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Impact of stirring regime on piezocatalytic dye degradation using $BaTiO_3$ nanoparticles

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ABSTRACT

There is increasing demand to use readily accessible waste energy to drive environmentally friendly processes. Piezocatalysis, the process of converting mechanical energy such as vibration into a chemical process, is a breakthrough next generation approach to meet this challenge. However, these systems currently focus on using ultrasound to drive the chemical reaction and are therefore expensive to operate. We show that by using simple mechanical stirring and BaTiO₃ particles we can remove Rhodamine B dye molecules from solution. After evaluating a range of stirring parameters, we demonstrate that there is an interplay between stirring speed, volume of liquid, catalyst structure and rate of dye removal. Our maximum degradation rate was 12.05 mg. g^{-1} catalyst after 1 h of mechanical stirring at favourable conditions. This development provides a new insight into a low energy physical technique that can be used in environmental remediation processes.

1. Introduction

Global population growth and industrial development has significantly increased our energy demand in the last 30 years. There is an accepted and growing need to find sustainable processes to mitigate the generation of toxic waste to provide a cleaner and greener future. While there have been growing efforts to decrease our reliance on fossil fuels, they are still heavily used to meet our energy requirements. The discharge of industrial chemicals, such as dyes, play a role in affecting the aquatic environment and impact on the availability of clean water. Catalytic processes can be used to remove pollutants from wastewater streams where traditional materials and functional ferroic materials have shown promise [1-4].

The use of piezoelectric materials to enhance chemical conversion, often termed piezocatalysis, such as water purification and hydrogen generation is generating increasing attention [5–7]. There are currently

two competing schools of thought to explain the mechanisms driving piezocatalysis. These are the energy band effect originating from surface charge separation which is caused by the deformation of the piezoelectric crystal by incoming mechanical energy [8,9]. The second theory is that local chemisorbed species on the surface of the piezoelectric material are driven to products through band bending. The polarisation changes due to the converse piezoelectric effect cause an oscillation in the band position through which mobile carriers can be delivered to chemisorbed species driving a chemical reaction. This can be considered analogous to energy band theory and the fundamental physics of photocatalysis. Akin to photocatalysis, the position band levels (valence and conduction bands) in the material [10] limit the chemistry that can be performed. This theory relies on the polarisation and associated band bending of a piezoelectric material to allow carriers to move across the boundary between piezoelectric and reactive species. This movement of carriers drives the chemical reaction. In either case, the overall result is

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Full paper



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that there is sufficient energy available from the piezoelectric material when coupled to mechanical vibration to drive a chemical reaction.

To date, research has been primarily focused on ultrasonic excitation to deliver the mechanical input required to activate piezoelectric charge formation. This is a relatively high energy approach with evidence that ultrasonic cavitation generates mechanical forces responsible for activation of the piezoelectric effect. The induced strain on the ferroelectric particles results in the formation of charges due to the development of a dipole and resulting depolarisation field. This potential can induce chemisorption of water molecules, or dye molecules, at the piezoelectric material water interface to undergo redox reactions [11-14]. The net result is a piezoelectric process that performs chemistry and degrades dye molecules. There is evidence that the morphology of the functional ceramic particle can impact overall performance, with claims a more pronounced effect for 1D or 2D piezoelectric materials. These materials have a higher bending radius and therefore a higher induced strain and increased resulting dipole. This has led to increased investigations in nanorods and nanoflower structures [12-15]. Piezocatalytic water splitting and oxidation of dye molecules using BaTiO₃ micro-dendrites under ultrasonic vibrations has been reported by Hong et.al [14–16]. Lv et al. reported the degradation of organic pollutants by using BaTiO₃ coral branches under ultrasonic vibrations [17].

A question remains as to whether a range of mechanical vibrations can activate piezocatalysis in BaTiO3 or a lower frequency mechanical input can drive the piezocatalysis process and achieve high efficiency degradation. There is some evidence in highly orientated ZnO nanorods that low energy vibrations can induce piezocatalysis [18]. These long and thin rods demonstrate exceptional flexibility and can be considered a special case. It is already known that ZnO rods, when subject to vibration, can impact the lifetime of carriers which is important when considering system to perform chemical reactions [19]. The application of low energy vibration, such as stirring or tumbling, to drive piezocatalysis for structures that are more typical of ceramic powders such as nano- or micro-sized approximately round particles is a key interest. In this work, we prepared and compare the performance of a range of BaTiO₃ samples under different mechanical stirring regimes to activate piezocatalysis and report the results of materials properties and stirring on dye removal.

2. Methodology

2.1. Synthesis

BaTiO₃ (BTO) powders were prepared by a solid-state reaction method. BTO powders were produced from barium carbonate (BaCO₃, Sigma Aldrich, >99%) and titanium dioxide (TiO₂, Sigma Aldrich, >99%) in stoichiometric composition. The precursors were ball milled in a Retsch PM100 planetary with ethanol and zirconia (ZrO₂) milling media. The ball-to-powder weight ratio was 10:1 and milling were performed at 200 rpm for 5 h. Milling was paused every 20 min for a period of 10 min to prevent overheating. The milled powders were sifted through 250 μ m stainless steel mesh to obtain fine particles. The asobtained BTO powders were calcined for 2 h in air at different temperatures: 900 °C, 1000 °C and 1200 °C; the samples obtained are hereafter referred to as BTO-900 °C, BTO-1000 °C and BTO-1200 °C, respectively. The heating and cooling rate was 5 °C per min. Finally, the calcined BTO powders were ball milled following the previously described procedure for better homogeneity.

2.2. Characterisation

The polycrystalline material's phase structure was analysed using X-Ray Diffraction (XRD, Bruker D8 Advance) with monochromatic Cu K α radiation with a wavelength of 1.54 Å generated by a voltage of 40 kV and filament current of 40 mA. The data was collected with an angle of rotation $2\theta = 10-60^{\circ}$ with a step size of 0.01 and scan speed of 0.6

degrees per minute. The surface morphology of powders was examined by scanning electron microscopy (SEM; Zeiss Supra 55 VP). Transmission electron microscopy (TEM) was used examine the size, morphology, and crystallinity of the barium titanate particles. A JEOL JEM-2100Plus multi-purpose transmission electron microscope was used, which was combined with a JEM-2100 optical system to view the images. Barium titanate particles were suspended in 2-3 ml of ethanol and sonicated for 20 min; a drop of the barium titanate suspension was then deposited onto a copper TEM grid, and the solvent allowed to completely dry to allow the particles to attach to a TEM copper grid. The specific surface area of the powders (BET) was determined through the Bruner (BET) nitrogen adsorption isotherms on a Gemini VII 3.03 nitrogen adsorption apparatus (Micrometrics Instruments). The lattice phase of the as prepared and commercial BTO (Sigma Aldrich, >99%) was investigated by Raman spectroscopy on an XploRATM Plus (Horiba, Japan) with laser excitation at 535 nm.

2.3. Piezocatalytic activity measurements

The piezocatalytic activities of the as synthesized and commercial BTO were evaluated through the degradation of Rhodamine B (RhB, Merck). Typically, a measured amount of the BTO was added to the 100 ml-Erlenmeyer flask (Biohal) containing a desired volume of RhB solution whose concentration varies from 5 to 200 mg/L. The solution was magnetically stirred using a PTFE magnetic bar (ø 8 mm, 40 mm, Isolab) at a desired rotational speed which varied from 120 rpm to 620 rpm in the dark at room temperature. The BTO particles were removed by a centrifuge and the RhB concentration was measured by a UV-Vis spectrophotometer (HP) at the characteristic wavelength. Since the lowgrade mechanical energy can drive a piezocatalytic degradation of RhB, the adsorption experiment was carried out without magnetic stirring. An amount of 20 mg of the catalysts was added to a 20 mlcentrifuge tube containing 10 ml of RhB solution whose concentration is 5 mg/L. The suspension was gently shaken by hand during a couple seconds every 30 min for 8 h.

2.4. Kinetics of piezocatalytic RhB degradation

According to Langmuir-Hinshelwood mechanism, the initial degradation rate of RhB (r_0 , mM. h^{-1}) is a function of its initial concentration as follows:

$$r_0 = \frac{kKC_0}{1 + KC_0}$$
(1)

where, C_0 (mM) is the initial RhB concentration, k (mM.h⁻¹) is the rate constant and K (mM⁻¹) is the equilibrium constant that is represented to the ratio of the adsorption and desorption rate constants of RhB at the catalyst interfaces.

Eq. (1) can be rewritten in a linear form, permitting the determination of K and k from the intercept and slope of the following equation:

$$C_0 = k \frac{C_0}{r_0} - \frac{1}{K}$$
(2)

At low concentrations, Eq. (1) can be rewritten in the form of a pseudo-first order equation:

$$r_i = -\frac{dC_i}{dt} = kKC_i \tag{3}$$

Or

$$\ln\left(\frac{C_o}{C}\right) = K_{obs} \quad t \tag{4}$$

Where $k_{obs} = kK$ is the observed pseudo-first order reaction rate constant and *C* (mM) is the final concentration of the dye after stirring over a period of time. Thus, the reaction rate k_{obs} can be obtained from the slope of $\ln(C_0 / C)$ vs. time (*t*).

3. Results and discussions

3.1. Structural characterisation

3.1.1. X-Ray Diffraction

As shown in Fig. 1, all the diffraction peaks correspond to perovskite structure of BaTiO₃ diffraction pattern and are well indexed with the JCPDS data No. 05–0626. XRD pattern of commercial BTO indicates the purity of the material and its tetragonal crystal structure, as evidenced by the peak splitting at $2\theta = 45^{\circ}$. The commercial BTO has a lower degree of tetragonal distortion compared to as-synthesised BTO-1200 °C as shown in Fig. S.1.

3.1.2. SEM and TEM analysis

The morphology of the as produced BTO samples that were used piezocatalysts were analysed by SEM, shown in Fig. 2. The SEM micrographs show that the particle size gradually increases on increasing the annealing temperature. The BTO-900 °C shows some small particles interspersed with larger primary particles. The average primary particle size is smaller than 500 nm. Upon heating the smaller particles agglomerate into the larger particle to produce a larger average size of primary particle. For BTO-1200°C there is evidence of necking and early stages of sintering with particles growing to exceed 500 nm with some particles growing bigger than 1 μ m.

Transmission electron microscope images of as-produced barium titanate produced at 900 °C, 1000 °C, and 1200 °C at different magnifications are shown in Fig. S.2. It can be observed that the degree of agglomeration reduced with increasing annealing temperature with increasing primary particle size. In addition, as the processing temperature increased the particles transformed from an amorphous structure as in Fig. S.2 (a,d) to partly crystalline Fig. S.2 (b,e) and a more defined crystaline stucture Fig. S.2 (c,f). The lognormal distribution curves indicate that the crystal size grows as the annealing temperature increases from 900 °C to 1200 °C. From an average of 10 particles the crystallite size increases from an average of 40 nm at 900 °C to 400 nm at an annealing temperature of 1200 °C.

3.1.3. BET surface area analysis

The N_2 adsorption-desorption isotherm displayed a single hysteresis loop between relative pressures of 0.05 and 0.25, and the specific



Fig. 1. XRD patterns for BTO-900 °C, BTO-1000 °C, and BTO-1200 °C.

surface area of BTO samples was measured at different calcination temperatures of BTO-900 °C, BTO-1000 °C, and BTO-1200 °C were calculated to be $3.96 \text{ m}^2/\text{g}$, $2.52 \text{ m}^2/\text{g}$, and $1.61 \text{ m}^2/\text{g}$, while that of commercial BTO was determined to be only $1.4 \text{ m}^2/\text{g}$. The specific surface area of BTO decreased upon an increase in the heat treatment temperature. This reduction in surface area is attributed sintering during the thermal treatment.

3.1.4. Raman analysis

Overlapping of the characteristic peaks of tetragonal and cubic phases in XRD spectra makes determination of tetragonality of BTO complicated. In this context, Raman spectroscopy has been more widely used to study the tetragonal-cubic symmetry of BTO [20–22]. It was well established that the sharp peak at 305 cm⁻¹ and broader peak at 720 cm^{-1} can be assigned for the tetragonal phase. As can be seen in Fig. S.3, Raman spectra of all samples exhibited both peaks, confirming the presence of tetragonal phase regardless of synthesis conditions. However, the characteristic peaks of the as-prepared BTO samples at different calcination temperatures showed different scattering intensities, indicating that the tetragonality of the synthesized BTO is affected by calcination temperature. It can be seen that BTO-1200 °C exhibited the largest amount of tetragonal phase, while there is no obvious difference in the tetragonal-cubic symmetry of BTO-900 °C and BTO-1000 °C. In addition, all synthesized samples showed higher tetragonality compared to the commercial BTO.

3.2. Piezocatalytic activity

3.2.1. Effect of BTO structural properties

It was widely known that only the ferroelectric tetragonal phase contributes to the piezocatalytic activity of BTO [23-25]; the cubic phase is centrosymmetric and is therefore not ferroelectric. In the other words, a higher piezocatalytic activity should be observed in the sample with higher tetragonality that is calcined at the highest temperature (BTO-1200 °C). Therefore, the performance of RhB degradation on different BTO sample was investigated to confirm the role of its tetragonality. Typically, 40 mg of the as prepared and commercial BTO powders was used to study the piezocatalytic degradation of 20 ml RhB solution whose concentration is 5 mg/L. After being stirred at 520 rpm for the required time, the supernatant was centrifuged and analysed. Each data point in Fig. 3 was derived from a distinct experiment with a different reaction time. As expected, 93% of RhB was degraded within 240 min in the presence of BTO-1200 °C (see Fig. 3(a) and (b)) shows more clearly that the data fits well with a pseudo-first order reaction (adjusted R-square > 0.99), confirming the reproducibility of the study. Accordingly, the degradation rate k_{obs} of RhB using BTO-1200 °C is k_{obs} $= 0.011 \text{ min}^{-1}$ which is 3.5 times higher than those using samples calcined at lower temperatures and 13 times higher than that using the commercial BTO. As shown previously, BTO-1200 °C exhibited the highest tetragonality which can be attributed to its highest piezocatalytic activity despite its lower BET surface and higher particle size. In addition, the smallest piezocatalytic activity of the commercial BTO may be attributed to both its lowest tetragonality and BET surface area.

Non-ferroelectric control and blank experiments to confirm the piezocatalytic activity of the ferroelectric BTO were achieved by testing in the presence of commercial alumina (> 99%, Sigma Aldrich) and in the absence of any particles. As can be seen in Fig. 3(a), stirring the RhB solution with no particles present at high-speed results in a slight decrease in RhB concentration which may be due to the friction between the stirrer bar and solution. The addition of non-ferroelectric alumina leads to a greater degradation of RhB, which may be due to the increased friction in the presence of solid particles. However, there is a clear difference between the activity of the ferroelectric (BTO) and nonferroelectric (Al₂O₃), indicating the importance of dipole in driving chemistry.



Fig. 2. SEM images for (a) BTO-900 °C (b) BTO-1000 °C (c) BTO-1200 °C (d) commercial BTO.



Fig. 3. (a). Piezocatalytic degradation of RhB in the presence of different BTO samples with time on stream; (b) kinetic fitting.

3.2.2. Effect of operating conditions

The effect of catalyst loading level was studied by degradation of 20 ml RhB solution, whose concentration was 5 mg/L under magnetic stirring at 520 rpm for 120 mins in the presence of different amounts of the highly tetragonal material (BTO-1200°C). Fig. S.4(a) shows that only 2% of RhB was degraded in the absence of a catalyst. In addition, adding only 1 mg of BTO enhanced the degradation efficiency by up to 12%. The results also show that the degradation efficiency increased with an increase in the BTO loading level to 20 mg (catalyst loading dose is 1 mg/ml). A further increase in the BTO loading level decreased the RhB degradation efficiency due to an excessive collision probability of the particles [25,26]. Zhu et al. also observed that a high loading level would lead to an interplay between BZT-BCT fibres, resulting in the decrease of total piezoelectric potential [27]. However, if we examine the piezocatalytic capacity of BTO in terms of the amount of degraded RhB per amount of catalyst in Fig. S.4(a), we observe that increasing the catalyst loading level leads to a decrease in its piezocatalytic capacity. This indicates that collision probability is unavoidable under magnetic stirring, while this effect can be eliminated at low loading dose levels under ultrasound vibration [25].

In this work, a magnetic stirrer was used to impart the rotational field to the fluid medium, which induces stress on the surface of BTO particles. Therefore, changing the rotation speed is likely to affect the piezoelectric response [28,29] and the formation of a free surface vortex and subsequently entrained gas [30,31]. Both factors will in turn affect the piezocatalytic activity of BTO on RhB degradation. Since the effect of rotational speed at different catalyst loading level may be different, we evaluation the degradation of 20 ml of RhB whose concentration is 5 mg/L using both 5 mg and 20 mg of BTO-1200°C. As expected, both the RhB degradation efficiency and capacity increased with increasing rotational speed, regardless of the catalyst loading level; see Fig. S.4(b). However, while a linear relationship can be observed in the case of low BTO loading level (5 mg), the high BTO loading level (20 mg) exhibited a more curvilinear-plateau relationship due to the higher collision probability.

It have been previously reported that the amount of entrained air decreased with increasing liquid height as a result of the increase in resultant gravitational pull [31]. Therefore, different volumes of RhB

solution were investigated by changing the catalyst loading level and the liquid volume of the RhB solution (5 ml and 10 ml), whose concentration was fixed at 5 mg/L. Each experimental condition was repeated with at least four different periods of time to determine the reaction rate constant k_{obs} and confirm the reproducibility of the data. The results showed that all the data fitted well to a pseudo-first order reaction (adjusted R-square > 0.99). As can be seen in Fig. S.4(c), for a consistent catalyst loading level the 5 ml volume demonstrated the highest reaction rate constant k_{obs} . This may be attributed to two reasons: (i) a lower liquid height results in a greater amount of entrained air [31]; and (ii) a lower liquid height results in a larger tangential velocity, thereby inducing a larger stress on the BTO particles [32]. The RhB degradation efficiency and capacity also reached a plateau with increasing catalyst loading level when treating 10 ml of RhB. In addition, the RhB degradation efficiency (k_{obs}) increased with increasing BTO content up to 1 mg/ml, then significantly decreased with increasing BTO up to 2 mg/ml when treating 5 ml of RhB. As described above, a lower liquid height results in a higher degree of turbulence, and consequently a greater collision probability of BTO particles which reduces the total piezoelectric response since the piezoelectric potentials of opposite polarity can offset each other.

To maximise the degradation efficiency, the catalyst loading dose of 1 mg/ml was therefore chosen for further study. Experiments were performed to determine the Langmuir-Hinshelwood constants by maintaining the same BTO catalyst dosage (1 mg/ml), while changing the liquid volume using different RhB solutions. The data was then recalculated based on Eq. (2) and is shown in Fig. S.4(d). A high R-square value ($R^2 > 0.995$) indicates an excellent linearity of the correlation plots. The values of the rate constant (*k*) are shown in the Table 1.

The results show that the rate constant increase significantly with decreasing liquid volume and which is unusual since other operating parameters such as stirring speed and catalyst dosage were fixed. To study this further, experiments were performed by changing the liquid volume with RhB concentration of 5 mg/L under both air and argon atmosphere.

By studying the RhB degradation (*C*/*C*₀) with time (*t*), the *k*_{obs} constant and RhB degradation capacity of BTO, which indicate the piezocatalytic activity of BTO, were determined and is shown in Fig. 4. Under air, three distinct regions were observed, low volume Region III (RhB volume < 10 ml), intermediate volume Region II (RhB volume from 10 to 25 ml) and high-volume Region I (RhB volume > 25 ml) where different trends in the piezocatalytic activity of BTO were observed. In addition, only two distinct regions, low volume Region II (RhB volume < 25 ml) and a high-volume Region I (RhB volume > 25 ml) were detected in the absence of any air under argon.

There are two possible ways to produce reactive oxygen species (ROS): (i) from gas-phase and dissolved oxygen (Eq. 5) and (ii) from a water splitting reaction (Eq. 6).

$$O_2 + e \rightarrow O_2^{\bullet} - 0.33 \text{ V (vs NHE)}$$
(5)

$$H_2O + h^+ \rightarrow HO^{\bullet} + H^+ + 2.72 \text{ V (vs NHE)}$$
(6)

BTO is a ferroelectric material that exhibits piezoelectric properties. Under mechanical deformation BTO produces a surface charge that induces the migration of electron and holes. This is associated with an intrinsic potential associated with the ca. 3.2 eV band gap that gives a potential capable of forming hydrogen from water. If the potential is below the required reduction potential - 0.33 V vs NHE superoxide radical formation will not take place.

Table 1

The influence of liquid volume on the kinetics of piezocatalytic degradation of RhB using mechanic stirring.

0	0			
Liquid volume, ml	5	10	30	50
k, mM.h ⁻¹	0.050	0.012	0.006	0.003



Fig. 4. Piezocatalytic performance of BTO-1200°C in the presence of air and argon (Conditions: RhB initial concentration: 5 mg/L, BTO dose: 1 mg/L).

In the absence of air, only a small amount of dissolved oxygen can take part in the ROS production reaction, resulting in a smaller reaction rate. However, the decrease in RhB degradation rates under air and argon atmosphere follow almost the same trend, except that observed at a low liquid volume of 5 ml. In general, the piezocatalytic activity of BTO linearly increases with decreasing RhB volume due to higher stirring force, as can be seen in the Region I in Fig. 4. However, when the RhB volume is reduced to < 25 ml the liquid-gas interface is lower than the height of the magnetic stirring bar, and more turbulence takes place which results in a different trend (gradient) in Region II compared to Region I. When the liquid volume was decreased to 5 ml, only a thin layer of liquid phase was observed. The piezoelectric material is therefore likely to operate more efficiently in air due to the absence of a Stern layer and the produced ROS will rapidly contact RhB in the liquid phase and degrade it by means of stirring bar. This can explain the high piezocatalytic activity of BTO in the presence of gas-phase oxygen at a liquid volume of 5 ml compared to that in the presence of argon. These phenomena are demonstrated by the schematic mechanism in Fig. 5.

The highest RhB degradation capacity in this work was found to be 12.05 mg per gram of catalyst after 1 h of mechanical stirring. This value is comparable to those obtained from the other piezocatalysts and photocatalysts which were synthesized by the more complex procedures, as can be seen in Table 2.

4. Conclusion

The findings of this study highlighted the important role of the liquid volume in determining the piezocatalytic activity of BTO for the degradation of RhB in water to use readily accessible waste energy to drive environmentally friendly processes. We have also shown that the level of tetragonality of the ferroelectric BTO plays a significant role in the piezocatalytic activity, with a higher level of tetragonality leading to higher piezocatalytic activity. The effect of operating conditions such as catalyst loading level, rotational speed, and liquid volume was also studied in detail, and the RhB degradation capacity were found to be higher in the presence of air compared to argon. The piezocatalytic activity of BTO linearly increased in Region I (RhB volume > 25 ml) with a decrease in liquid volume showed a different trend (gradient) in Region II (RhB volume < 25 ml) due to increased turbulence at a lower liquid volume. This led to a significant increase in the rate constants for RhB degradation with a decrease in liquid volume due to higher stirring force. In addition, the piezocatalyst BTO was found to be more effective in the presence of air due to the greater turbulence at the liquid-gas interface and the absence of the stern layer when the RhB liquid volume was low (5 ml). These results provide valuable new insights into the



Vortex-Induced Shearing Force

Liquid height

Fig. 5. Graphical representation of the "Effect of liquid height and gas presence on the piezocatalytic activity of BTO for RhB degradation: Linear increase in region I, turbulence-driven enhancement in region II, and air-enhanced performance at low liquid volume in region III.".

Table 2

Comparison of RhB Degradation Capacity of Piezo- and Photo-catalysts.

Method	Catalyst	RhB concentration $(mg \cdot L^{-1})$	k _{obs} (min ⁻¹)	RhB degradation capacity $(mg \cdot g^{-1} \cdot h^{-1})$	Ref.
Piezocatalysis (driven by mechanic stirring)	вто	5	0.040	12.05	This work
Piezocatalysis (driven by mechanic stirring)	0.5Ba(Zr _{0.2} Ti _{0.8})O ₃ -0.5(Ba _{0.7} Ca _{0.3})TiO ₃ fibbers	2.5	0.340	12.8	[27]
Piezocatalysis (driven by ultrasound)	Self-modified black BaTiO _{3-x} nanoparticles	10	0.009	5.4	[33]
Piezocatalysis (driven by ultrasound)	BiFeO ₃ nanowires	5	0.045	10.8	[34]
Piezocatalysis (driven by ultrasound)	NaNbO ₃ nanofibers	5	0.009	2.91	[35]
Piezocatalysis (driven by ultrasound)	(Bi0.5Na0.5)TiO3-based nanofibers	10	0.012	7.26	[36]
Piezocatalysis (driven by ultrasound)	ZnSnO ₃ nanoparticles	2.25	0.045	12.15	[37]
Piezo-photocatalysis (driven by ultrasound)	$Bi_4Ti_3O_{12}$ nanosheets	5	0.214	64.2	[38]
Photocatalysis	Nanosized Ag_2S –ZnS loaded on cellulose	30	0.006	19.2	[39]

factors that influence the piezocatalytic activity of BTO, which enabled catalytic dye degradation in water at mixing intensities that were much lower than conventional ultrasound.

CRediT authorship contribution statement

Guru Prasanna: Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing - original draft. Hoang-Duy P. Nguyen: Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing - original draft. Steve Dunn: Conceptualization, Project administration, Resources, Investigation, Methodology, Supervision, Validation, Funding acquisition, Writing review & editing. Akalya Karunakaran: Formal analysis, Investigation, Software, Visualization. Frank Marken: Validation, Writing - review & editing. Chris R. Bowen: Validation, Writing - review & editing. Bao-Ngoc T. Le: Software, Visualization. Hoang-Duy Nguyen: Formal analysis, Investigation, Software, Visualization. Thuy-Phuong T. Pham: Conceptualization, Project administration, Resources, Investigation, Methodology, Supervision, Validation, Funding acquisition, 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.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.nanoen.2023.108794.

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