

Hydrothermal Synthesis of Z-Scheme $\text{FeWO}_4/\text{BiVO}_4$ Nanocomposite for Photocatalytic Degradation of Tetracycline

RAHUL KUMAR^{1,*}, PRIYANKA MATHUR¹, GAJENDRA KUMAR² and GANDHARVE KUMAR^{3,*}

¹Department of Chemistry, Bhagwant Global University, Kotdwar-246149, India

²Department of Chemistry, Constituent Government College (Affiliated to M.J.P. Rohilkhand University, Bareilly), Hasanpur-244241, India

³Department of Chemistry & Sustainability, School of Basic Sciences, Galgotias University, Greater Noida-203201, India

*Corresponding author: E-mail: gandharve.kumar@galgotiasuniversity.edu.in

Received: 5 July 2026

Accepted: 9 September 2026

Published online: 9 October 2026

AJC-22494

A visible-light-active $\text{FeWO}_4/\text{BiVO}_4$ heterostructured photocatalyst was fabricated by decorating irregular BiVO_4 nanoplates with FeWO_4 nanoparticles for the photocatalytic degradation of tetracycline. The as-prepared composites were systematically characterized using PXRD, FESEM, HRTEM, XPS, UV-Vis spectroscopy and photoluminescence (PL) analysis to investigate their structural, morphological, optical and electronic properties. Among the different compositions studied, 0.15 $\text{FeWO}_4/\text{BiVO}_4$ showed the best photocatalytic performance, with 99% degradation of tetracycline (20 mg L^{-1}) and a rate constant of 0.0471 min^{-1} . This result demonstrates the enhanced photocatalytic efficiency of the optimized composite toward tetracycline degradation. This rate constant was approximately six and eight times higher than those of pristine BiVO_4 (0.0083 min^{-1}) and FeWO_4 (0.0061 min^{-1}), respectively. The enhanced photocatalytic performance is attributed to improved visible-light absorption, favourable Z-scheme interfacial charge transfer, reduced electron-hole recombination and enhanced generation of reactive oxygen species. These findings highlight the potential of $\text{FeWO}_4/\text{BiVO}_4$ heterostructures as visible-light-driven photocatalysts for removal of tetracycline from aqueous environments.

Keywords: Z-scheme, Iron(II) tungstate, Bismuth vanadate, Solar photocatalyst, Antibiotics degradation.

INTRODUCTION

Tetracycline (TC) is a widely used broad-spectrum antibiotic in human and veterinary medicine owing to its low cost and high therapeutic efficacy [1-3]. Its incomplete metabolism and persistence in aquatic environments have contributed to the contamination of surface water and groundwater, raising concerns regarding ecological toxicity and the development of antibiotic-resistant microorganisms [4,5]. Semiconductor-assisted photocatalysis has emerged as a promising approach for antibiotic degradation and the remediation of contaminated water [4-6]. The practical application of conventional semiconductor photocatalysts is frequently constrained by rapid electron-hole recombination, inadequate redox capability, and structural defects that limit their photocatalytic efficiency.

Bismuth vanadate (BiVO_4) has attracted considerable research interest as a visible-light-responsive photocatalyst owing to its monoclinic scheelite structure, chemical stability, relatively low toxicity and narrow band gap of approximately 2.4-2.5 eV [7-9]. Its electronic structure, characterized by the

hybridization of Bi 6s and O 2p orbitals, facilitates visible-light absorption compared with conventional wide band-gap semiconductors such as TiO_2 . The photocatalytic activity of pristine BiVO_4 remains restricted by the rapid recombination of photogenerated electron-hole pairs, which reduces the availability of charge carriers for surface redox reactions [10,11].

Semiconductor heterojunction engineering offers a viable strategy for addressing these limitations by regulating charge carrier migration and separation. Among the various heterojunction configurations, Z-scheme systems are of particular interest since they can promote charge-carrier separation while retaining the strong redox potentials of the constituent semiconductors. Their operation depends on suitable band-edge alignment and effective interfacial charge transfer. In a conventional Z-scheme mechanism, charge carriers with comparatively weaker redox capabilities undergo selective recombination, allowing highly reducing electrons and strongly oxidizing holes to remain available for surface reactions. This charge transfer pathway can suppress unproductive recombination and

facilitate the formation of reactive oxygen species (ROS), which participate in the oxidative degradation of organic pollutants.

Several studies have reported improved photocatalytic performance in BiVO₄-based Z-scheme systems. Tang *et al.* [12] developed an In₂S₃/BiVO₄ Z-scheme photocatalyst and reported enhanced photocatalytic degradation of glyphosate. Luo *et al.* [13] constructed a MoSe₂/BiVO₄ heterojunction with improved glyphosate removal, attributing its performance to favourable interfacial charge-transfer characteristics. Chen *et al.* [14] investigated an AgI/BiVO₄ Z-scheme heterojunction and reported enhanced tetracycline degradation under visible-light irradiation. These investigations establish the relevance of interfacial coupling and band alignment in the design of BiVO₄-based photocatalysts with improved charge carrier dynamics and pollutant-degradation activity.

Iron tungstate (FeWO₄) represents a potential semiconductor component for coupling with BiVO₄ owing to its narrow band gap and potentially suitable band-edge positions, which may facilitate interfacial charge transfer and extend the light-response characteristics of the resulting heterostructure [15,16]. The photocatalytic behaviour of FeWO₄/BiVO₄ composites is expected to depend on the relative proportions of the constituent semiconductors, the quality of their interface and the resulting structural and electronic properties. A systematic investigation of composition-dependent characteristics is consequently necessary to establish the relationship between heterostructure formation, charge-carrier behaviour and photocatalytic activity.

In present study, FeWO₄/BiVO₄ heterostructured photocatalysts were synthesized through a two-step hydrothermal approach. The influence of FeWO₄ content on the structural, morphological and optical properties of the resulting composites was investigated using a range of physico-chemical characterization techniques. Their photocatalytic performance was evaluated through the degradation of tetracycline under natural sunlight, with particular attention to identifying the optimal composite composition. Interfacial charge-transfer behaviour was examined and a plausible Z-scheme-mediated photocatalytic mechanism was proposed based on the experimental findings. The optimized FeWO₄/BiVO₄ nanocomposite exhibited enhanced tetracycline degradation activity, establishing its potential for solar-driven antibiotic removal from aqueous environments.

EXPERIMENTAL

Pure analytical grade ferrous ammonium sulphate, sodium tungstate dihydrate, bismuth nitrate pentahydrate, ammonium vanadate, ethylene glycol, ammonium oxalate, isopropyl alcohol and chloroform were procured from SRL Pvt. Ltd. and used as received. Tetracycline was employed as the model contaminant for photocatalytic experiments. The phase composition was characterized using a Bruker AXS X-ray diffractometer with CuK α radiation ($\lambda = 1.5418 \text{ \AA}$), operating at 40 kV and 1° min^{-1} . Morphological investigation was performed using FESEM on a ZEISS Ultra Plus 55 apparatus operating at 20 kV. The optical absorption study was performed using a Shimadzu UV-2450 UV-Visible spectrophotometer with BaSO₄ as the reference reflectance material.

Synthesis of FeWO₄: Iron tungstate (FeWO₄) nanoparticles were prepared *via* the hydrothermal technique. Ferrous ammonium sulphate hexahydrate (2 mmol) and sodium tungstate (2 mmol) were mixed together in 80 mL of deionized water and sealed in a 100 mL Teflon-lined steel autoclave. The process was carried out at 180 °C for 12 h. The product obtained was then decanted, washed with distilled water and ethanol and dried at 50 °C.

FeWO₄/BiVO₄ synthesis: Hydrothermal synthesis of FeWO₄/BiVO₄ nanocomposites was conducted through the dissolution of NH₄VO₃ (2 mmol) and Bi(NO₃)₃·5H₂O (2 mmol) in 50 mL deionized water with stirring for 30 min. The pH of the mixture was adjusted to 5-6 with 10 M NaOH. Specified FeWO₄ amounts (10, 15 and 20 wt.%) were added to the solution with continuous stirring. The suspension was transferred to the Teflon-lined autoclave and heated to 160 °C for 24 h. After cooling to room temperature, the nanocomposites were collected by centrifugation and repeatedly washed with water and ethanol. The drying step was carried out at 60 °C for 12 h. The synthesized samples were named as 0.10FeWO₄/BiVO₄, 0.15FeWO₄/BiVO₄ and 0.20FeWO₄/BiVO₄.

Photocatalytic studies: The photocatalytic performance of the FeWO₄/BiVO₄ nanocomposites (NCs) was evaluated using tetracycline hydrochloride (TC, 20 mg L⁻¹) as the target antibiotic, with pristine BiVO₄ nanoplates and FeWO₄ serving as reference photocatalysts. For each experiment, 30 mg of photocatalyst was dispersed in 50 mL of TC solution in a 250 mL beaker. The initial pH of the solution was 3.0. The resulting suspensions were continuously stirred at a low speed (< 100 rpm) in dark for 60 min to establish adsorption-desorption equilibrium between TC molecules and the photocatalyst surfaces. Sunlight irradiation was initiated after this equilibration period and the experiments were performed at Galgotias University (29° 51'N, 77° 53' E) during April and May 2026. The solar irradiance was approximately 221 W m⁻² on the experimental day [17].

RESULTS AND DISCUSSION

XRD analysis: The crystal structure of the synthesized composite materials was studied using XRD analysis (Fig. 1a). It was found that the diffraction peaks of BiVO₄ and FeWO₄ coincide well with the monoclinic scheelite (JCPDS No. 14-0688) and monoclinic structures (JCPDS No. 74-1130), respectively, which confirm the formation of the corresponding phases [16,17]. The spectrum of FeWO₄/BiVO₄ is similar to that of BiVO₄, indicating that the presence of FeWO₄ in the composite does not alter BiVO₄ crystal structure. While the diffraction peaks of FeWO₄ are not clearly defined due to its low concentration and dispersity, the spectral expansion revealed a displacement of some peaks at $2\theta = 29.1^\circ$ and 30.7° towards larger angles (Fig. 1b).

FESEM and HRTEM analysis: From morphological studies, it was established that the FeWO₄ materials contained agglomerated nanoparticles having sizes between 30-90 nm (Fig. 2a-c). In contrast, the BiVO₄ material had a smooth, irregular nanoplate structure with dimensions of 300-700 nm. After the formation of the composite, FeWO₄ nanoparticles were evenly distributed on the surface of the BiVO₄ nano-

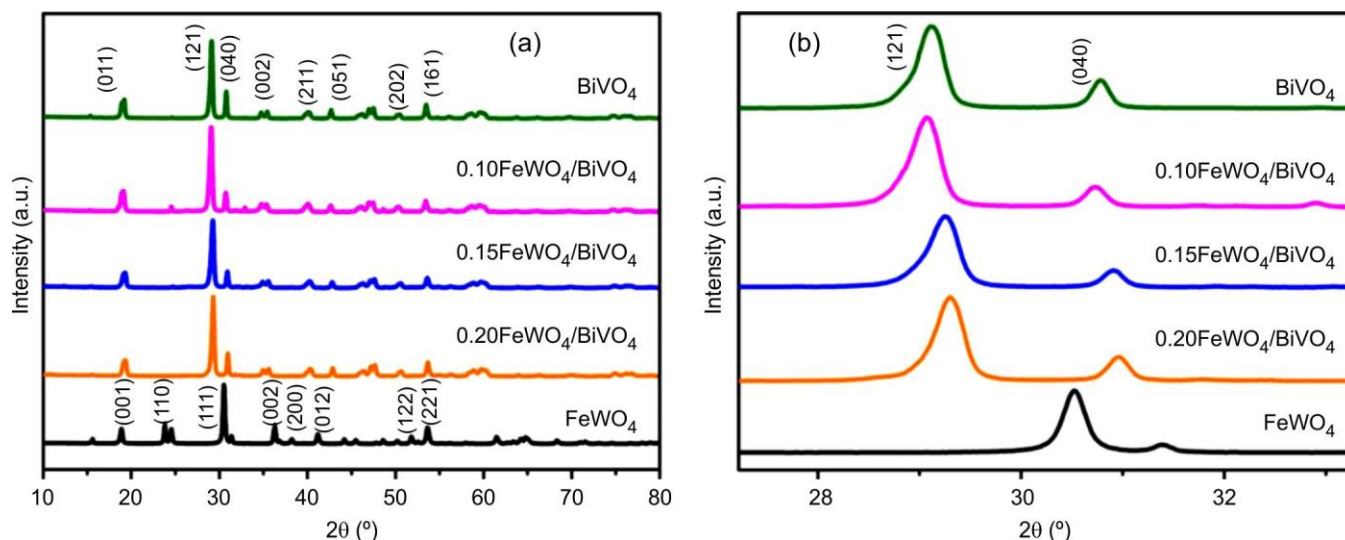


Fig. 1. (a) XRD patterns, (b) corresponding XRD patterns in the range 28° – 32° of BiVO_4 , FeWO_4 and $\text{FeWO}_4/\text{BiVO}_4$ nanocomposite

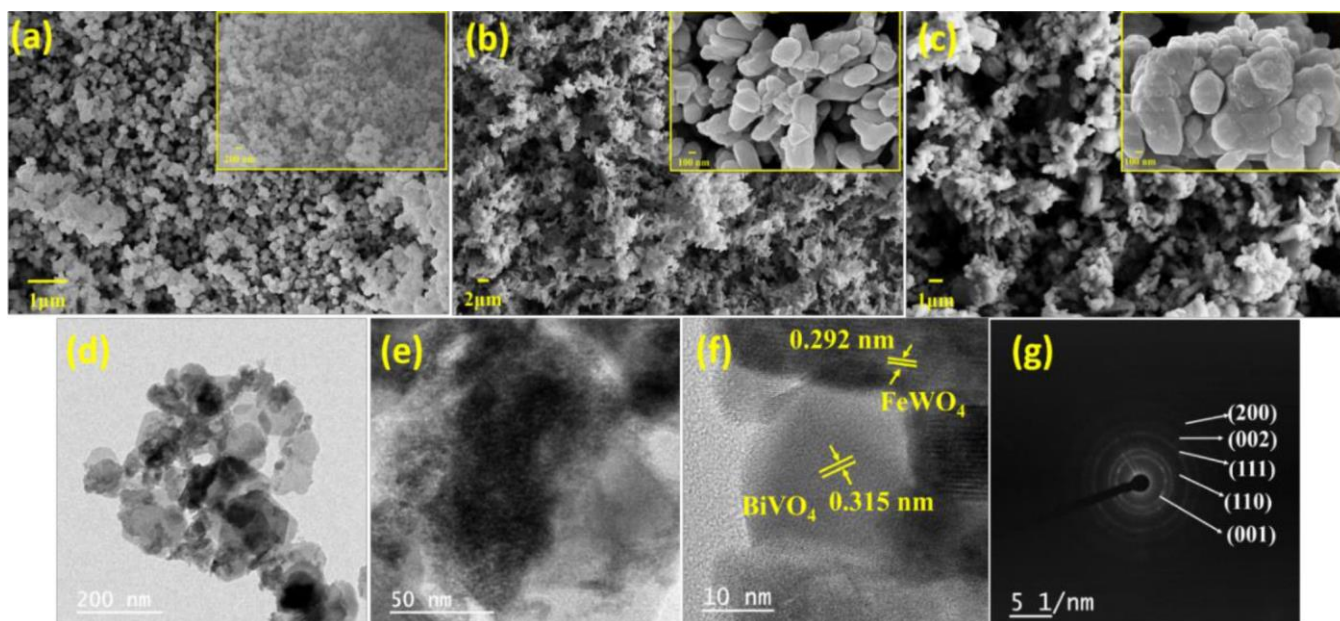


Fig. 2. FESEM images of (a) FeWO_4 , (b) BiVO_4 , (c) $0.15\text{FeWO}_4/\text{BiVO}_4$ nanocomposite; TEM images of $0.15\text{FeWO}_4/\text{BiVO}_4$ (d), HR-TEM images of $0.15\text{FeWO}_4/\text{BiVO}_4$ (e–f) and (g) SAED pattern of $0.15\text{FeWO}_4/\text{BiVO}_4$

plates without changing the original shape of the BiVO_4 material. It can be expected that such an arrangement will promote charge transfer between particles. HRTEM images (Fig. 2d–f) have further confirmed the heterostructure, showing that finely dispersed FeWO_4 nanoparticles (~ 10 – 15 nm) are distributed on BiVO_4 nanoplates. Lattice fringes (Fig. 2g) of the interplanar spacing of 0.315 nm and 0.29 nm belonged to (121) planes of BiVO_4 and (111) planes of FeWO_4 materials, respectively.

XPS analysis: XPS was employed to investigate the surface composition and oxidation states of the optimized $0.15\text{FeWO}_4/\text{BiVO}_4$ sample. Survey spectra confirmed the presence of Bi, V, Fe, W and O (Fig. 3). High-resolution spectra identified Bi in the Bi^{3+} state, V as V^{5+} , Fe as Fe^{2+} and W as W^{6+} . The O 1s spectrum contained contributions from lattice oxygen, surface hydroxyl groups and adsorbed oxygen

species or defect-related oxygen, which indicate the presence of surface-active sites beneficial for photocatalysis.

UV-Vis DRS analysis: The optical absorption behaviour of BiVO_4 , FeWO_4 and $\text{FeWO}_4/\text{BiVO}_4$ composites was analyzed using UV-Vis diffuse reflectance spectroscopy. Pristine BiVO_4 showed strong absorption up to ~ 480 nm, while FeWO_4 absorbed mainly in the visible region. Incorporation of FeWO_4 into BiVO_4 progressively shifted the absorption edge toward longer wavelengths, extending the light-absorption range of the composites. Tauc plot analysis yielded band-gap energies of 2.45 eV for BiVO_4 and 2.20 eV for FeWO_4 . The $\text{FeWO}_4/\text{BiVO}_4$ nanocomposites exhibited band-gap energies of 2.38 , 2.37 and 2.34 eV for the 0.10 , 0.15 and 0.20 compositions, respectively (Fig. 4). The gradual decrease in band-gap energy with increasing FeWO_4 content suggests that the incorporation of FeWO_4 modifies the electronic structure of BiVO_4 and

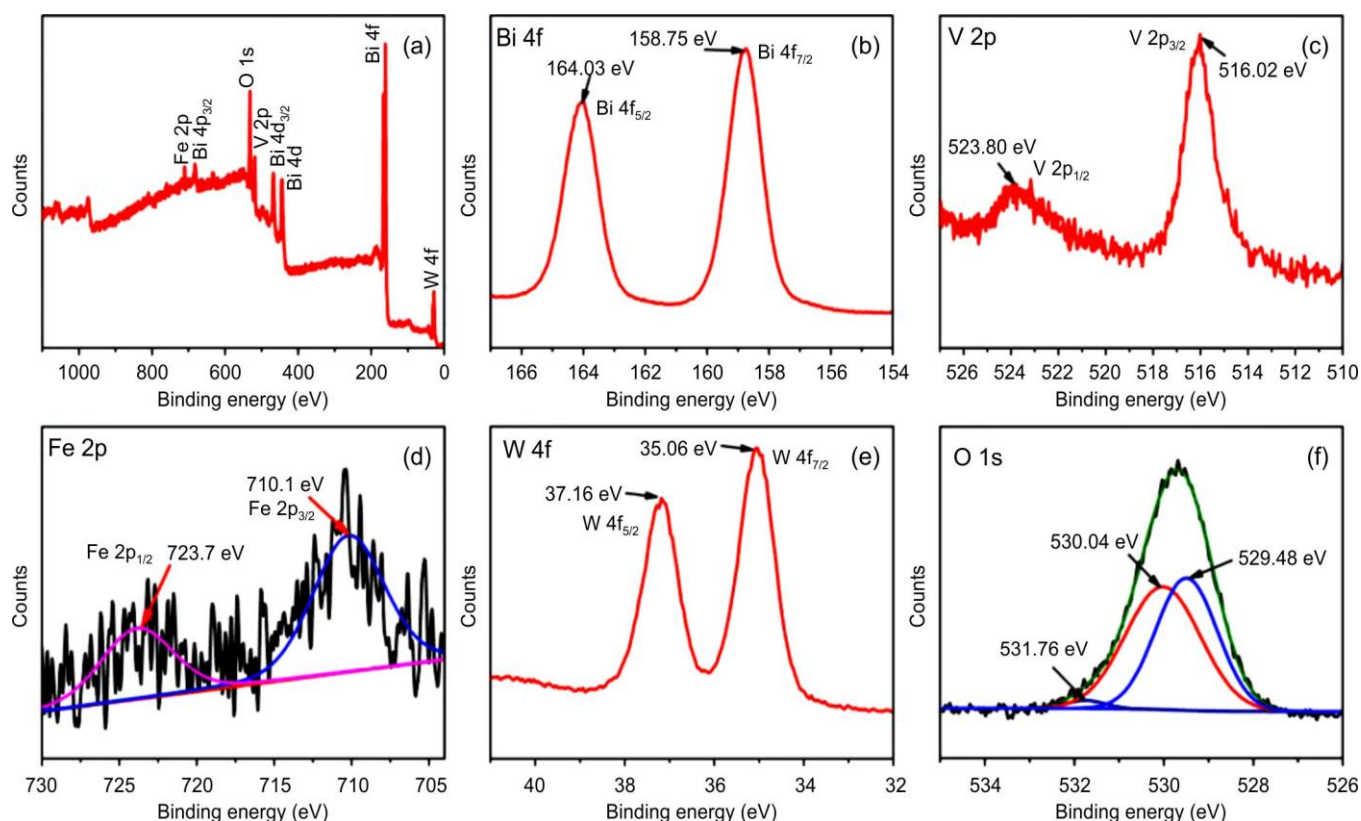


Fig. 3. XPS spectra of 0.15FeWO₄/BiVO₄ nanocomposite (a) survey spectra, (b) Bi 4f, (c) V 2p, (d) Fe 2p, (e) W 4f and (f) O 1s

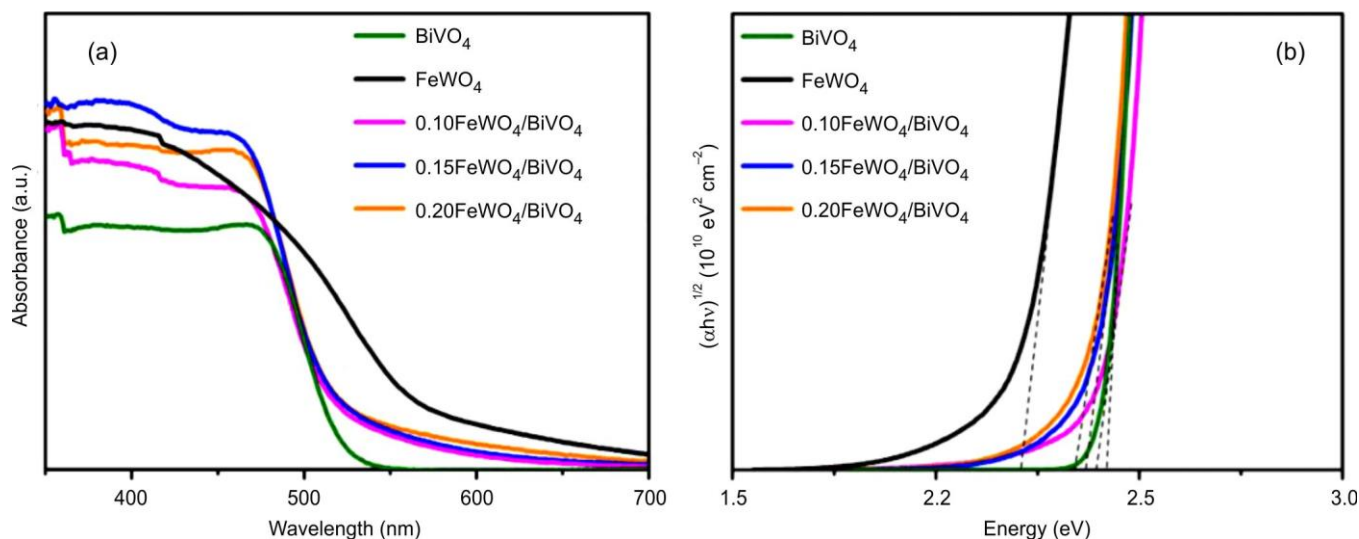


Fig. 4. (a) UV-DRS spectra, (b) Tauc's plot of FeWO₄, BiVO₄ and FeWO₄/BiVO₄

extends its optical absorption toward longer wavelengths, which may facilitate visible-light utilization.

Photocatalytic performance: Negligible tetracycline hydrochloride (TC) degradation was observed in the absence of a photocatalyst, while pristine BiVO₄ and FeWO₄ exhibited comparatively limited photocatalytic activity. Among the investigated samples, 0.15FeWO₄/BiVO₄ exhibited the highest activity, achieving 99% TC degradation within 80 min of sunlight irradiation. The photocatalytic efficiency increased with FeWO₄ loading from 0.10 to 0.15, which may be attributed to more effective separation of photogenerated charge

carriers. Further increasing the loading to 0.20 resulted in a decrease in the activity, potentially due to the partial blockage of active sites and reduced light penetration within the photocatalyst suspension.

The degradation kinetics were analysed using the pseudo first-order model, expressed as $\ln(C_0/C) = kt$, where C_0 and C represent the TC concentrations at the beginning of irradiation and at time t , respectively and k is the apparent rate constant. The 0.15FeWO₄/BiVO₄ composite exhibited the highest apparent rate constant of 0.0471 min⁻¹, approximately six and eight times those of pristine BiVO₄ (0.0083 min⁻¹) and

FeWO₄ (0.0061 min⁻¹), respectively. The progressive decrease in the characteristic TC absorption peak at 357 nm in the UV-Vis spectra provided further evidence of its degradation under sunlight irradiation (Fig. 5 and Table-1).

Sample name	Ads. (%)	Deg. (%)	First-order kinetics (TC)	
			k (min ⁻¹)	R ²
0.20FeWO ₄ /BiVO ₄	15	86	0.0246	0.994
0.15FeWO ₄ /BiVO ₄	19	99	0.0471	0.996
0.10FeWO ₄ /BiVO ₄	17	77	0.0187	0.993
BiVO ₄	14	62	0.0083	0.998
FeWO ₄	14	45	0.0061	0.985
Blank	NA	10	0.0009	0.996

Comparative studies: Table-2 compares the photocatalytic performance of the FeWO₄/BiVO₄ nanocomposite

with previously reported BiVO₄-based photocatalysts. In comparison, the optimized 0.15FeWO₄/BiVO₄ composite achieved 99% degradation of TC within 80 min under natural sunlight at an initial concentration of 20 mg L⁻¹. Its apparent rate constant of 0.0471 min⁻¹ further supports its effective photocatalytic activity. This performance may be associated with improved light absorption and interfacial charge transfer following FeWO₄ incorporation. Direct comparison requires caution, as the studies differ in irradiation conditions, pollutant concentrations and reaction parameters.

Radical trapping and stability study: Reactive oxygen species trapping experiments were performed to identify the dominant active species involved in degradation. Chloroform [20], ammonium oxalate [21] and isopropyl alcohol [16] were used as scavengers for superoxide radicals (O₂^{•-}), holes (h⁺) and hydroxyl radicals (•OH), respectively. A pronounced decrease in the photocatalytic activity was observed after suppressing O₂^{•-} and h⁺, whereas hydroxyl radical quenching caused only a minor decrease (Fig. 6). These findings indicate that superoxide radicals and photogenerated holes are the primary oxidative species driving tetracycline degradation.

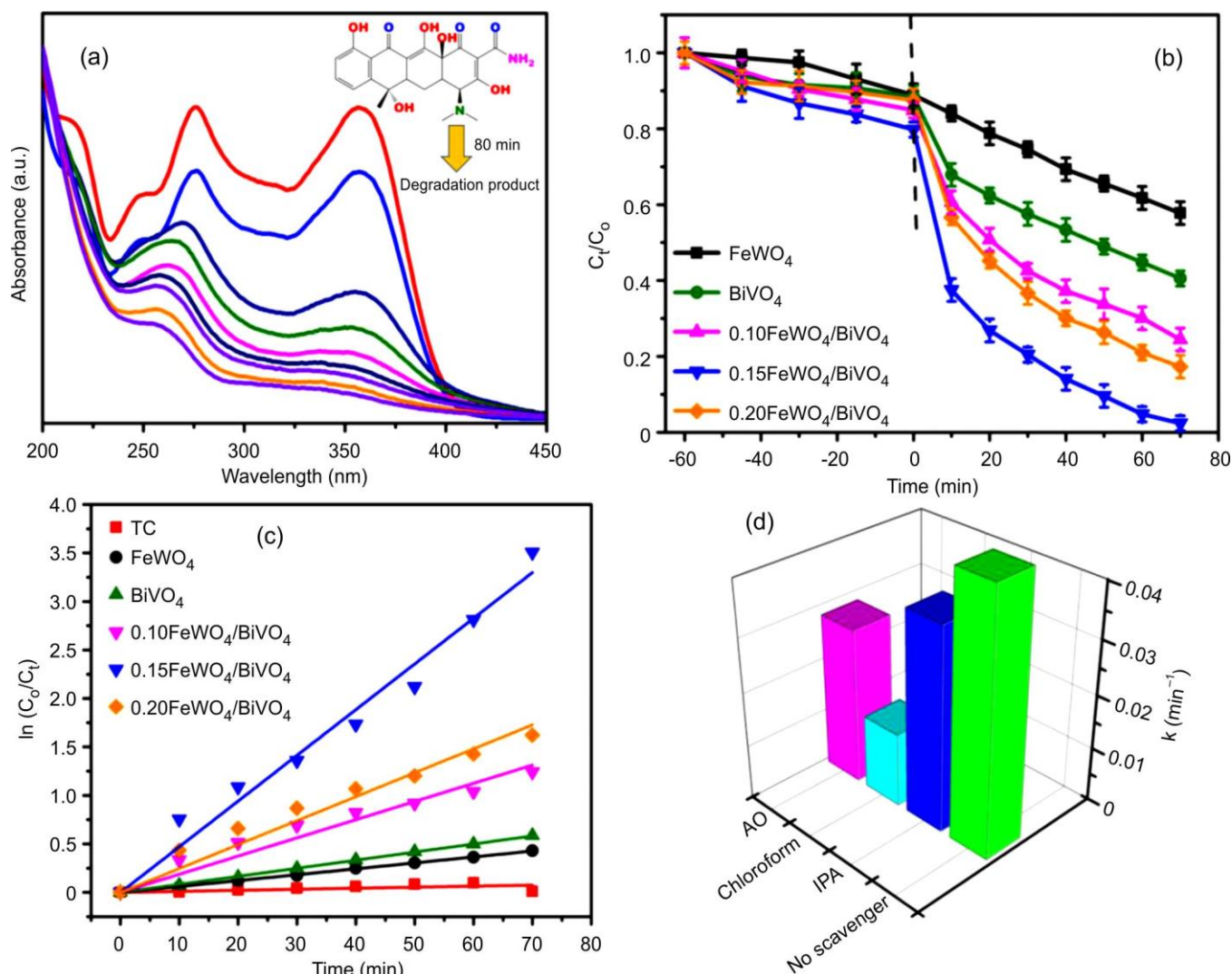


Fig. 5. (a) UV-Vis spectra of tetracycline degradation over 0.15FeWO₄/BiVO₄, (b) degradation profiles, (c) kinetic plots and (d) radical trapping study

TABLE-2
COMPARISON OF OUR STUDY WITH SOME OTHER PHOTOCATALYSTS

Catalyst	Light source	Conc.	Degradation (%) (efficiency)	Ref.
$g\text{-C}_3\text{N}_4/\text{BiVO}_4$	300 W, Xe lamp	10 mg/L (CIP)	120 min (96%)	[11]
$\text{In}_2\text{S}_3/\text{BiVO}_4$	300 W, Xe lamp	10 mg/L (glyphosate)	180 min (80%)	[12]
AgI/BiVO_4	500 W, Xe lamp	20 mg/L (TC)	100 min (85%)	[18]
$\text{MnFe}_2\text{O}_4/\text{BiVO}_4$	30 W lamp	10 mg/L (TC)	120 min (90%)	[19]
$\text{FeWO}_4/\text{BiVO}_4$	Sunlight	20 mg/L (TC)	80 min (99%)	This work

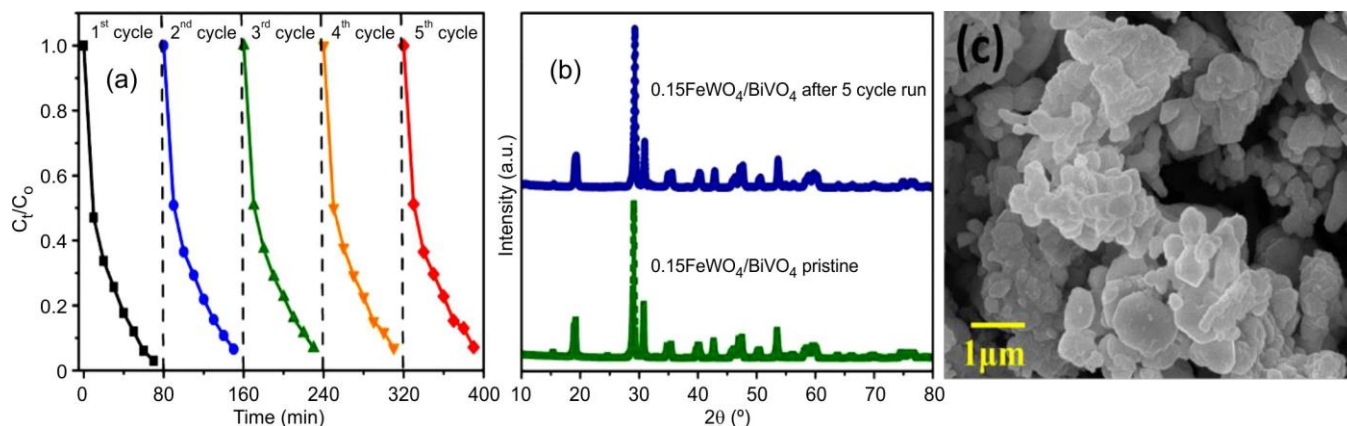


Fig. 6. (a) Recyclability experiment, (b) XRD and (c) FESEM image of the recycled photocatalyst

The recyclability of the optimized $0.15\text{FeWO}_4/\text{BiVO}_4$ photocatalyst was evaluated over five consecutive cycles. Nearly unchanged degradation efficiency across repeated runs demonstrated excellent durability. Structural stability after repeated use was further confirmed by negligible changes in crystallinity and morphology, indicating strong resistance to photocorrosion and metal leaching (Fig. 7).

Photocatalytic mechanism: Photoluminescence analysis was carried out to evaluate charge-carrier recombination in BiVO_4 and $\text{FeWO}_4/\text{BiVO}_4$ composites. All samples exhibited a broad emission band centred near 513 nm. The pristine BiVO_4 sample exhibited a more intense PL response than the $\text{FeWO}_4/\text{BiVO}_4$ composites. The lower emission intensity of the composites suggests a reduction in radiative charge-carrier recombination following FeWO_4 incorporation, which may be associated with interfacial charge transfer across the heterostructure. This improved charge separation promotes interfacial charge migration and enhances reactive oxygen species

generation. Photoelectrochemical analysis provided further insight into the charge-transfer behaviour of the $\text{FeWO}_4/\text{BiVO}_4$ heterostructures. The optimized $0.15\text{FeWO}_4/\text{BiVO}_4$ nanocomposite exhibited a higher photocurrent response than pristine FeWO_4 and BiVO_4 , signifying more effective separation and transport of photogenerated charge carriers. Its electrochemical impedance spectrum featured the smallest Nyquist semicircle among the investigated samples, consistent with lower interfacial charge-transfer resistance and more facile electron transport. The Warburg response further provided information on charge-carrier diffusion within the heterostructure, although its interpretation depends on the equivalent circuit model and the frequency range considered [22,23]. These electrochemical characteristics are consistent with the enhanced photocatalytic activity of the optimized composite.

The calculated band-edge positions raised concerns regarding the suitability of a conventional type-II charge-transfer pathway. In this configuration, the retained electrons

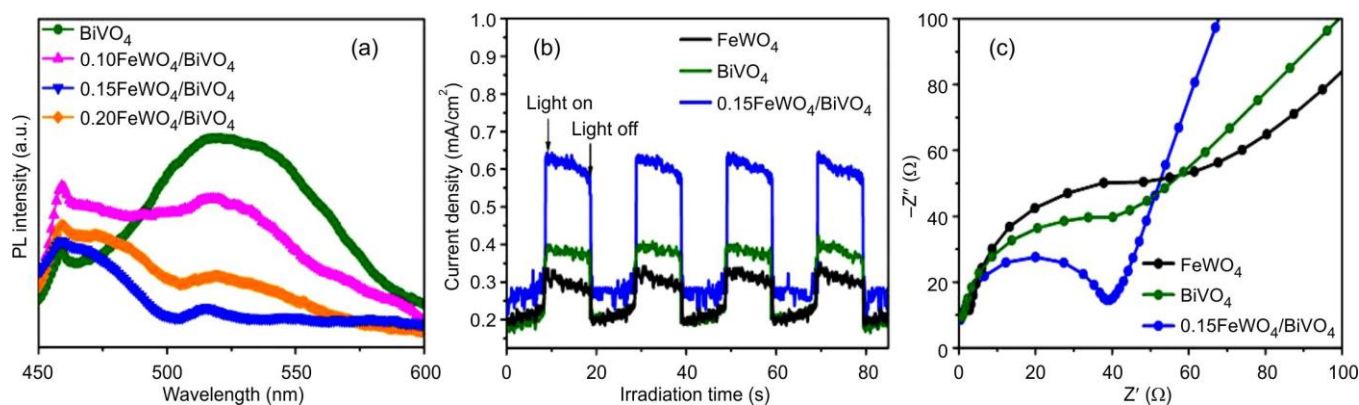
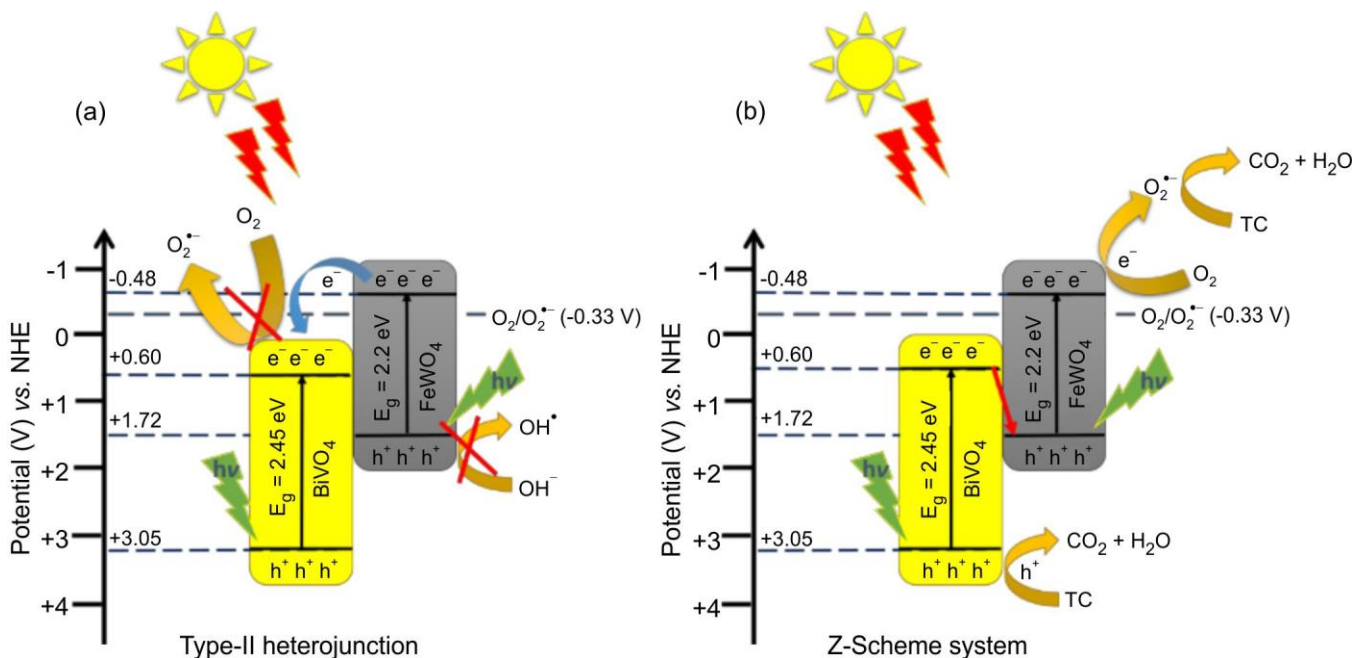
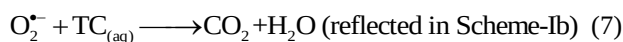
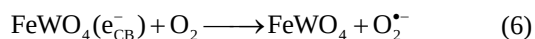
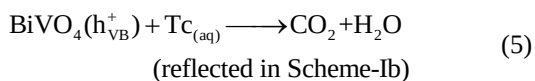
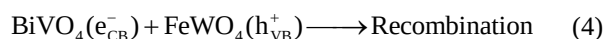
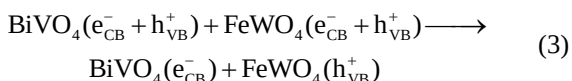
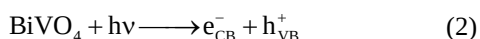
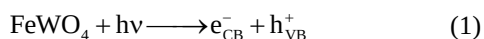


Fig. 7. (a) PL spectra, (b) photocurrent and (c) EIS, plots of BiVO_4 , FeWO_4 and $\text{FeWO}_4/\text{BiVO}_4$



Scheme-I: Proposed photocatalytic degradation pathway of tetracycline over FeWO₄/BiVO₄ under sunlight: (a) conventional type-II heterojunction and (b) Z-scheme charge-transfer mechanism

would not possess a sufficiently negative reduction potential for the formation of superoxide radicals ($O_2^{\bullet-}$), which conflicts with the radical-trapping results identifying $O_2^{\bullet-}$ as a major reactive species. A Z-scheme charge-transfer pathway is consequently proposed to account for the observed redox activity. Under sunlight irradiation, both FeWO₄ and BiVO₄ generate electron-hole pairs. At the interface, electrons in the conduction band of BiVO₄ are proposed to recombine with holes in the valence band of FeWO₄, leaving electrons in the conduction band of FeWO₄ and holes in the valence band of BiVO₄. The retained electrons can reduce adsorbed oxygen to $O_2^{\bullet-}$, while the holes can directly oxidize tetracycline or participate in the formation of other reactive species, depending on the reaction conditions (**Scheme-I**). These processes provide a plausible explanation for the enhanced photocatalytic degradation of tetracycline over the optimized FeWO₄/BiVO₄ nanocomposite.



Conclusion

A visible-light-active Z-scheme FeWO₄/BiVO₄ heterostructure was successfully synthesized *via* an *in situ* hydrothermal method for efficient Tetracycline degradation under natural sunlight. The optimized 0.15FeWO₄/BiVO₄ composite exhibited markedly enhanced photocatalytic activity, with degradation rate constants 4.83 and 6.41 times higher than those of pristine BiVO₄ and FeWO₄, respectively. Its superior performance arises from improved visible-light absorption and efficient charge separation enabled by the Z-scheme interface. In addition, the composite demonstrated excellent stability and recyclability, highlighting its potential for practical antibiotic removal from wastewater.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

DECLARATION OF AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used an AI-assisted tool(s) to improve the language and no data, results or scientific conclusions were generated by AI. All analyses, interpretations and conclusions are the authors' own. The authors reviewed and edited the content and take full responsibility for the published work.

REFERENCES

1. S. Manzetti and R. Ghisi, *Mar. Pollut. Bull.*, **79**, 7 (2014); <https://doi.org/10.1016/j.marpolbul.2014.01.005>
2. R. Zhang, J. Tang, J. Li, Z. Cheng, C. Chaemfa, D. Liu, Q. Zheng, M. Song, C. Luo and G. Zhang, *Sci. Total Environ.*, **450-451**, 197 (2013); <https://doi.org/10.1016/j.scitotenv.2013.02.024>

3. J. Fick, H. Söderström, R.H. Lindberg, C. Phan, M. Tysklind and D.G.J. Larsson, *Environ. Toxicol. Chem.*, **28**, 2522 (2009);
<https://doi.org/10.1897/09-073.1>
4. Y. Wang, K. Ding, R. Xu, D. Yu, W. Wang, P. Gao and B. Liu, *J. Clean. Prod.*, **247**, 119108 (2020);
<https://doi.org/10.1016/j.jclepro.2019.119108>
5. R. Yang, Z. Zhu, C. Hu, S. Zhong, L. Zhang, B. Liu and W. Wang, *Chem. Eng. J.*, **390**, 124522 (2020);
<https://doi.org/10.1016/j.cej.2020.124522>
6. Y. Wang, D. Yu, W. Wang, P. Gao, S. Zhong, L. Zhang, Q. Zhao and B. Liu, *Separ. Purif. Tech.*, **239**, 116562 (2020);
<https://doi.org/10.1016/j.seppur.2020.116562>
7. N. Wetchakun, S. Chaiwichain, B. Inceesungvorn, K. Pingmuang, S. Phanichphant, A.I. Minett and J. Chen, *ACS Appl. Mater. Interfaces*, **4**, 3718 (2012);
<https://doi.org/10.1021/am300812n>
8. G.S. Kamble, T.S. Natarajan, S.S. Patil, M. Thomas, R.K. Chougale, P.D. Sanadi, U.S. Siddharth and Y.-C. Ling, *Nanomaterials*, **13**, 1528 (2023);
<https://doi.org/10.3390/nano13091528>
9. M. Yan, Y. Wu, Y. Yan, X. Yan, F. Zhu, Y. Hua and W. Shi, *ACS Sustain. Chem. Eng.*, **4**, 757 (2016);
<https://doi.org/10.1021/acssuschemeng.5b00690>
10. T. Soltani, A. Tayyebi and B. Lee, *J. Environ. Manage.*, **232**, 713 (2019);
<https://doi.org/10.1016/j.jenvman.2018.11.133>
11. Y. Deng, L. Tang, C. Feng, G. Zeng, J. Wang, Y. Zhou, Y. Liu, B. Peng and H. Feng, *J. Hazard. Mater.*, **344**, 758 (2018);
<https://doi.org/10.1016/j.jhazmat.2017.11.027>
12. Q. Tang, X. Luo, S. Yang and Y. Xu, *Sep. Purif. Technol.*, **248**, 117039 (2020);
<https://doi.org/10.1016/j.seppur.2020.117039>
13. X. Luo, Z. Chen, S. Yang and Y. Xu, *J. Colloid Interface Sci.*, **532**, 456 (2018);
<https://doi.org/10.1016/j.jcis.2018.07.142>
14. S. Chen, D. Huang, G. Zeng, W. Xue, L. Lei, P. Xu, R. Deng, J. Li and M. Cheng, *Chem. Eng. J.*, **382**, 122840 (2020);
<https://doi.org/10.1016/j.cej.2019.122840>
15. M. Farhan, A.K. Singh and G. Kumar, *Macromol. Symp.*, **415**, e70277 (2026);
<https://doi.org/10.1002/masy.70277>
16. G. Kumar, *J. Inorg. Organomet. Polym. Mater.*, **33**, 2710 (2023);
<https://doi.org/10.1007/s10904-023-02711-y>
17. T.V. Ramachandra, R. Jain and G. Krishnadas, *Renew. Sustain. Energy Rev.*, **15**, 3178 (2011);
<https://doi.org/10.1016/j.rser.2011.04.007>
18. W. Zhao, J. Li, B. Dai, Z. Cheng, J. Xu, K. Ma, L. Zhang, N. Sheng, G. Mao, H. Wu, K. Wei and D.Y.C. Leung, *Chem. Eng. J.*, **369**, 716 (2019);
<https://doi.org/10.1016/j.cej.2019.03.115>
19. N.T. Dieu Cam, H.-D. Pham, T.-D. Pham, T.T. Thu Phuong, C. Van Hoang, M.H. Thanh Tung, N.T. Trung, N.T. Huong and T.T. Thu Hien, *Ceram. Int.*, **47**, 1686 (2021);
<https://doi.org/10.1016/j.ceramint.2020.08.285>
20. G. Kumar, *Macromol. Symp.*, **415**, e70273 (2026);
<https://doi.org/10.1002/masy.70273>
21. G. Kumar, *Macromol. Symp.*, **415**, e70315 (2026);
<https://doi.org/10.1002/masy.70315>
22. M.E. Orazem and B. Tribollet, *Electrochemical Impedance Spectroscopy*, Wiley: Hoboken, NJ, USA, edn 2 (2017).
23. J. Huang, *Electrochim. Acta*, **281**, 170 (2018);
<https://doi.org/10.1016/j.electacta.2018.05.136>