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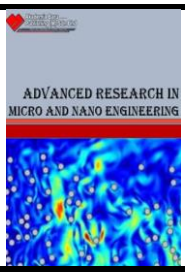
Journal of Advanced Research in Micro and Nano Engineering

Journal homepage:
https://www.akademiabaru.com/submit/index.php/armne/index
ISSN: 2756-8210



Advancement in Photocatalyst and Piezophotocatalyst Micromotor for Environmental Remediation: A Concise Review

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ARTICLE INFO

Article history:
Received 1 May 2024
Received in revised form 10 June 2024
Accepted 15 July 2024
Available online 31 August 2024

Keywords:
Environmental remediation; microrobots; photocatalysts; piezophotocatalysts; semiconductor heterojunctions

ABSTRACT

This review analyses recent advancements in the synthesis and environmental applications of photocatalysts and piezophotocatalysts, pivotal for organic pollutant degradation and water remediation. Traditional semiconductor photocatalysts often face rapid electron-hole recombination and limited visible light absorption. Innovations have led to the development of semiconductor heterojunctions that enhance photocatalytic efficiency by improving charge separation and expanding light absorption. This review emphasizes semiconductor-semiconductor and semiconductor-metal interfaces, which significantly improve photocatalytic performance. Additionally, piezophotocatalysts have emerged, utilizing mechanical energy to augment chemical reactions, thereby increasing efficiency and applicability under various conditions. The review also highlights the role of photocatalyst-based microrobots in targeted water treatment, utilizing local chemical energy for precise operations. These advancements showcase the potential of photocatalytic and piezophotocatalytic technologies in environmental sustainability, highlighting current trends and future prospects for effective environmental remediation.

1. Introduction

Environmental pollution, especially from organic contaminants, poses a significant challenge to global health and the ecological balance. Photocatalysis, which leverages the power of light to initiate chemical reactions, has emerged as a promising technology for addressing such pollution. Recent advancements in photocatalytic materials have significantly enhanced their efficiency and effectiveness in degrading a wide range of pollutants. These materials, often composed of semiconductors like titanium dioxide, can break down harmful organic compounds into less toxic

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https://doi.org/10.37934/armne.22.1.116125

substances. Furthermore, the development of novel photocatalysts with improved light absorption and charge separation properties holds great potential for large-scale environmental remediation applications.

Traditional photocatalysts, such as titanium dioxide (TiO_2), have been widely studied for their ability to utilize ultraviolet (UV) light to degrade pollutants. Despite their efficacy, their application is limited by quick electron-hole recombination and restricted ability to absorb visible light. This review discusses innovative modifications to traditional photocatalysts, including the development of semiconductor heterojunctions, with the aim of overcoming these limitations. Semiconductor heterojunctions, involving a combination of different semiconductors, have shown potential for enhancing charge separation and extending the light absorption spectrum to the visible range. This is achieved through the strategic alignment of the bandgaps, which facilitates improved photocatalytic activity under natural sunlight.

In addition to semiconductor-based solutions, this review explores piezophotocatalysts, a novel class of materials that integrate piezoelectric properties with photocatalytic functionalities. By utilizing both light and mechanical energy, piezophotocatalysts offer a dual-stimulus approach to enhance the chemical reactions necessary for environmental cleanup. Mechanical energy, derived from environmental vibrations or pressure changes, induces electrical charges in these materials, aiding in the separation of charge carriers and boosting the overall catalytic efficiency.

Another innovative area covered in this review is the application of photocatalyst-based microrobots for environmental remediation. These microscale robots are capable of autonomous movement and harness photocatalysts to drive localized chemical reactions for targeted pollutant degradation. Engineered on the nanoscale, microrobots can access confined spaces and perform precise operations, making them particularly suitable for applications such as water treatment, where they can directly interact with and degrade contaminants.

This review focuses on the advancements in the field of photocatalyst and piezophotocatalyst synthesis, particularly for environmental remediation. The primary objective of this review is to examine the recent developments in the synthesis of these materials, their mechanistic actions, and their environmental applications, with a focus on the degradation of organic pollutants and water treatment. This concise review aims to set the stage for a comprehensive discussion on the significant strides made in photocatalytic technology, highlighting innovative approaches that have the potential to revolutionize environmental remediation efforts. Through this review, readers will gain an understanding of key advancements, the underlying principles driving these innovations, and their implications for future research and applications in the field of environmental science. The remainder of this paper is organized as follows. It begins with a discussion of the limitations of traditional photocatalysts and the rationale behind the development of advanced heterojunctions. It then delves into the synthesis and mechanistic insights of semiconductor heterojunctions and piezophotocatalysts, followed by an exploration of emerging applications of microrobots in environmental contexts. Each section details the current state of research and critically evaluates the efficacy and practicality of these technologies for real-world applications.

2. Photocatalyst Synthesis and Environmental Applications

Photocatalysts have gained significant attention for their potential to decompose organic pollutants, as documented in various studies [1]. Specifically, semiconductor photocatalysts are valued for their environmentally friendly applications, such as splitting water into hydrogen and oxygen [2]. These materials absorb light energy, which leads to the generation of reactive oxygen species (ROS) and the creation of charge carriers including electrons and holes [3]. Electrons excited

to the conduction band react with oxygen to produce superoxide radicals, while holes in the valence band interact with water to generate hydroxyl radicals and protons (H^+) [4]. These ROS then initiate surface redox reactions that degrade pollutants, ultimately resulting in the formation of carbon dioxide, water, and various lower-carbon organic compounds [5,6].

Despite the benefits of pollutant degradation, semiconductor photocatalysts face challenges such as the rapid recombination of charge carriers and limited absorption of visible light. Addressing these limitations has led to the development of photocatalyst heterojunctions, which often involve the combination of different types of photocatalysts [2]. For instance, TiO_2, an effective semiconductor, has a wide bandgap that requires ultraviolet or near-ultraviolet radiation for activation. The current trend is focused on the development of visible-light-driven photocatalysts to enhance their usability under broader light conditions. Nonetheless, challenges such as short-lived electron-hole pairs and limited visible light absorption continue to persist, emphasizing the necessity for further development in this area.

Various enhancements have been implemented to improve photocatalytic efficiency, including advanced textural design, doping, and the formation of semiconductor heterojunctions with metals or other semiconductors. Recent literature reviews by Wang *et al*., have explored the rational design and fabrication of heterojunction photocatalysts, encompassing semiconductor-semiconductor, semiconductor-metal, semiconductor-carbon, and multicomponent heterojunctions [2]. Each modification offers distinct improvements in the photocatalyst performance. In particular, in semiconductor-semiconductor heterojunctions, enhanced charge collection and separation are achieved when p- and n-type semiconductors form a p-n junction, as illustrated in Figure 1 [2]. This junction establishes a space-charge region at the interface, creating a built-in electrical potential that directs the electrons and holes to travel in opposite directions. This setup not only facilitates effective charge separation, but also ensures rapid charge transfer to the catalyst, extends charge carrier lifetimes, and segregates locally incompatible reduction and oxidation reactions at the nanoscale, thereby significantly boosting the photocatalytic performance.

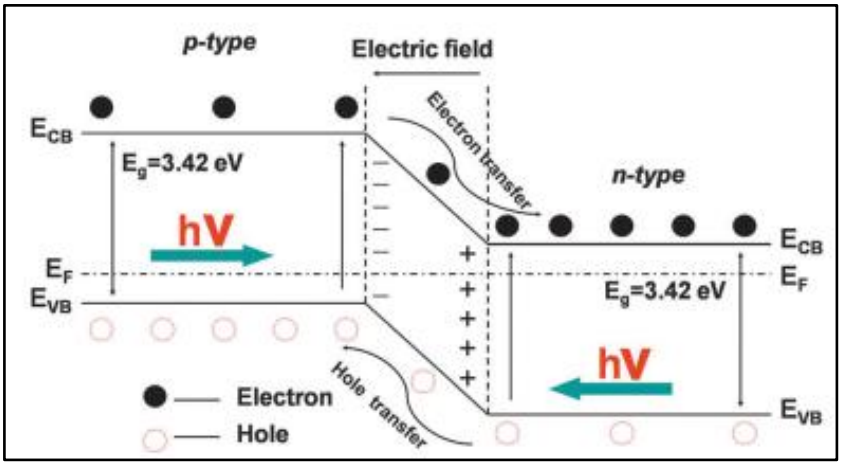

Fig. 1. Schematic diagram of energy band structure and electron pair in p-n heterojunction. Adapted from [2]

TiO_2-based semiconductor-semiconductor heterojunctions have garnered considerable attention owing to their surface modification capabilities. These systems are particularly notable for their high dye adsorption capacity, extended range of light absorption, enhanced charge separation, and improved mass transfer, which collectively contribute to significantly increased photocatalytic efficiency. A notable example is the Bi_2WO_6-TiO_2 heterojunction developed by Wang *et al.,* which demonstrated a remarkable enhancement in visible-light-driven photocatalytic activity. This

heterojunction was shown to decompose CH_3CHO with an efficiency eight times greater than that of Bi_2WO_6 or TiO_2 alone. This improved performance was attributed primarily to a reduction in electron-hole recombination and enhanced migration of photogenerated carriers [7].

Additionally, semiconductor-metal heterojunctions introduce a Schottky barrier that acts as another region for space-charge separation, effectively altering the movement of electrons from a higher to a lower Fermi level. The presence of this Schottky barrier significantly mitigates the recombination of electrons and holes, thereby enhancing the photocatalytic performance of the system [2]. For instance, Li *et al*., developed Ag/Bi_2WO_6 three-dimensional flow-like microspheres measuring approximately 4 µm in diameter using a straightforward hydrothermal method. The photocatalytic efficacy of these microspheres was assessed by the decolorization of rhodamine B under simulated sunlight. The results indicated a marked increase in the photocatalytic activity of the samples containing 1 wt% Ag-loaded Bi_2WO_6. This enhancement was largely due to the synergistic effects of the strong surface plasmon resonance of Ag and the efficient separation of photogenerated electrons and holes [8].

3. Piezophotocatalytic Materials and Water Remediation Application

Certain nanomaterials possess piezoelectric properties that enable the conversion of mechanical energy into chemical energy, offering a promising solution to the limitations faced by conventional photocatalysts, such as rapid electron-hole pair recombination and low charge carrier mobility [9-11]. The piezoelectric effect in these materials can significantly enhance photocatalytic activity by effectively separating electron-hole pairs through polarization, which directly influences the catalytic performance [12].

The piezoelectric catalysis technology utilizes this capability to harness environmental mechanical energy and convert it into electrical energy. The intense electric fields generated by piezoelectric materials produce reactive oxygen species (ROS), such as •OH, $\bullet O^{2-}$, and $\bullet HO_2$, which are highly effective in degrading organic pollutants, eliminating microbes, and reducing heavy metal ions in wastewater [13,14], highlighting the broad applicability of piezoelectric materials in environmental cleanup.

Reflecting on this wide usage, extensive research, including reviews by Pan *et al.,* has been conducted, focusing on the enhancement of photocatalysis and photoelectrocatalysis through piezoelectric and photoelectric effects. These studies underline how piezo-enhanced photocatalytic reactions and piezo-phototronics can modulate band bending and charge migration, thereby optimizing the photocatalytic process [15]. Similarly, Wang *et al.,* reviewed how mechanical energy variations, such as stress and temperature changes, in piezoelectric and pyroelectric materials can be harnessed to generate active species crucial for purifying pollutants [16].

Piezoelectricity involves the conversion of mechanical strain into electrical charge and vice versa. External mechanical stress induces dielectric displacement within these materials, affecting their surface charge density and altering the direction and magnitude of polarized electric fields. Such changes enhance the separation of electron-hole pairs or photo-induced charge carriers, reducing recombination and increasing the availability of electrons and holes for redox reactions [17,18].

Current research on piezoelectric catalysts has primarily explored three types of materials: zinc oxide (ZnO), transition metal dichalcogenides (TMDs), and ABX_3 perovskite-type oxides. ZnO, known for its 1D structure, enhances the charge carrier mobility, with its bent nanowires creating a piezoelectric field that facilitates charge movement [19,20]. TMDs, including MoS_2, WS_2, $MoSe_2$, and WSe_2, are recognized for their high specific surface area and van der Waals gaps, offering unique properties such as an asymmetric structure, exceptional mechanical flexibility, high conductivity,

abundant active edge sites, large piezoelectric response, and extensive surface area, making them ideal for piezoelectric applications [21,22].

Perovskites, characterized by the general formula ABX_3, provide a versatile framework for piezoelectric materials, enabling a mix of different A, B, and X ions to produce materials with excellent optical, catalytic, and physicochemical properties. For instance, $BaTiO_3$ exhibits spontaneous polarization and is highly effective in degrading organic pollutants, while $BiFeO_3$ nanopowders, with their small bandgap energy and strong visible-light absorption, are also widely utilized for this purpose [9,23].

This extensive body of research underscores the potential of piezo-photocatalyst materials to achieve high degradation rates for a variety of organic pollutants, including dyes, antibiotics, and other organic substances, as summarized in various studies and reports in Table 1.

Table 1
Summary of piezo-photocatalyst degradation toward organic pollutants

No	Piezo-photocatalyst material	Types of pollutants	Degradation time	References
1	Ag-$Na_{0.5}Bi_{0.5}TiO_3$	Rhodamine (RhB)	98.6% degradation in 120 min	[24]
2	Ag/ZnO	Methyl orange	100% degradation in 25 min	[25]
3	AuPt/BiOBr	Rhodamine (RhB)	99.8% degradation in 30 min	[26]
		Tetracycline (TC)	36.5% degradation in 40 min	
4	$BiVO_4/BiFeO_3$	Rhodamine (RhB)	98% degradation in 120 min	[27]
5	$MoSe_2/Bi_2WO_6$	Rhodamine (RhB)	99.8% degradation in 60 min	[28]
6	$BaTiO_3@TiO_2$	Rhodamine (RhB)	99.5% degradation in 75 min	[29]
		Methyl Blue (MB)	99.8% degradation in 105 min	
		Indigo Carmine (IC)	99.7% degradation in 45 min	
7	BiOI/ZnO	Bisphenol Solution (BPA)	100% degradation in 30 min	[30]
8	$NiO/BaTiO_3$	Rhodamine (RhB)	93% degradation in 90 min	[31]
9	$In_2O_3/BiFeO_3$	Tetracycline (TC)	93.2% degradation in 120 min	[32]

4. Photocatalyst-Based Microswimmer/Micromotor/Microrobot for Water Treatment

Microswimmers are micrometer-sized particles that convert local chemical energy into a propulsive force, mirroring natural phenomena observed in microorganisms, such as bacteria, algae, and spermatozoa, which are crucial in biological processes [33]. This biological inspiration has fueled the growing interest in developing micro- and nano-swimmers in recent decades, driven by the need for precise operation within complex and confined environments [34]. Micromotors and self-propelled particles epitomize this concept by extracting energy from their immediate surroundings to achieve directed motion [35].

Wirelessly operated microrobots are increasingly being used in various fields. These applications range from capturing microplastics and handling nuclear waste to purifying bacteria-contaminated water, engaging in precise chemical mixing, facilitating targeted drug delivery, conducting non-invasive microsurgery, and supporting various microfluidic applications [36-42]. Despite variations in size, shape, and propulsion mechanisms, all microswimmers operate at low Reynolds numbers, which enhances their ability to facilitate mass transfer [33]. However, a major challenge in the development of small-scale swimmers is the difficulty in incorporating internal batteries, given their limited volume [34].

To address this challenge, researchers have explored alternative energy sources, such as magnetic, electric, acoustic, and optical energy, although these approaches often face limitations, such as insufficient penetration depth, high costs, and the need for complex monitoring systems for effective feedback control [34]. Recently, advancements have been made in powering micromotors

with local chemical fuels (e.g., H_2O_2) as well as energy fields such as light or magnetic fields, and even using self-motile biological components such as algae and sperm. These developments are aimed at improving the functionality of non-motile objects for applications in water remediation, sensing, and medical therapies [43].

A landmark discovery in 2004 revealed the spontaneous swimming capabilities of a Pt Janus device in hydrogen peroxide fuel, achieving speeds up to 10 µm/s [44]. This breakthrough demonstrated that the catalytic degradation of chemical fuels can effectively propel the motion of these devices. The propulsion mechanisms identified included neutral solute self-diffusiophoresis, ionic self-diffusiophoresis, and self-electrophoresis, contributing to a deeper understanding of how microswimmers can utilize chemical reactions for autonomous movement, as depicted in Figure 2.

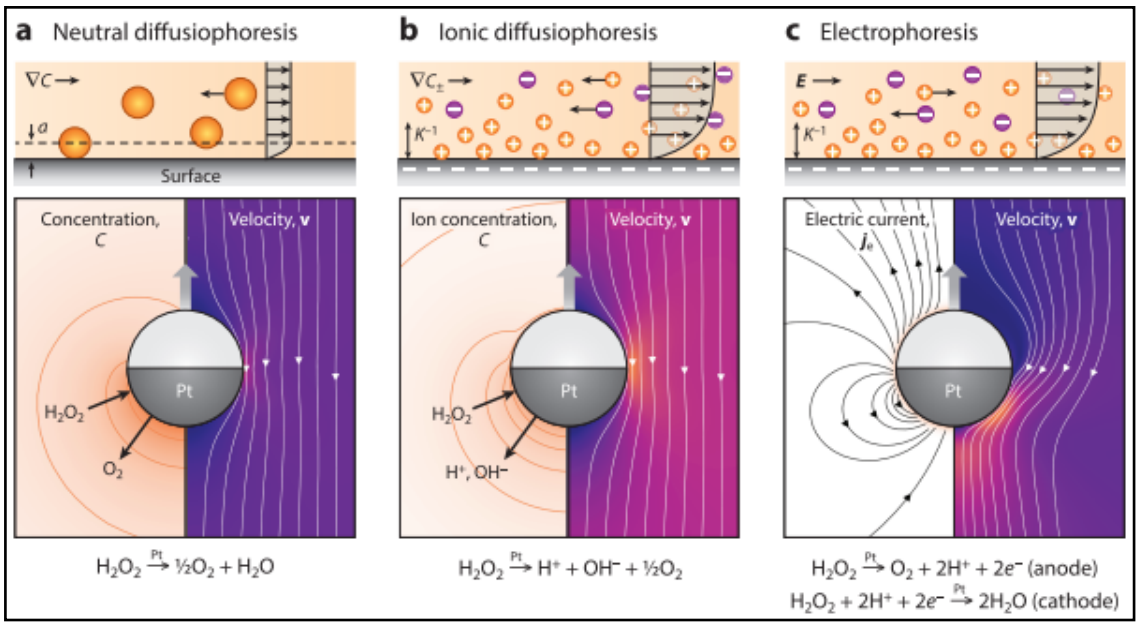

Fig. 2. Phoretic mechanisms for self-propulsion of Pt-Janus Sphere. Adapted from [45]

In the mechanism of neutral solute self-diffusiophoresis, the surface of a Pt-Janus particle creates a local concentration gradient by generating oxygen because of the interaction between hydrogen peroxide and the Pt surface. This concentration gradient leads to particle motion, which is also known as diffusiophoresis. In ionic self-diffusiophoresis, the ion concentration gradient arises from the interaction between the H^+ and OH^- ions produced from H_2O_2. This interaction drives the flow from the negatively charged surface to the positively charged surface, propelling the micromotor [45]. Furthermore, in self-electrophoresis, anodic currents are intensified near the equator of the Janus particle, whereas cathodic currents are concentrated at the poles. The resulting electric field induces an electroosmotic flow at the surface, which propels the motion of the Pt-Janus sphere.

Fuel-driven micromotors, also referred to as chemical or catalytic micromotors, utilize the reaction between a catalyst, typically platinum, owing to its efficiency in decomposing hydrogen peroxide, and chemical fuel to facilitate movement. This reaction often results in propulsion through bubble ejection or self-phoresis [46]. Externally driven microrobots, on the other hand, harness energy from external fields, such as light, acoustic, and electromagnetic fields. In particular, light-driven robots operate by generating electron-hole pairs in a photoactive material under irradiation. This process is often optimized by incorporating a metal-semiconductor junction to prevent the recombination of photogenerated carriers, thereby enhancing the motion through self-electrophoresis [47,48].

Magnetic fields also play a crucial role in enhancing the maneuverability of micromotors, thereby allowing them to operate in diverse media. These robots move either through magnetophoresis in a magnetic field gradient, or by converting rotational motion into translational movement via torque transfer in a rotating magnetic field. For example, helical propellers demonstrate translational movements under such conditions [49]. Recent advancements have showcased chalcogenide semiconductors as promising materials for the construction of light-driven microrobots. Notable studies include that of Zhan *et al.,* who observed strong dichroic swimming behavior in core-shell Sb_2Se_3/ZnO nanomotors under controlled light conditions [50]. Additionally, Chen *et al.,* demonstrated dynamic control over the assembly, disassembly, and reconfiguration of light activated MoS_2 colloidal motor swarms, revealing capabilities beyond those achievable in static systems [51]. Moreover, de la Asuncion-Nadal *et al.,* highlighted the light-triggered photophoretic motion of WS_2 micromotors, which displayed positive photophoretic motion and swarming-like schooling behavior [52] These insights into propulsion mechanisms and the diverse applications of microswimmers and micromotors emphasize their potential in advancing technologies for targeted environmental and biomedical applications, reflecting significant strides in material science and robotic engineering.

5. Conclusion and Future Outlook

Advancements in photocatalyst and piezophotocatalyst technologies are significant milestones in the quest for efficient and sustainable environmental remediation solutions. The development of semiconductor heterojunctions has played a pivotal role in overcoming the intrinsic limitations of traditional photocatalysts, such as rapid electron-hole recombination and limited visible-light absorption. These heterojunctions enhance the charge separation and broaden the absorption spectrum, thereby maximizing the utilization of solar energy.

Piezophotocatalysts further extend the capabilities of traditional photocatalytic systems by incorporating mechanical energy harvesting, which boosts charge carrier separation and catalytic efficiency. This dual-stimuli responsiveness allows for the activation of photocatalytic processes under various environmental conditions, enhancing the versatility and effectiveness of these materials in practical applications.

Moreover, innovative integration of photocatalysis into microrobot systems opens new avenues for targeted and efficient pollutant degradation. These microrobots, equipped with self-propulsion capabilities and precise control, can access and treat pollution at their source, offering a promising approach for tackling environmental challenges on a microscale.

In the future, continuous refinement of these technologies is essential. Emphasis should be placed on enhancing the stability and scalability of these advanced materials to facilitate their transition from laboratory to real-world applications. Additionally, further research on the integration of multiple types of energy harvesting within single systems could lead to even more robust and effective environmental remediation technologies.

The convergence of materials science, nanotechnology, and environmental engineering in the development of advanced photocatalytic materials holds great promise in delivering practical, efficient, and sustainable solutions to combat environmental pollution. This field can significantly impact global sustainability efforts by addressing technical and scalability issues.

Acknowledgement

This research was supported by the EMZI-UiTM Nanoparticle Colloids & Interface Industrial Research Laboratory (EMZI NANO-CORE) under industrial grant (MIH-(008/2020). We acknowledge also the Ministry of Higher Education, Malaysia through the Fundamental Research Grant Scheme (Grant No. FRGS//1/2022/STG05/UITM/02/10)). for the support provided in this work.

References

[1] Khin, Mya Mya, A. Sreekumaran Nair, V. Jagadeesh Babu, Rajendiran Murugan, and Seeram Ramakrishna. "A review on nanomaterials for environmental remediation." *Energy & Environmental Science* 5, no. 8 (2012): 8075-8109. https://doi.org/10.1039/c2ee21818f

[2] Wang, Huanli, Lisha Zhang, Zhigang Chen, Junqing Hu, Shijie Li, Zhaohui Wang, Jianshe Liu, and Xinchen Wang. "Semiconductor heterojunction photocatalysts: design, construction, and photocatalytic performances." *Chemical Society Reviews* 43, no. 15 (2014): 5234-5244. https://doi.org/10.1039/C4CS00126E

[3] Wang, Zhongying, and Baoxia Mi. "Environmental applications of 2D molybdenum disulfide (MoS2) nanosheets." *Environmental science & technology* 51, no. 15 (2017): 8229-8244. https://doi.org/10.1021/acs.est.7b01466

[4] Moradi, Vahid, Martin BG Jun, Arthur Blackburn, and Rodney A. Herring. "Significant improvement in visible light photocatalytic activity of Fe doped TiO2 using an acid treatment process." *Applied Surface Science* 427 (2018): 791-799. https://doi.org/10.1016/j.apsusc.2017.09.017

[5] Wagner, M., and S. Lambert. "Freshwater Microplastics The Handbook of Environmental Chemistry 58 Series Editors: Damià Barceló· Andrey G." *Kostianoy. Andrey G. Kostianoy* (2017).

[6] Su, Kaiyi, Huifang Liu, Chaofeng Zhang, and Feng Wang. "Photocatalytic conversion of waste plastics to low carbon number organic products." *Chinese Journal of Catalysis* 43, no. 3 (2022): 589-594. https://doi.org/10.1016/S1872-2067(21)63885-8

[7] Shang, Meng, Wenzhong Wang, Ling Zhang, Songmei Sun, Lu Wang, and Lin Zhou. "3D Bi2WO6/TiO2 hierarchical heterostructure: controllable synthesis and enhanced visible photocatalytic degradation performances." *The Journal of Physical Chemistry C* 113, no. 33 (2009): 14727-14731. https://doi.org/10.1021/jp9045808

[8] Li, Junqi, Zhanyun Guo, and Zhenfeng Zhu. "Ag/Bi2WO6 plasmonic composites with enhanced visible photocatalytic activity." *Ceramics International* 40, no. 5 (2014): 6495-6501. https://doi.org/10.1016/j.ceramint.2013.11.102

[9] Ji, Myeongjun, Jeong Hyun Kim, Cheol-Hui Ryu, and Young-In Lee. "Synthesis of self-modified black BaTiO3− x nanoparticles and effect of oxygen vacancy for the expansion of piezocatalytic application." *Nano Energy* 95 (2022): 106993. https://doi.org/10.1016/j.nanoen.2022.106993

[10] El Golli, Asma, Murilo Fendrich, Nicola Bazzanella, Chérif Dridi, Antonio Miotello, and Michele Orlandi. "Wastewater remediation with ZnO photocatalysts: green synthesis and solar concentration as an economically and environmentally viable route to application." *Journal of Environmental Management* 286 (2021): 112226. https://doi.org/10.1016/j.jenvman.2021.112226

[11] Liang, Zhang, Chang-Feng Yan, Sami Rtimi, and Jayasundera Bandara. "Piezoelectric materials for catalytic/photocatalytic removal of pollutants: Recent advances and outlook." *Applied Catalysis B: Environmental* 241 (2019): 256-269. https://doi.org/10.1016/j.apcatb.2018.09.028

[12] Yuan, Baowei, Jiang Wu, Ni Qin, Enzhu Lin, and Dinghua Bao. "Enhanced piezocatalytic performance of (Ba, Sr) TiO3 nanowires to degrade organic pollutants." *ACS Applied Nano Materials* 1, no. 9 (2018): 5119-5127. https://doi.org/10.1021/acsanm.8b01206

[13] Bagchi, Biswajoy, Nur Amin Hoque, Norbert Janowicz, Sukhen Das, and Manish K. Tiwari. "Re-usable self-poled piezoelectric/piezocatalytic films with exceptional energy harvesting and water remediation capability." *Nano Energy* 78 (2020): 105339. https://doi.org/10.1016/j.nanoen.2020.105339

[14] Zhao, Yang, Ze-Xian Low, Yifan Pan, Zhaoxiang Zhong, and Guandao Gao. "Universal water disinfection by piezoelectret aluminium oxide-based electroporation and generation of reactive oxygen species." *Nano Energy* 92 (2022): 106749. https://doi.org/10.1016/j.nanoen.2021.106749

[15] Pan, Lun, Shangcong Sun, Ying Chen, Peihong Wang, Jiyu Wang, Xiangwen Zhang, Ji-Jun Zou, and Zhong Lin Wang. "Advances in piezo-phototronic effect enhanced photocatalysis and photoelectrocatalysis." *Advanced Energy Materials* 10, no. 15 (2020): 2000214. https://doi.org/10.1002/aenm.202000214

[16] Wang, Jingjing, Cheng Hu, Lei Shi, Na Tian, Hongwei Huang, Hongling Ou, and Yihe Zhang. "Energy and environmental catalysis driven by stress and temperature-variation." *Journal of Materials Chemistry A* 9, no. 21 (2021): 12400-12432. https://doi.org/10.1039/D1TA02531G

[17] Katsouras, Ilias, Kamal Asadi, Mengyuan Li, Tim B. Van Driel, Kasper S. Kjaer, Dong Zhao, Thomas Lenz et al. "The negative piezoelectric effect of the ferroelectric polymer poly (vinylidene fluoride)." *Nature materials* 15, no. 1 (2016): 78-84. https://doi.org/10.1038/nmat4423

[18] Zhu, Qiuhui, Ke Zhang, Danqing Li, Nan Li, Jingkun Xu, Detlef W. Bahnemann, and Chuanyi Wang. "Polarization-enhanced photocatalytic activity in non-centrosymmetric materials based photocatalysis: A review." *Chemical Engineering Journal* 426 (2021): 131681. https://doi.org/10.1016/j.cej.2021.131681

[19] He, J. Hsin, Cheng L. Hsin, Jin Liu, Lih J. Chen, and Zhong L. Wang. "Piezoelectric gated diode of a single ZnO nanowire." *Advanced Materials* 19, no. 6 (2007): 781-784. https://doi.org/10.1002/adma.200601908

[20] Hamrayev, Hemra, Kamyar Shameli, and Mostafa Yusefi. "Preparation of zinc oxide nanoparticles and its cancer treatment effects: A review paper." *Journal of Advanced Research in Micro and Nano Engineering* 2, no. 1 (2020): 1-11.

[21] Choi, Wonbong, Nitin Choudhary, Gang Hee Han, Juhong Park, Deji Akinwande, and Young Hee Lee. "Recent development of two-dimensional transition metal dichalcogenides and their applications." *Materials Today* 20, no. 3 (2017): 116-130. https://doi.org/10.1016/j.mattod.2016.10.002

[22] Wu, Jiang, Ni Qin, Enzhu Lin, Baowei Yuan, Zihan Kang, and Dinghua Bao. "Synthesis of Bi 4 Ti 3 O 12 decussated nanoplates with enhanced piezocatalytic activity." *Nanoscale* 11, no. 44 (2019): 21128-21136. https://doi.org/10.1039/C9NR07544E

[23] Cho, Chin Moo, Jun Hong Noh, In-Sun Cho, Jae-Sul An, Kug Sun Hong, and Jin Young Kim. "Low-temperature hydrothermal synthesis of pure BiFeO3 nanopowders using triethanolamine and their applications as visible-light photocatalysts." *Journal of the American Ceramic Society* 91, no. 11 (2008): 3753-3755. https://doi.org/10.1111/j.1551-2916.2008.02689.x

[24] Shi, Xingyu, Li Li, Wenjun Cao, Xiaoqi Xuan, Jun Zheng, and Chunchang Wang. "Piezoelectric assisted photocatalytic degradation of dyes by plasmon Ag nanoparticles modified Na0. 5Bi0. 5TiO3 nanospheres." *Materials Letters* 335 (2023): 133827. https://doi.org/10.1016/j.matlet.2023.133827

[25] Zhang, Linlin, Dan Zhu, Haoxuan He, Qiang Wang, Lili Xing, and Xinyu Xue. "Enhanced piezo/solar-photocatalytic activity of Ag/ZnO nanotetrapods arising from the coupling of surface plasmon resonance and piezophototronic effect." *Journal of Physics and Chemistry of Solids* 102 (2017): 27-33. https://doi.org/10.1016/j.jpcs.2016.11.009

[26] Xian, Tao, Xiaofeng Sun, Lijing Di, Chenyang Sun, Hongqin Li, Caixia Ma, and Hua Yang. "Enhancing the piezo-photocatalytic tetracycline degradation activity of BiOBr by the decoration of AuPt alloy nanoparaticles: degradation pathways and mechanism investigation." *Applied Surface Science* 638 (2023): 158136. https://doi.org/10.1016/j.apsusc.2023.158136

[27] Jing, Qinfang, Zhiyong Liu, Xian Cheng, Cichun Li, Pengrong Ren, Kun Guo, Haojie Yue et al. "Boosting piezo-photocatalytic activity of BiVO4/BiFeO3 heterojunctions through built-in polarization field tailoring carrier transfer performances." *Chemical Engineering Journal* 464 (2023): 142617. https://doi.org/10.1016/j.cej.2023.142617

[28] Sun, Guifang, Nan Li, Shixiang Zuo, Wenjing Shen, Mianmian Wu, Qingfei Li, Minghao Shi, and Jiangquan Ma. "Piezo-photocatalysis over phase-engineered MoSe2 modified Bi2WO6 hierarchical microspheres: Utilizing piezoelectric effect to enhance photocatalytic performance." *Ceramics International* 48, no. 24 (2022): 37242-37252. https://doi.org/10.1016/j.ceramint.2022.08.302

[29] Liu, Qiong, Di Zhai, Zhida Xiao, Chen Tang, Qiwei Sun, Chris R. Bowen, Hang Luo, and Dou Zhang. "Piezo-photoelectronic coupling effect of BaTiO3@ TiO2 nanowires for highly concentrated dye degradation." *Nano Energy* 92 (2022): 106702. https://doi.org/10.1016/j.nanoen.2021.106702

[30] Zhang, Chaojun, Weihua Fei, Haoqing Wang, Najun Li, Dongyun Chen, Qingfeng Xu, Hua Li, Jinghui He, and Jianmei Lu. "pn Heterojunction of BiOI/ZnO nanorod arrays for piezo-photocatalytic degradation of bisphenol A in water." *Journal of Hazardous Materials* 399 (2020): 123109. https://doi.org/10.1016/j.jhazmat.2020.123109

[31] Wang, Kaiqi, Bingxin Li, Chunran Zhao, Shude Yuan, Chengshuo Zhang, Xiaoya Liang, Junfeng Wang, Ying Wu, and Yiming He. "A novel NiO/BaTiO3 heterojunction for piezocatalytic water purification under ultrasonic vibration." *Ultrasonics sonochemistry* 92 (2023): 106285. https://doi.org/10.1016/j.ultsonch.2022.106285

[32] Sun, Xiaofeng, Ting Xu, Tao Xian, Zao Yi, Guorong Liu, Jianfeng Dai, and Hua Yang. "Insight on the enhanced piezo-photocatalytic mechanism of In2O3/BiFeO3 heterojunctions for degradation of tetracycline hydrochloride." *Applied Surface Science* 640 (2023): 158408. https://doi.org/10.1016/j.apsusc.2023.158408

[33] Córdoba, Andrés, and Jay D. Schieber. "The effects of hydrodynamic interactions on the swimming velocity and stability of a swarm of microswimmers." *Physics of Fluids* 35, no. 11 (2023). https://doi.org/10.1063/5.0174558

[34] Jang, Bumjin, Min Ye, Ayoung Hong, Xiaopu Wang, Xianghong Liu, Dohyeok Bae, Josep Puigmartí Luis, and Salvador Pané. "Catalytically Propelled Micro-and Nanoswimmers." *Small Science* 3, no. 11 (2023): 2300076. https://doi.org/10.1002/smsc.202300076

[35] Ebbens, Stephen J., and Jonathan R. Howse. "In pursuit of propulsion at the nanoscale." *Soft Matter* 6, no. 4 (2010): 726-738. https://doi.org/10.1039/b918598d

[36] Urso, Mario, and Martin Pumera. "Nano/microplastics capture and degradation by autonomous nano/microrobots: a perspective." *Advanced Functional Materials* 32, no. 20 (2022): 2112120. https://doi.org/10.1002/adfm.202112120

[37] Ying, Yulong, Amir Masoud Pourrahimi, Zdeněk Sofer, Stanislava Matějková, and Martin Pumera. "Radioactive uranium preconcentration via self-propelled autonomous microrobots based on metal–organic frameworks." *ACS nano* 13, no. 10 (2019): 11477-11487. https://doi.org/10.1021/acsnano.9b04960

[38] Vilela, Diana, Morgan M. Stanton, Jemish Parmar, and Samuel Sánchez. "Microbots decorated with silver nanoparticles kill bacteria in aqueous media." *ACS applied materials & interfaces* 9, no. 27 (2017): 22093-22100. https://doi.org/10.1021/acsami.7b03006

[39] Subendran, Satishkumar, Chun-Fang Wang, Dineshkumar Loganathan, Yueh-Hsun Lu, and Chia-Yuan Chen. "An aquatic microrobot for microscale flow manipulation." *Scientific reports* 12, no. 1 (2022): 5041. https://doi.org/10.1038/s41598-022-07938-2

[40] Ren, Liqiang, Nitesh Nama, Jeffrey M. McNeill, Fernando Soto, Zhifei Yan, Wu Liu, Wei Wang, Joseph Wang, and Thomas E. Mallouk. "3D steerable, acoustically powered microswimmers for single-particle manipulation." *Science advances* 5, no. 10 (2019): eaax3084. https://doi.org/10.1126/sciadv.aax3084

[41] Lee, Seungmin, Jin-young Kim, Junyoung Kim, Ali Kafash Hoshiar, Jongeon Park, Sunkey Lee, Jonghyun Kim, Salvador Pané, Bradley J. Nelson, and Hongsoo Choi. "A needle-type microrobot for targeted drug delivery by affixing to a microtissue." *Advanced healthcare materials* 9, no. 7 (2020): 1901697. https://doi.org/10.1002/adhm.201901697

[42] Xie, Meihua, Wei Zhang, Chengying Fan, Chu Wu, Qishuai Feng, Jiaojiao Wu, Yingze Li et al. "Bioinspired soft microrobots with precise magneto-collective control for microvascular thrombolysis." *Advanced Materials* 32, no. 26 (2020): 2000366. https://doi.org/10.1002/adma.202000366

[43] Urso, Mario, Martina Ussia, Xia Peng, Cagatay M. Oral, and Martin Pumera. "Reconfigurable self-assembly of photocatalytic magnetic microrobots for water purification." *Nature communications* 14, no. 1 (2023): 6969. https://doi.org/10.1038/s41467-023-42674-9

[44] Paxton, Walter F., Kevin C. Kistler, Christine C. Olmeda, Ayusman Sen, Sarah K. St. Angelo, Yanyan Cao, Thomas E. Mallouk, Paul E. Lammert, and Vincent H. Crespi. "Catalytic nanomotors: autonomous movement of striped nanorods." *Journal of the American Chemical Society* 126, no. 41 (2004): 13424-13431. https://doi.org/10.1021/ja047697z

[45] Bishop, Kyle JM, Sibani Lisa Biswal, and Bhuvnesh Bharti. "Active colloids as models, materials, and machines." *Annual Review of Chemical and Biomolecular Engineering* 14, no. 1 (2023): 1-30. https://doi.org/10.1146/annurev-chembioeng-101121-084939

[46] Moran, Jeffrey, and Jonathan Posner. "Microswimmers with no moving parts." *Physics today* 72, no. 5 (2019): 44-50. https://doi.org/10.1063/PT.3.4203

[47] Zhou, Dekai, Rencheng Zhuang, Xiaocong Chang, and Longqiu Li. "Enhanced light-harvesting efficiency and adaptation: a review on visible-light-driven micro/nanomotors." *Research* (2020). https://doi.org/10.34133/2020/6821595

[48] Gao, Yuxin, Ze Xiong, Jizhuang Wang, Jinyao Tang, and Dan Li. "Light hybrid micro/nano-robots: From propulsion to functional signals." *Nano Research* 15, no. 6 (2022): 5355-5375. https://doi.org/10.1007/s12274-022-4119-7

[49] Zhou, Huaijuan, Carmen C. Mayorga-Martinez, Salvador Pané, Li Zhang, and Martin Pumera. "Magnetically driven micro and nanorobots." *Chemical Reviews* 121, no. 8 (2021): 4999-5041. https://doi.org/10.1002/adma.201903329

[50] Zhan, Xiaojun, Jing Zheng, Yang Zhao, Bairen Zhu, Rui Cheng, Jizhuang Wang, Jun Liu, Jiang Tang, and Jinyao Tang. "From strong dichroic nanomotor to polarotactic microswimmer." *Advanced Materials* 31, no. 48 (2019): 1903329. https://doi.org/10.1002/adma.201903329

[51] Chen, Meiling, Zhihua Lin, Mingjun Xuan, Xiankun Lin, Mingcheng Yang, Luru Dai, and Qiang He. "Programmable dynamic shapes with a swarm of light-powered colloidal motors." *Angewandte Chemie International Edition* 60, no. 30 (2021): 16674-16679. https://doi.org/10.1002/anie.202105746

[52] de la Asunción-Nadal, Víctor, Daniel Rojas, Beatriz Jurado-Sánchez, and Alberto Escarpa. "Transition metal dichalcogenide micromotors with programmable photophoretic swarming motion." *Journal of Materials Chemistry A* 11, no. 3 (2023): 1239-1245. https://doi.org/10.1039/D2TA07792B