

Cite this article: S. Banerjee, Nanostructured metal oxides for photoelectrochemical energy conversion and biomedical sensing: A review connecting energy and medical applications, *RP Materials: Proceedings* Vol. 5, Part 1 (2026) pp. 1–6.

Review Article

Nanostructured metal oxides for photoelectrochemical energy conversion and biomedical sensing: A review connecting energy and medical applications

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**Selection and Peer-Review under responsibility of the Scientific Committee of the 4th International Conference on Recent Trends in Materials Science & Devices 2026 (ICRTMD 2026) held at JVMGRR College, Charkhi Dadri, Haryana, India during 6–8 April 2026.

ARTICLE HISTORY

Received: 15 April 2026
Revised: 27 May 2026
Accepted: 27 May 2026
Published online: 12 June 2026

KEYWORDS

Metal oxides;
Water splitting;
Biosensing applications;
Biocompatibility;
Metabolic monitoring.

ABSTRACT

Nanostructured metal oxides play a crucial role as catalytic materials in photoelectrochemical water splitting owing to their favourable electronic properties, chemical stability and earth abundance. With the rising environmental concerns and advances in sustainable technologies, renewable energy storage and conversion technologies rely heavily on metal oxide-based materials. Metal oxides such as ZnO, TiO₂, BiVO₄ are widely used semiconductors due to their availability, cost effectiveness and stability and they can be readily synthesised under ambient conditions, making them suitable for large scale production. Beyond energy conversion, these materials have garnered significant attention for their potential role in biomedical sensing application. Their high surface area, chemical reactivity and sensitivity to chemical species make them a promising candidate for biosensing and metabolic monitoring. This review provides a detailed medically oriented insight on nanostructured metal oxides, offering an in-depth analysis of their sensing applications in the physiological environment. Current challenges related to finding long durable and biocompatible materials are discussed along with efforts to connect interdisciplinary advances in energy driven semiconductor materials with medical sensing technologies.

1. Introduction

With the increasing development in the technology, the global rise in energy consumption and over dependence of fossil fuel has made the scenario worth noting. It has a direct impact on energy sustainability, efficiency and environmental concerns. The industrial evolution and the CO₂ emission make it more significant to switch towards the renewable energy sources because of its availability and clean energy [1]. In this context, the semiconductor materials-based energy conversion helps in converting solar energy to chemical energy via Photoelectrochemical water splitting (PEC) systems making it scalable keeping a pace with the environment [1,2]. Along with the challenge of the global energy consumption and the development of semiconducting energy. The semiconductor materials drive the hydrogen evolution reaction, Nanostructured semiconducting materials such as TiO₂, ZnO, BiVO₄, SnO etc provides an aligned band structure, enhanced charge separation, and electrochemical durability making them effective as a PEC material [3,4].

On the other hand, modern biomedical technology particularly sensing materials used for metabolic monitoring and early disease diagnosis strongly depends on the efficiency of functional materials and their ability to transduce signals in complex physiological environments. Nanostructured materials are especially attractive in this context because they

provide a high surface-to-volume ratio, tunable band gaps, and large interfacial areas that facilitate efficient charge transfer between analytes and sensing platforms [5].

From a physics perspective, photoelectrochemical (PEC) energy conversion and biosensing share several fundamental mechanisms. Both processes involve the absorption of electromagnetic radiation, generation of charge carriers, and their subsequent transport across interfaces. In addition, the electric potential at the semiconductor–electrolyte interface plays a crucial role in governing charge transfer processes, while electrolyte screening effects and the formation of the electrical double layer significantly influence the interfacial dynamics [6,7].

Therefore, understanding the behaviour of the semiconductor–electrode interface becomes a key parameter in designing multifunctional systems for renewable energy and sensing applications. This review aims to bridge photoelectrochemical water splitting and biomedical biosensing through a physics-oriented perspective, with particular emphasis on charge transport mechanisms, the behaviour of the electrode–electrolyte interface, and the stability of these systems in aqueous environments. Furthermore, we discuss the major challenges related to performance, durability, and biocompatibility, and explore the



potential integration of sensing capabilities into energy-driven materials for long-term sustainable technologies [8,9].

2. Physical properties of nanostructured metal oxides

Photoelectrochemical water splitting (PEC) mechanism comes under transformative technology where they harness solar energy to generate clean and renewable source of energy. The process uses semiconductor materials as the photoelectrode in presence of aqueous electrolyte absorbs the sunlight that facilitates chemical reactions necessary for effective water splitting. Among various nanostructured materials metal oxides are used quite often because of their stability and adaptability. A sensor on the other hand, is a miniaturized device that tracks the chemical, biological and physical changes and convert it to a signal. The sensor comprises of specific components (enzyme, antibody, nucleic acid, a receptor protein etc). It mainly works in two sections firstly the materials that are used to sense, reacts only in the presence of effective analyte, which does not allow other elements to participate minimizing the interference secondly the detector of the device converts the reaction into sample. It is important to understand the charge transport properties and the interfacial dynamics between the semiconductor and the electrolyte systems [10,11].

2.1 Significance of band gap engineering

Band gap engineering is the process that governs the modulation of band gap of a material as an when required as it serves as the critical parameter for almost all technological applications. For instant, solar cells, photocatalytic devices, lasers etc. This process is typically carried out in semiconductors where the composition of alloy can be altered and layers of different materials can also be converged to attain the desired band gap. Upon illumination, the electrons mediate from the valence band to the conduction band generating electron-hole pairs. The narrow band helps in absorbing the visible light irradiation which covers the greater portion of the spectrum enhancing the photocatalytic activity [12]. There are different methods opted for alteration (a) Doping where new atoms of similar ionic radii is introduced in the host material (b) Heterostructures, combining two different semiconductors which helps in tuning the band gap as required. These are some of them that create new energy states for facilitating charge transfer. In nanostructured systems, band alignment at the electrode-electrolyte interface has a significant role in separating the charges. When two semiconductors are connected together, they form an internal electric field with fermi equilibration. These internal field that is built in the coupled nanostructures helps in directional charge transfer inhibiting the recombination losses. This internalized functioning is effective for both the photoelectrochemical energy conversion and storage along with biosensing application. Although there are lot of advancements, still there is challenge regarding the precise balance between charge separation and recombination inhabitation [13,14].

Recent studies have been carried that showed that band gap engineering strategy through incorporation of dopant, formation of heterojunction and designing nanostructures are some important parameters that enhances the ability of light absorption and thereby enhancing charge transport in metal oxide matrix. For example, thorough research has been done on TiO_2 , BiVO_4 , ZnO , Fe_2O_3 etc. where their strategies of

band edge modification and defect state incorporation helped in visible light accumulation and enhanced PEC efficiency. A study on ZnO has shown that using different dopants of similar ionic radii has narrowed the band gap where ZnO usually has wide band gap (~ 3.37 eV) while TiO_2 has a band gap of (3.2 eV) making them less effective in absorbing the visible light of the solar spectrum. To tackle this limitation, there are band engineering approaches that employed to shift the band gap for expanding the range of absorption of the material of the solar spectrum [13-15].

2.2 Different strategies used for light absorption expansion

(a) Doping: Doping is a strategy where foreign atoms are introduced into the crystal structure with analogous ionic radii to modify the band gap. Localized energy states are created within the forbidden energy states that narrows the wide band gap facilitating the absorption of visible light from the solar spectrum which covers the most part of it. Metal ion dopants, non-metal ion dopants, co-dopants are used for the strategic alteration and their research analysis has been carried till date to enhance the photocatalytic efficacy [13].

(b) Heterojunction: Here, two semiconductors of different band alignments are connected which comprehends the charge separation with the generation of internal electric field. The difference in Fermi level helps in separating the charges and inhibiting the recombination losses that is a common limitation in PEC systems [14].

(c) Defect Engineering: The strategic introduction of oxygen vacancies or crystal defects for creating defect states in the material within the band gap significantly enhances the conductivity along with the light absorption ability.

(d) Morphological Engineering: Quantum confinement approach has been widely studied because of their wide range advantages. Nano structuring the materials into different dimensions rods, sheets, tubes, wires make it effective for the quantum confinement effects. Band alignment in the electrode/electrolyte interface plays an important role in nanostructured systems. When electrodes are immersed in the solution, the electrode and electrolyte connection forms an internal electric field due to fermi energy equilibration, promoting the directional charge transfer. This strategy suppresses the recombination of charges facilitating smooth charge transfer increasing efficiency both in PEC water splitting and PEC biosensing systems. Recent technological advancements show that combining multifaceted engineering strategies produces synergistic improvements in the materials used. For instance, ZnO and TiO_2 nanorods have significantly improved its light absorption ability when coupled with secondary semiconductors or foreign atoms of similar ionic radii has been incorporated. On the other hand, BiVO_4 and Fe_2O_3 have also increased the photocurrent density and photoconversion efficiency with the incorporation of oxygen vacancies.

Despite these advancements challenges still remain in precisely controlling the concentration of the added defects, dopant concentration and distribution. Because, excessive defect or dopant inculcation may disrupt the equilibration thereby increasing the charge recombination further decreasing the efficiency. Therefore, careful optimization of band gap remains a critical parameter [15-17].

Table 1: Important physical properties of nanostructured metal oxides connecting PEC and Sensing application.

Properties	Description	Significance in PEC-WS application	Significance in PEC Biosensing application
Band gap energy	Energy difference between Valence band and Conduction band	Determines range of light absorption and photocatalytic efficiency	Influences photo-induced sensing response
Surface Area	Available active area per unit volume	Enhances water oxidation/reduction active sites	Increases analyte adsorption and sensitivity
Charge Carrier Mobility	Ability of electrons/holes to move through material	Improves photocurrent and charge separation	Enables rapid electron transfer and photo-signal generation
Morphology	Structural shape (nanorods, nanotubes, nanosheets)	Affects light harvesting and transport pathways	Improves analyte accessibility and sensor response

3. Application in photoelectrochemical energy systems

Photoelectrochemical (PEC) are known for their outstanding approach of converting solar energy into chemical energy, it facilitates a sustainable pathway for generation of green and clean energy. And with the implementation of nanostructured metal oxides helps in further increasing the efficiency of the PEC systems owing to their high surface to volume ratio, high surface area, modifying band gaps and chemical durability and stability. As the entire concept of PEC system depends on charge generation, transfer and separation. Recent studies have brought the attention improving light absorption capability, charge separation and long-term enduring ability. The main mechanism of the PEC systems is their photon absorption ability, generation and excitation of electrons with precise redox kinetics. However, they come up with limitation and restrict the efficiency with charge recombination and suppressed redox kinetics. To work on these shortcomings, several studies have been carried out for advanced engineering approaches [4,11,18]. For instance, Dong et. al. explored cobalt-based metal-organic framework (Co-MOF) modified Ti-doped hematite photoanode for enhancing the PEC performance. The material used to modify the PEC system has significantly improved photocurrent density (1.80 mA cm^{-2} at 1.23 V) with excellent increment of stability with only 5% decay for duration of 10 hours. This modification helped in enhancing the charge separation and facilitated a faster redox kinetics [19]. Similarly, Raub et. al. gave a thorough analysis of nanostructured metal oxides photoanodes such as TiO_2 , Fe_2O_3 , WO_3 , and BiVO_4 for PEC water splitting. The study done in this research mainly comprehends the doping and heterojunction strategy that enhances the photocurrent density and hydrogen generation efficiency [20]. Moreover, Kumar et. al. inherently discussed

about the significance of co-catalysts in improving the PEC stability and efficiency. The research study implied that with the addition of transition metal based cocatalysts improves the charge transfer dynamics reducing the overpotential thereby increasing rate of hydrogen evolution [21]. Banerjee et. al. talked about the ZnO nanorods loaded with CuI nanoparticles. Here, ZnO nanorods and CuI nanoparticles form a heterojunction structure properly forming an p-n heterostructures where both the advantage of p-type structure and n-type structure is obtained enhancing the photocurrent density and facilitating charge separation ability for a longer duration. There was an enhancement in photoconversion efficiency (0.18%) while the electrochemical impedance spectroscopy (EIS) study confirmed increased donor density implying better charge transfer facility and reduced recombination [22]. So, the overall recent research studies give a comprehensive analysis that the heterostructures, doping strategies, cocatalyst implementation and nano structuring of metal oxides are some of the effective approaches in the field of PEC water splitting systems for enhancing the PEC efficiency and performances. Along with proper charge separation and transport these strategies also helps in swift redox kinetics for evolution and reduction reactions. Despite several advantages there are certain key challenges that remains intact: such as the limited visible light absorption, although the charge separation strategy helps in enhancing the efficiency yet the high electron-hole recombination rate prevails. The stability of the materials for a longer duration still needs to be analysed and worked upon. And there is yet difficulty in large scale generation and commercialization of energy and long-term energy storage continues to highlight difficulties.

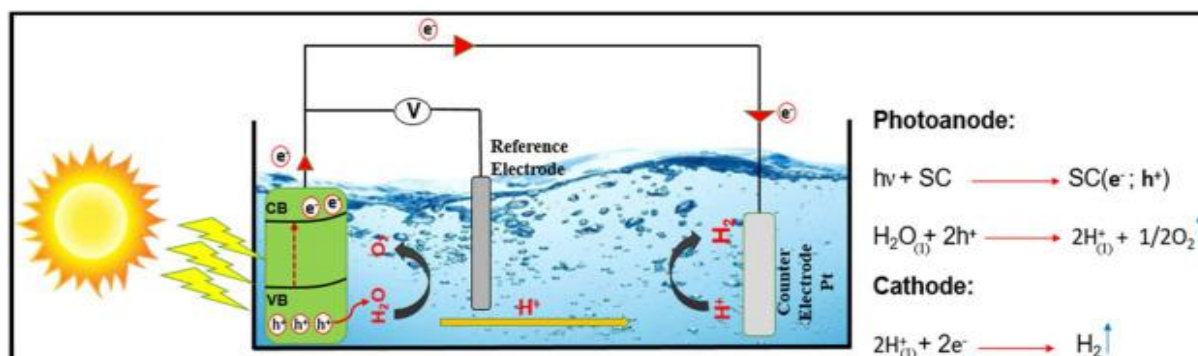
**Figure 1:** Schematic representation of the photoelectrochemical water splitting process. Adapted from Ref. [4].

Table 2: Recent studies carried out for the nanostructured metal oxide-based PEC water splitting system.

Photoelectrode material	Modification Strategy	Key Performance	Major Finding	Ref.
Ti-doped Hematite	Co-MOF surface modification	1.80 mA cm ⁻² at 1.23 V	Enhanced charge transfer and improved PEC stability	[19]
TiO ₂ , Fe ₂ O ₃ , WO ₃ , BiVO ₄	Nanostructuring and doping	Enhanced PEC efficiency	Improved charge mobility and hydrogen generation	[20]
Metal oxide photoelectrodes	Cocatalyst deposition	Improved hydrogen evolution performance	Enhanced surface kinetics and reduced overpotential	
ZnO nanorods	CuI nanoparticle loading / p-n heterojunction	0.67 mA cm ⁻² at 1.23 V vs RHE	Six-fold enhancement in photocurrent due to improved charge separation and donor density	

4. Application in photoelectrochemical biosensor

PEC biosensing technique has come up as an innovative analytical technique that combines the principles of photochemistry and electrochemistry helping in detecting highly sensitive biological analytes. Compared to the conventional electrochemical sensor, PEC biosensors keep the irradiation process separate from the current signal that is obtained as output that significantly reduces background noise and gives an improved signal-to-noise ratio. This specific pathway of PEC biosensor makes it ideal for biomedical diagnostics, environmental assessment and food quality evaluation. Recent advances in the nanostructured metal oxides continued to modify the PEC biosensing through band gap alteration, increased photostability, high surface area and excellent catalytic properties. The basic idea of PEC biosensing is that when light is irradiated in the semiconductor surface the electrons excites from valence band to the conduction band creating the electron-hole (e⁻-h pair). These charges when interacts with the analyte drives the chemical reactions generating electric signals (Photo current). At the sensing surface when a target interacts it changes the photo current. And evaluating this change helps the system to detect and measure the target. The efficiency of PEC biosensors mainly depends on the ability of charge separation, light absorption efficacy and how well the charges transfer. These factors can greatly be facilitated using nanostructured metal oxides [23,24].

Among different semiconductor materials, ZnO has garnered attention because it has fast electron movement facility, strong exciton binding energy and easily modifiable surface. Recent study has been carried out by Qiu et. al. fabricating ZnO/graphene hybrid photoelectrode using laser treatment. Their system allows photocurrent polarity switching facility in PEC biosensing combined with a DNA walker

amplification method. Such fabrication helped in obtaining fewer false signals and has the ability to resist interference. The amalgamation of ZnO and graphene improved photocurrent polarity switching and improved charge transfer showing a better scope of the ZnO heterostructures biosensing [25].

Beyond TiO₂ and ZnO, porous photoactive materials have become immensely significant in PEC biosensing. Liu et. al. researched about the porous material systems and explored that their nanostructure synthesis increases more active sites for chemical reactions to take place, allows the analytes to interact more easily thereby improving the charge transport. These features with high sensitivity together help in smoothly monitoring pollutants and biomolecules [26].

In glucose biosensing, nanostructured ZnO and TiO₂ are widely used because of their efficient biocompatibility and their amazing enzyme holding capacity. Sengupta et. al. showed that TiO₂ nanotube-based biosensors improve glucose detection by providing enhanced electron transfer, larger number of active sites and increased stability for a longer duration. Such properties make them suitable to be used as implantable and wearable glucose monitoring systems [27].

Recent studies shows that nanostructured metal oxides make PEC biosensors more effective by enhancing light absorption, charge separation, and providing large number of active sites to interact with the biomolecules. Still, there are challenges prevailing upon weak absorption of visible light, poor stability and durability, recombination losses and their large-scale commercialization. To solve these issue, future focus should be impeded into heterostructures, precise control of defect concentration, hybrid nanocomposites etc. With the progress in making new nanomaterials and miniature devices. PEC biosensors could become important tools in real-time monitoring and wearable healthcare diagnostics.

Table 3: Recent advancements in Nanostructured metal oxide-based PEC Biosensor

Materials	Target Application	Key Findings	Ref.
ZnO/Graphene hybrid photoelectrode	DNA biosensing	Developed a photocurrent-polarity-switching PEC biosensor with enhanced DNA detection sensitivity. Thereby, decreased false signals and improved efficiency	[25]
Porous nanostructured photoactive materials	Biomolecule and pollutant sensing	Porous photoactive structures help analytes move more easily, provides more active sites, and improve charge transport.	[26]
TiO ₂ nanotube-based PEC biosensor	Glucose biosensing	Reported better glucose detection because of improved electron transfer, a larger surface area, and strong long-term stability of the sensor.	[27]

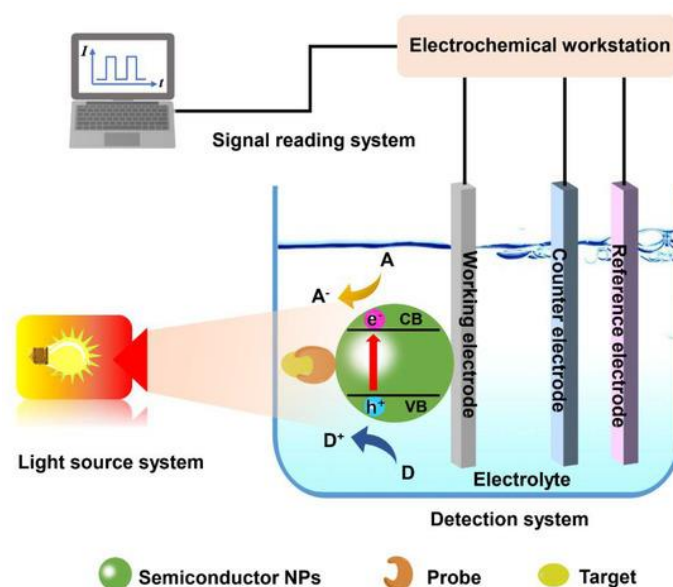


Figure 2: Schematic representation of the photoelectrochemical biosensing process. Adapted from Ref. [28].

5. Future prospects

The future of nanostructured metal oxides in Photoelectrochemical systems whether in energy conversion or health care diagnostics appears to be promising. It is because of the continuous nanofabrication, progress in material synthesis and design and the interdisciplinary approaches. Although photocurrent density and efficiency have increased effectively but the limitation of charge recombination, weak light absorption, photocorrosion still hinders their practical use. Future research is mostly directed towards advanced band gap engineering method for instance the co-doping strategy, defect control and strategic heterojunction design and also combining it with doping are some of them. Incorporating hybrid nanocomposites and plasmonic nanoparticles helps in boosting the light absorption of the base surface, directional charges and recombination. Fabricating hierarchical nanostructures and multi-faceted designs also may offer active sites for interaction and better migration enhancing the overall efficiency. Another future parallel directional is to create multifunctional self-powered systems that comprises of energy harnessing and sensing in a single automation. Combining PEC energy conversion with biosensing can bring forth solar power-driven devices such as implantation and wearable diagnostic devices, portable monitoring canvas. Usage of Artificial Intelligence can further aid the material designing and safety with its advanced computer modelling techniques. Scalable and low-cost materials are also important in building large scale production and commercialization. With these ongoing nanotechnology advancement and miniaturization, PEC based nanostructured metal oxides are expected to play a transformational role in energy, health care and environmental sector [2,29].

6. Conclusion

Nanostructured metal oxides are wide-ranging materials with strong potential in Photoelectrochemical energy conversion and biomedical sensing because of their multifunctional properties. Such as their potent optical, electronic, chemical properties. Their modifiable band gap,

large surface to volume ratio, strong photocatalytic activity and efficient charge transport makes them viable for solar driven hydrogen generation and sensitive biosensing. Strategies like band gap doping, fabrication of heterostructures and morphological optimization have already facilitated its current transfer and efficiency. Still, limitation of charge recombination, weak light absorption, corrosion and poor durability prevails. Recent advancements in material tuning and nanostructure designing have helped in overcoming these problems at a certain limit. Overall, using these nanostructures in advanced functional PEC systems offers a promising step towards sustainable energy and advanced medical diagnostics showing their significance in future smart technologies.

Acknowledgements

The author acknowledges Srimanta Sankaradeva University of Health Sciences, Assam, India, for providing an academic environment that enabled the exploration of interdisciplinary approaches linking energy materials and healthcare diagnostics.

Authors' contributions

The author reviewed and approved the final version of the manuscript for publication.

Conflicts of interest

The author declares no conflict of interest.

Funding

This research received no external funding.

Data availability

No new data were created.

References

- [1] G. Dong, L. Yan, Y. Bi, Advanced oxygen evolution reaction catalysts for solar-driven photoelectrochemical water splitting, *J. Mater. Chem. A* **11** (2023) 3888–3903.

- [2] Y. Zhao, Z. Niu, J. Zhao, L. Xue, X. Fu, J. Long, Recent advancements in photoelectrochemical water splitting for hydrogen production, *Electrochem. Energy Rev.* **6** (2023) 14.
- [3] P. Mane, I.V. Bagal, H. Bae, A.N. Kadam, V. Burungale, J. Heo, S.-W. Ryu, J.-S. Ha, Recent trends and outlooks on engineering of BiVO₄ photoanodes toward efficient photoelectrochemical water splitting and CO₂ reduction: A comprehensive review, *Int. J. Hydrogen Energy* **47** (2022) 39796–39828.
- [4] M. El Ouardi, A. El Idrissi, H. Ait Ahsaine, A. BaQais, M. Saadi, M. Arab, Current advances on nanostructured oxide photoelectrocatalysts for water splitting: A comprehensive review, *Surf. Interfaces* **45** (2024) 103850.
- [5] Q. Liu, D. Liu, M.A. Alpuche-Aviles, W. Ma, Editorial: Nanotechnology facilitated photo(electrochemical) biosensors, *Front. Bioeng. Biotechnol.* **11** (2023) 1136565.
- [6] H. Zhang, B. Zhang, X. Wang, et al., Effective charge separation in photoelectrochemical water splitting: A review from advanced evaluation methods to materials design, *Sustain. Energy Fuels* **8** (2024) 2357–2382.
- [7] Y. Zhan, Y.-C. Chen, X. Long, Interfacial engineering enabling solution-processed Cu:NiO_x/Sb₂Se₃/TiO₂/Pt photocathodes for highly efficient photoelectrochemical water-splitting, *Sustain. Energy Fuels* (2024).
- [8] R.A. Jayarathna, J.-H. Heo, E.-T. Kim, Enhanced photoelectrochemical water splitting of In₂S₃ photoanodes by surface modulation with 2D MoS₂ nanosheets, *Nanomaterials* **14** (2024) 1628.
- [9] J. Shi, Z. Chen, C. Zhao, et al., Photoelectrochemical biosensing platforms for tumor marker detection, *Coord. Chem. Rev.* **469** (2022) 214675.
- [10] Z. Li, J. Lu, W. Wei, M. Tao, Z. Wang, Z. Dai, Recent advances in electron manipulation of nanomaterials for photoelectrochemical biosensors, *Chem. Commun.* **58** (2022) 12418–12430.
- [11] L.M. Peter, Fundamental aspects of photoelectrochemical water splitting at semiconductor electrodes, *Curr. Opin. Green Sustain. Chem.* **31** (2021) 100505.
- [12] Y. Wang, A. Vogel, M. Sachs, et al., Current understanding and challenges of solar-driven hydrogen generation using polymeric photocatalysts, *Nat. Energy* **4** (2019) 746–760.
- [13] N.A. Erfan, M.S. Mahmoud, H.Y. Kim, N.A.M. Barakat, Synergistic doping with Ag, CdO, and ZnO to overcome electron–hole recombination in TiO₂ photocatalysis for effective water photo splitting reaction, *Front. Chem.* **11** (2023) 1301172.
- [14] A. Balapure, J.R. Dutta, R. Ganesan, Recent advances in semiconductor heterojunctions: A detailed review of the fundamentals of photocatalysis, charge transfer mechanism and materials, *RSC Appl. Interfaces* **1** (2024) 43–69.
- [15] C. Liu, C. Xu, W. Wang, L. Chen, X. Li, Y. Wu, Oxygen vacancy mediated band-gap engineering via B-doping for enhancing Z-scheme A-TiO₂/R-TiO₂ heterojunction photocatalytic performance, *Nanomaterials* **13** (2023) 794.
- [16] L. Xu, Y. Zhang, B. Liu, et al., Nitrogen incorporated oxygen vacancy enriched MnCo₂O_x/BiVO₄ photoanodes for efficient and stable photoelectrochemical water splitting, *Nano Res.* **17** (2024) 1140–1150.
- [17] M. Guo, R. Chen, D. Wang, Y. Yan, Q. Shi, D. Chen, Z. Liang, Optimized photoelectrochemical water splitting via morphology-engineered TiO₂ nanostructured photoelectrodes: A comparative study, *Mater. Lett.* **400** (2025) 139124.
- [18] Y. Zhao, Z. Niu, J. Zhao, L. Xue, X. Fu, J. Long, Recent advancements in photoelectrochemical water splitting for hydrogen production, *Electrochem. Energy Rev.* **6** (2023) 14.
- [19] G. Dong, F. Xie, F. Kou, T. Chen, C. Xiao, S. Du, J. Liang, C. Lou, J. Zhuang, Enhancing photoelectrochemical performance and stability of Ti-doped hematite photoanode via pentanuclear Co-based MOF modification, *Front. Chem.* **12** (2024) 1454524.
- [20] A.A.M. Raub, R. Bahru, S.N.A. Mohd Nashruddin, J. Yunas, Advances of nanostructured metal oxide as photoanode in photoelectrochemical (PEC) water splitting application, *Heliyon* **10** (2024) e39079.
- [21] M. Kumar, B. Meena, P. Subramanyam, D. Suryakala, C. Subrahmanyam, Recent trends in photoelectrochemical water splitting: The role of cocatalysts, *NPG Asia Mater.* **14** (2022) 88.
- [22] S. Banerjee, R. Thangavel, Fabrication of p-Cu/n-ZnO heterostructure with a methodical interfacial charge transfer characteristics for photoelectrochemical water splitting, *Mater. Sci. Semicond. Process.* **146** (2022) 106690.
- [23] J. Shi, Z. Chen, C. Zhao, M. Shen, H. Li, S. Zhang, Z. Zhang, Photoelectrochemical biosensing platforms for tumor marker detection, *Coord. Chem. Rev.* **469** (2022) 214675.
- [24] Z. Li, J. Lu, W. Wei, M. Tao, Z. Wang, Z. Dai, Recent advances in electron manipulation of nanomaterials for photoelectrochemical biosensors, *Chem. Commun.* **58** (2022) 12418–12430.
- [25] X. Qiu, et al., Laser-induced ZnO/graphene hybrid for photocurrent-polarity-switching photoelectrochemical biosensing with bipedal DNA walker amplification, *J. Mater. Chem. B* **12** (2024) 984–990.
- [26] S. Liu, J. Zhan, B. Cai, Recent advances in photoelectrochemical platforms based on porous materials for environmental pollutant detection, *RSC Adv.* **14** (2024) 7940–7963.
- [27] J. Sengupta, C.M. Hussain, TiO₂ nanotube-enabled glucose biosensing: Transformative insights from 2009 to 2024, *Micromachines* **16** (2025) 1235.
- [28] L. Zhang, Y.C. Zhu, W.W. Zhao, Recent advances of nanostructured materials for photoelectrochemical bioanalysis, *Chemosensors* **10** (2022) 14.
- [29] S.N.A.M. Nashruddin, F.H.M. Salleh, R.M. Yunus, H.B. Zaman, Artificial intelligence-powered electrochemical sensor: Recent advances, challenges, and prospects, *Heliyon* **10** (2024) e37964.