibration source that was replaced by a Xe lamp (Perfect Light, PLS-SXE300, 300 W, 300 nm < λ < 1000 nm).

Information on catalyst characterization is provided in the supplementary materials.

3. Result and discussion

3.1. Characterization of the KNbO3/ZnO composite

The structure of the KNbO3/ZnO catalysts was investigated by XRD. The XRD patterns of ZnO, KNbO3, and the KNbO3/ZnO samples are presented in Fig. 1. Pristine ZnO shows several strong characteristic peaks at 2θ = 31.8°, 34.6°, 36.2°, 47.5°, 56.5°, 62.9°, which correspond to the (100), (002), (101), (102), (110), and (103) planes of hexagonal ZnO (PDF# 36–1451), respectively. For KNbO3, the characteristic peaks appear at 22.1°, 31.6°, 45.2°, 50.9°, and 56.1°, corresponding to the (110), (111), (002), (221), and (311) planes of orthorhombic structure of KNbO3 (PDF#02–0822), respectively. The XRD patterns of the KNbO3/ZnO catalyst only show the characteristic peaks of ZnO and KNbO3. No other phases are observed, suggesting the successful formation of the KNbO3/ZnO composite. When the KNbO3 content increases, the KNbO3 peaks of the composite catalyst are gradually enhanced. By contrast, the ZnO peaks only slightly change due to the low KNbO3 concentration. (Fig. S1).
KNbO$_3$, and KNbO$_3$/ZnO composites are presented in Fig. 1 b. Neat KNbO$_3$ shows several strong Raman signals at 188, 277, 528, 590, and 830 cm$^{-1}$, which can be assigned to the vibration of Nb–O bonds [28]. For ZnO, the characteristic peaks appear at 330 and 436 cm$^{-1}$, which originates from the $E_{2g}$ and $E_{2h}$ modes of ZnO, respectively [29]. KNbO$_3$ and ZnO phases are detected in the Raman spectra of the KNbO$_3$/ZnO composite. The Raman peak of KNbO$_3$ gradually reduces with the decrease in KNbO$_3$ concentration. This result is consistent with the XRD result. However, different from the XRD patterns, the KNbO$_3$ Raman signal is strong, though its content in the composite catalyst is low. This phenomenon may be ascribed to the strong Raman response of KNbO$_3$ under Ar ion laser excitation. Another possible reason is that the KNbO$_3$ may exist on the ZnO surface in the detected area, resulting in its abnormally strong Raman signal.

X-ray photoelectron spectroscopy (XPS) was conducted to investigate the valence state of the elements in the KNbO$_3$/ZnO samples. Fig. 2a displays the Zn 2p XPS spectra of ZnO and 1%KNbO$_3$/ZnO catalysts. The Zn 2p$_{3/2}$ and Zn 2p$_{1/2}$ peaks of ZnO are located at 1021.6 and 1044.8 eV, respectively, indicating that the zinc element has a valence state of +2 [30]. Compared those of with pristine ZnO, the Zn 2p peaks of KNbO$_3$/ZnO move 0.2 eV to the lower binding energy (BE) direction. This phenomenon can be ascribed to the different Femi levels of KNbO$_3$ and ZnO. Given that both samples are n-type semiconductors and the CB of KNbO$_3$ is higher than that of ZnO [26,27], KNbO$_3$ has a higher Femi level than ZnO. When the two semiconductors are in close contact to form a heterojunction structure, electron transfer from KNbO$_3$ to ZnO may occur. This process increases the electron density around Zn and subsequently reduces the BE of Zn. For the KNbO$_3$ phase in the KNbO$_3$/ZnO composite, the outflow of electrons decreases the density of the electron cloud and increases the BE of the related elements. As shown in Fig. 2b, pure KNbO$_3$ presents two K2p peaks at 290.7 and 293.5 eV, thus confirming the +1 valence state of the K element [31]. For the 1% KNbO$_3$/ZnO sample, an obvious blue shift of the two K2p peaks can be observed in addition to the greatly reduced peak intensity due to the low KNbO$_3$ content. A similar result is also noted for the Nb 3d XPS spectra. The Nb3d BE values of 1% KNbO$_3$/ZnO are 206.4 and 209.1 eV, which are 0.4 eV higher than that of KNbO$_3$. This finding confirms that a strong interaction exists between ZnO and KNbO$_3$ and the synthesized KNbO$_3$/ZnO is a composite rather than a physical mixture [32–34]. Fig. 2d shows the O1s spectra of ZnO, KNbO$_3$, and 1%KNbO$_3$/ZnO samples. The lattice oxygen signal of KNbO$_3$ and ZnO appears at 529.2 and 530.0 eV, respectively [35]. For the 1%KNbO$_3$/ZnO sample, the O1s spectrum is similar to that of ZnO due to the low KNbO$_3$ concentration. The atomic contents of all elements in ZnO, KNbO$_3$, and 1%KNbO$_3$/ZnO were calculated. The result in Table S1 indicates that the K/Nb ratio in the KNbO$_3$ and 1%KNbO$_3$/ZnO catalysts is close to 1.0, which is consistent with the XPS results.
with the theoretical value for KNbO$_3$. Meanwhile, the K/Zn ratio of the 1%KNbO$_3$/ZnO is 0.6%, which is lower than the theoretical value of 1.0%. Given that the larger particle size of KNbO$_3$ than ZnO limits the uniform dispersion of the former in the composite piezocatalyst (Fig. 3), the variation in the K/Zn ratio is acceptable.

Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) were implemented to reveal the morphology of the KNbO$_3$/ZnO composite. Fig. 3 displays the SEM and TEM pictures of KNbO$_3$, ZnO, and 1%KNbO$_3$/ZnO. Pure KNbO$_3$ appears as nanocubes (Fig. 3a), while ZnO can be seen as nanosheets attached with some nanoparticles (Fig. 3b). The SEM image of the 1%KNbO$_3$/ZnO sample only shows the ZnO sheets. KNbO$_3$ nanocubes are not observed mainly due to the low content of KNbO$_3$ and the serious aggregation of catalyst particles. However, in the TEM image, the KNbO$_3$ nanocubes can be easily distinguished due to their lesser electron penetrating ability than the ZnO nanosheets. As shown in Fig. 3d and e, ZnO nanosheets and nanoparticles adhere to the surface of KNbO$_3$ nanocubes. The HR-TEM image displays that the nanocube and the nanosheets show clear lattice fringes of 0.2813 and 0.2098 nm, which correspond to the (1 0 0) and (1 1 0) planes of KNbO$_3$ and ZnO, respectively. Combined with the XRD and XPS finding, this result verifies that the KNbO$_3$ nanocubes have closely adhered onto the ZnO surface.

The locale piezoelectric response of the KNbO$_3$/ZnO composite was investigated by using the piezoelectric force microscope (PFM) technique. Fig. 4a, b, and c display the atomic force microscope (AFM), PFM amplitude, and PFM phase images of the 1%KNbO$_3$/ZnO sample, respectively. The images do not provide the morphological information of the composite material as clear as SEM, and only several nanoparticles can be observed. However, the locale hysteresis loop (Fig. 4d) indicates that these particles (1% KNbO$_3$/ZnO sample) present a phase angle change of approximately 180° under the reversal of 10 V DC bias field, indicating that the 1%KNbO$_3$/ZnO composite has piezoelectric property and can drive the piezoelectric catalytic reaction.

Fig. 5 shows the DRS spectra of KNbO$_3$/ZnO composite with different KNbO$_3$ contents. ZnO and KNbO$_3$ present strong absorption peaks at the UV region. The light absorption edges are at approximately 400 nm. According to the Kubelka–Munk plot, the band gaps of ZnO and KNbO$_3$ are 3.07 and 3.03 eV, respectively. Therefore, the DRS spectra of KNbO$_3$/ZnO composites are similar to those of ZnO and KNbO$_3$. The consequence in Fig. 5 shows that the synthesized KNbO$_3$/ZnO can only work under UV light.
3.2. Photo/piezocatalytic activity

The photocatalytic performances of the synthesized KNbO$_3$/ZnO composites were examined by degrading the MO solution under simulated sunlight. Owing to the wide band gap of the KNbO$_3$/ZnO catalyst, only the UV light is harvested and can stimulate the photocatalytic reaction. As shown in Fig. 6a, no MO is degraded in the absence of a photocatalyst. Pure KNbO$_3$ shows negligible photocatalytic activity, whereas ZnO exhibits good photocatalytic performance with a MO degradation rate of 0.019 min$^{-1}$ (Fig. 6b). The KNbO$_3$/ZnO composite shows higher photocatalytic activity than ZnO, suggesting that the added KNbO$_3$ hastens the photocatalytic procedure of ZnO. The KNbO$_3$ concentration in the KNbO$_3$/ZnO composite is closely related to its photocatalytic activity. When the KNbO$_3$ content increases, the photocatalytic activity of the KNbO$_3$/ZnO composite enhances first and then reduces. The 1% KNbO$_3$/ZnO composite demonstrates the maximum MO degradation rate of 0.047 min$^{-1}$, which is 2.47 times higher than that of ZnO. In addition to the photocatalytic activity, the photocatalytic stability of KNbO$_3$/ZnO catalyst was evaluated by the cyclic test. The consequence in Fig. 6c indicates that the KNbO$_3$/ZnO composite still displays high photocatalytic activity after five cyclic tests, implying its good stability. Fig. 6d shows the effect of different capture agents on the photocatalytic activity of the 1% KNbO$_3$/ZnO sample. Isopropyl alcohol (IPA), potassium iodide (KI), and p-benzoquinone (BQ) were added to the reaction solution as the capture agents of *OH, h+, and O$_2$, respectively [36-37]. Fig. 6d shows that all scavengers can retard the photocatalytic reaction, indicating that the aforementioned reactive species contribute to the photocatalytic reaction. The order of the inhibitory effect is KI > BQ > IPA, which represents that the importance of the reactive species in the photocatalytic reaction is h+ > O$_2$ > *OH.

In addition to its high photocatalytic performance, the KNbO$_3$/ZnO composite presents good piezoelectric properties, and thus has potential in the piezoelectric catalytic reaction. Thus, the piezocatalytic activity of the synthesized KNbO$_3$/ZnO was evaluated via the piezocatalytic degradation of MO under ultrasonic vibration, and the result is presented in Fig. 7. The MO degraded under ultrasonic vibration can be ignored. In the presence of ZnO or KNbO$_3$, the MO content decreases when the vibration time increases. Consistent with literature [8,9,21], this finding indicated that the two semiconductors present good piezoelectric properties and can induce the piezocatalytic reaction. The degradation rates of ZnO and KNbO$_3$ are 0.0055 and 0.0047 min$^{-1}$, respectively (Fig. 7b). For the ZnO sample, this value in piezocatalysis is lower than that in photocatalytic reaction. However, for the KNbO$_3$ sample, its piezocatalytic degradation rate is higher than its photocatalytic efficiency. The KNbO$_3$/ZnO composite has higher piezocatalytic activity than pure ZnO or KNbO$_3$, indicating the synergistic effect of ZnO and KNbO$_3$. The 1% KNbO$_3$/ZnO is still the optimal sample with a MO degradation rate of 0.008 min$^{-1}$, which is approximately 1.5- and 1.7-folds faster than those of ZnO and KNbO$_3$, respectively. Therefore, the coupling of KNbO$_3$ and ZnO fabricates an efficient piezocatalyst for MO degradation. Cyclic test and reactive trapping experiment were also performed for the 1%KNbO$_3$/ZnO composite. The result indicates that the KNbO$_3$/ZnO has high piezocatalytic stability (Fig. 7c), and the main reactive species are still h+, *O$_2$, and *OH species (Fig. 52). Photo/piezoelectric synergistic catalytic reaction shows that the KNbO$_3$/ZnO sample has a higher MO degradation efficiency under the combined action of simulated sunlight and ultrasonic vibration (Fig. 7d). This result indicates that the catalyst can be applied to treat wastewater under different conditions and can achieve a high degradation efficiency through the synergistic effect of light and ultrasonic vibration. The KNbO$_3$/ZnO catalyst may have broad application prospects in pollutant degradation.
3.3. Discussion

Photocatalytic and piezocatalytic reaction test shows the synergetic effect of KNbO$_3$ and ZnO in the photocatalytic and piezocatalytic degradation of MO, indicating that coupling KNbO$_3$ with ZnO generates an efficient photo/piezocatalyst. Herein, a detailed discussion was conducted to clarify the origin of the increased catalytic activity based on the characterization results.

ZnO and KNbO$_3$ are well-known semiconductor photocatalysts. Various ZnO or KNbO$_3$ based composite photocatalysts have been reported, such as ZnO/KNb$_2$O$_6$ [38], NiO/KNbO$_3$ [26], MoS$_2$/ZnO [39], and In$_2$S$_3$/KNbO$_3$ [40]. Almost all the composite catalysts have achieved an increase in photocatalytic performance due to the increased efficiency in charge separation. Therefore, the improved photocatalytic activity of KNbO$_3$/ZnO has originated from the synergetic effect of KNbO$_3$ and ZnO in hindering the recombination of photoexcited electrons and holes. VB XPS analysis indicates that the VB top of KNbO$_3$ and ZnO are 2.13 and 2.54 eV, respectively (Figure S3). On the basis of DRS result and $E_g = E_{VB} - E_{CB}$, the conduction bottoms of KNbO$_3$ and ZnO are determined to be $-0.90$ and $-0.53$ eV, respectively. The energy band positions of KNO$_3$ and ZnO can also be calculated based on the empirical formula of $E_{VB} = X - E_0 + 0.5E_g$ (Table S2) [41,42]. Owing to the use of different testing methods, the CB and VB positions of KNbO$_3$ and ZnO are slightly different [26,27]. However, their relative position is not changed. KNbO$_3$ exhibits higher CB and VB position than ZnO. The matched band potential reveals that KNbO$_3$ and ZnO can fabricate a type-II heterojunction structure, which leads to the directional migration of free electrons and the decreased recombination possibility of charge carriers (Fig. 8). Hence, the photoactivity of the KNbO$_3$/ZnO composite is increased.

In addition to its good performance in photocatalytic reaction, KNbO$_3$/ZnO presents an impressive performance in the piezocatalytic degradation of MO under ultrasonic vibration. The good piezoelectric property of KNbO$_3$ and ZnO is undoubtedly the key factor. Semiconductors have low contents of the heat-excited free charges under normal circumstances [43]. No redox reaction can be observed. Under ultrasonic vibration, however, the mechanical force generated by the cavitation phenomenon strikes the surface of ZnO or KNbO$_3$ and causes them to form local strain. A piezoelectric potential is thus produced because of the collectively induced polarization of charges in whole unit cells in the crystal. This potential attracts the heat-excited free charges in the piezoelectric material towards the opposite directions of the crystal surfaces. These separated free charges accumulate at the interface and react with hydroxyl or dissolved oxygen to form reactive species, which then induces the surface electrochemical reactions to degrade dye molecules [43,44]. For the ZnO/KNbO$_3$ heterojunction, the different band potentials of the two semiconductors induce an electric potential field at the interface, which drives the second distribution of the piezoinduced charge carriers. The electrons prefer to accumulate on the ZnO side, and the positive charges are enriched on the KNbO$_3$ particles (Fig. 8). This process improves the separation and utilization of free charge carriers and thereby increases the piezocatalytic activity in MO degradation. When the light and ultrasonic vibration simultaneously act on the catalyst, the bending of the energy band induced by the piezoelectric effect speed up the migration of photoexcited charge carriers [45–47]. Therefore, the separation efficiency of electron-hole pairs is further improved, resulting in good photo/piezocatalytic activity.

For confirmation, a series of electrochemical experiments was implemented to examine the separation of electron-hole pairs in the KNbO$_3$/ZnO composite. Fig. 9a shows the transient photocurrent (PC) response of ZnO, KNbO$_3$, and KNbO$_3$/ZnO composites under simulated sunlight irradiation. ZnO electrode displays higher photocurrent response than KNbO$_3$, indicating its better capability in separating electron-hole pairs and higher photocatalytic activity [48–50]. This finding is consistent with Fig. 7. KNbO$_3$/ZnO composites possess higher photocurrent than ZnO, implying the synergistic effect of KNbO$_3$ and ZnO in retarding the recombination of charge carriers and confirming the suggested mechanism in Fig. 8. The highest photocurrent is observed in the 1% KNbO$_3$/ZnO sample, indicating its best capability in charge separation. Considering that the heterojunction structure of KNbO$_3$ and ZnO is the main reason for the improved charge separation, the 1% KNbO$_3$/ZnO may have a suitable KNbO$_3$ concentration. Therefore, this sample has the most heterojunction structures in the composite and efficiently accelerates the charge separation, thereby leading to its highest photo/piezocatalytic activity. In addition to the photocurrent experiment, electrochemical impedance spectroscopy (EIS) was
conducted to confirm the promotion effect of KNbO$_3$/ZnO heterojunction in charge separation. The EIS curves of ZnO, KNbO$_3$, and KNbO$_3$/ZnO composites with different KNbO$_3$ contents are shown in Fig. 9b. In general, a small arc size of the Nyquist circles represents a low electron transfer interface resistance [51–53]. The smallest arc radius is observed in the Nyquist circle of the 1% KNbO$_3$/ZnO composite, suggesting its lower interfacial resistance than other catalysts. Therefore, the introduced KNbO$_3$ increases the transfer and separation of carriers of ZnO by forming a heterojunction structure. This finding is in agreement with the PC results.

Fig. 10 shows the piezoelectric current response of KNbO$_3$, ZnO, and 1% KNbO$_3$/ZnO samples. The current response is still observed under periodic ultrasonic vibration, thus confirming the piezoelectric property of the three samples. The piezoelectric current is only approximately 0.1% of the photocurrent, which can be ascribed to the low content of heat-excited free electrons in the samples. The 1% KNbO$_3$/ZnO electrode produces the highest piezoelectric current, thus proving that the heterostructure of KNbO$_3$ and ZnO improves the separation of piezoelectric-induced charge carriers [54–56]. Therefore, the KNbO$_3$/ZnO composite displays an enhanced piezocatalytic performance.

4. Conclusion

A novel piezoelectric catalyst KNbO$_3$/ZnO composite was successfully synthesized by a two-step hydrothermal method and applied in the piezo/photocatalytic degradation of MO. KNbO$_3$ and ZnO showed a strong interaction that triggered the formation of a type-II heterojunction and enhanced the separation efficiency of electron-hole pairs. Hence, the KNbO$_3$/ZnO nanocomposite shows higher efficiency than pure ZnO or KNbO$_3$ in harvesting vibration energy or solar energy for MO degradation. In addition, the KNbO$_3$/ZnO nanocomposite also maintains stable photo/piezocatalytic efficiency in cyclic test, indicating its potential application in water purification.

CRediT authorship contribution statement

Yi Li: Writing – original draft, Investigation, Formal analysis, Data curation. Huafeng Chen: Investigation, Validation. Linkun Wang: Investigation. Tiantian Wu: Investigation. Ying Wu: Conceptualization, Resources, Methodology, Writing – review & editing. Yiming He: Conceptualization, Supervision, Project administration, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
Fig. 7. Piezocatalytic activity of ZnO, KNbO₃, KNbO₃/ZnO composites (a) and the corresponding degradation rate (b), the cycling test of 1% KNbO₃/ZnO composite under ultrasonic vibration (c), and the catalytic activity of 1% KNbO₃/ZnO under simulated sunlight and ultrasonic vibration (d).

Fig. 8. Possible mechanism of KNbO₃/ZnO in photocatalysis and piezocatalysis.
Fig. 9. The transient photocurrent response (a) and EIS (b) of ZnO, KNbO$_3$, and KNbO$_3$/ZnO composites with different KNbO$_3$ contents.

Fig. 10. The generated current response of ZnO, KNbO$_3$, and 1% KNbO$_3$/ZnO under ultrasonic vibration.

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Appendix A. Supplementary data

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