PROGRESS IN APPLIED
SCIENCE AND TECHNOLOGY
Faculty of Science and Technology
Rajamangala University of Technology Thanyaburi
*Prog Appl Sci Tech.* 2025; 15(1):19-25
ISSN (Online): 2730-3020
https://ph02.tci-thaijo.org/index.php/past

**Research Article**

**Received:** March 02, 2025
**Revised:** April 22, 2025
**Accepted:** April 23, 2025

DOI: 10.60101/past.2025.258126

# Optimizing Precursor pH for Enhanced $WO_3$/$BiVO_4$ Heterojunction Photoanode Performance

Nuttanon Jarnpho, Chavapon Rungrittipanyo and
Khunthong Klaythong*
*Princess Chulabhorn Science High School Pathum Thani, Pathum Thani 12140, Thailand*
*Email: khunthong.kla@gmail.com

## Abstract

The pH of the precursor solution significantly influences the efficacy of $WO_3$/$BiVO_4$ heterojunction photoanodes; however, the exact impact on the photoelectrocatalytic (PEC) process remains unclear. This study objectively examines the influence of the pH of the $WO_3$ precursor on the structural, optical, and electrochemical characteristics of FTO/$WO_3$/$BiVO_4$ electrodes to enhance their performance in photoelectrochemical (PEC) applications. $WO_3$ and $BiVO_4$ are prepared via dip-coating, subsequently subjected to calcination at 500°C. The photoanode characteristic properties were examined using scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), UV-Vis spectroscopy, and electrochemical impedance spectroscopy (EIS). The results indicated that the electrode efficiently segregated charge carriers due to its reduced bandgap energy (2.15 eV) and substantial light absorption ($\lambda = 576$ nm) at pH 11. In comparison to Ag/AgCl, we obtained a significant increase in current density (1.91 mA/cm$^2$) with the utilization of visible light at 1.0 V. This addressed to a significant capacitance (CPE = $1.19 \times 10^{-5}$ F) and a small charge transfer resistance ($R_{ct} = 116\ \Omega$). A uniform, detailed morphology was noted in the SEM images at a pH of 11, which enhanced interfacial bonding and charge transfer. The results emphasize the necessity of adjusting the precursor's pH to improve the efficacy of $WO_3$/$BiVO_4$ heterojunctions employed in solar-driven oxidation processes. These findings will facilitate the advancement of sophisticated photoelectrocatalytic applications for sustainable energy conversion.

**Keywords:** $WO_3$/$BiVO_4$ Heterojunction, Photoelectrocatalysis, Precursor pH, Charge Transfer Resistance, Bandgap Tuning

## 1. Introduction

The growing global need for renewable energy is increasing research into sustainable energy conversion technology. Photoelectrochemical (PEC) water splitting has attracted significant interest as an efficient technique for generating hydrogen fuel from solar energy (1). PEC systems employ semiconductor photoanodes to facilitate water oxidation under solar light, offering material selection an essential consideration in enhancing efficiency. Tungsten oxide ($WO_3$) and bismuth vanadate ($BiVO_4$) were recognized as attractive photoanode materials owing to their advantageous bandgap energies, chemical stability, and ability to absorb visible light.

$WO_3$ is an extensively researched n-type semiconductor with bandgap energy between 2.6 and 2.8 eV, making it appropriate for visible-light-driven photoelectrochemical applications (2). Furthermore, $WO_3$ demonstrates exceptional charge transport characteristics,

© 2025 Faculty of Science and Technology, RMUTT

facilitating effective charge extraction. However, a significant charge recombination rate impeded its overall PEC performance, affecting its photocatalytic efficiency. Conversely, $BiVO_4$, possessing a bandgap energy of approximately 2.4 to 2.5 eV, is capable of absorbing a wider spectrum of visible light; nevertheless, its utilization is limited by low charge carrier mobility and inefficient charge transport efficiency (3).

To overcome these limitations, developing heterojunction photoanodes is recognized as a practical approach for enhancing charge separation and improving photocatalytic performance. The integration of $WO_3$ and $BiVO_4$ into a heterojunction structure has shown considerable promise in reducing charge recombination while utilizing the synergistic benefits of both materials (4-6). The establishment of a heterojunction between $WO_3$ and $BiVO_4$ engenders an internal electric field at the interface, enhancing charge transfer efficiency and improving the overall PEC performance (7). Achieving an optimal heterojunction necessitates meticulous regulation of material synthesis parameters, as the interfacial structure significantly affects charge transport kinetics.

The pH of the $WO_3$ precursor solution during synthesis is an essential factor influencing the quality and performance of $WO_3/BiVO_4$ heterojunctions. The pH of the precursor solution is crucial in influencing the structural, optical, and electrochemical characteristics of the deposited $WO_3$ layer, thereby impacting the heterojunction interface (8). Variations in pH might result in alterations in surface morphology, crystallinity, and charge transport properties, thereby affecting the overall effectiveness of the photoanode (9-11). Considering its importance, the optimization of precursor pH for improved heterojunction performance continues to be a subject of engaged research.

This study systematically investigates the influence of the pH adjustment in the $WO_3$ precursor solution on the enhancement of $WO_3/BiVO_4$ heterojunction photoanodes. We try to clarify the relationship between precursor pH, interfacial characteristics, and PEC performance by optimizing synthesis conditions. This research promises to provide significant insights into the function of solution chemistry in heterojunction engineering, accordingly advancing high-efficiency photoanodes for solar-driven water oxidation.

## 2. Materials and Experiment

### 2.1 WO₃, BiVO₄ precursor solution preparation

A 0.100 M $WO_3$ precursor solution preparation was carried out by dissolving 2.499 g of tungstic acid ($H_2WO_4$) in 100 mL of a 30% w/v ammonia solution. The pH of the $WO_3$ precursor solutions was adjusted to values of 3, 5, 7, 9, and 11 while avoiding the occurrence of precipitates or inappropriate phase transitions. The solution was refluxed at 60°C for 60 minutes prior to its use. A 50 mL solution of 0.100 M $BiVO_4$ precursor was prepared by combining 4.8517 g of $Bi(NO_3)_2{\bullet}5H_2O$ (99.5%) with 50 mL of acetylacetone and 2.65 g of VO(acac)2 (98%) in 99.5% acetone ($CH_3COCH_3$) solution. The combined solutions were shaken for an additional ten minutes to ensure uniformity. Subsequently, the homogeneity and stability of the combined solution were enhanced by sonication for 120 minutes.

### 2.2 Fabrication of WO₃/BiVO₄ film on anode electrode

Fluorine-doped tin oxide (FTO) conducting glass was used as the electrode substrate following cleaning with ethanol and deionized water. The first layer of the $WO_3$ coating was coated to the FTO substrate utilizing an automated dip-coating method. The $FTO/WO_3$ electrode, after coating, was dried at 60°C for 5 minutes and subsequently calcined at 500°C for 30 minutes. The $FTO/WO_3$ electrode was immersed in the $BiVO_4$ precursor solution, dried at 60°C for 5 minutes, and calcined at 500°C for 60 minutes to fabricate the $FTO/WO_3/BiVO_4$ electrode. In this study, a single coating cycle was applied for both $WO_3$ and $BiVO_4$ layers, following optimized conditions reported in previous studies to ensure effective film formation and photoelectrochemical performance.

### 2.3 Characterization and photoelectrocatalytic properties study

The optical characteristics of the $WO_3/BiVO_{4-}$ electrode were analyzed utilizing a UV-visible spectrophotometer. The films' surface morphology was investigated using a Scanning Electron Microscope (SEM), and their elemental composition was assessed via Energy Dispersive X-ray Spectroscopy (EDX). The photocatalytic activities were examined using electrochemical investigation at an applied potential of 1.0 V under visible light irradiation. Electrochemical impedance was assessed via Electrochemical Impedance Spectroscopy (EIS) to validate enhancements in the charge transfer mechanism.

## 3. Results and Discussion

Initial investigation found that precursor solutions with a pH below 5 led to precipitate formation and reduced phase stability, hence affecting the uniformity and reproducibility of the films. similarly attempts to employ pH levels above 11 resulted in significant dissolution and unstable film formation, so limiting their appropriateness for systematic investigation. Therefore, we focused our efforts on the pH range of 5 to 11, wherein film stability, surface homogeneity, and adhesion were reliably attained. This pH range value provided the most effective and dependable conditions for evaluating the impact of pH on the morphology and photoelectrocatalytic efficacy of $WO_3/BiVO_4$ heterojunctions. Consequently, the subsequent experimental results will elucidate the impact of pH values ranging from 5 to 11 on the characteristics of the fabricated $FTO/WO_3/BiVO_4$ electrodes.

### 3.1 $WO_3/BiVO_4$ film characterization

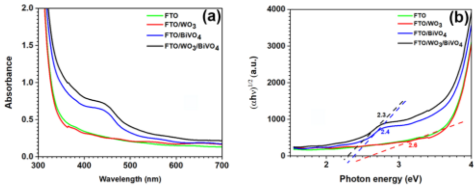
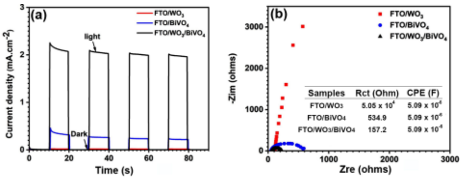


**Figure 1** (a) Absorption spectra and (b) Relationship between the absorbance coefficient and the bandgap energy of FTO, $FTO/WO_3$, $FTO/BiVO_4$, and $FTO/WO_3/BiVO_4$ electrodes

The optical properties of the $FTO/WO_3$, $FTO/BiVO_4$, and $FTO/WO_3/BiVO_4$ electrodes were analyzed using UV–Vis spectroscopy, as shown in Figures 1(a) and 1(b). The absorption spectra of the $FTO/WO_3/BiVO_4$ electrodes can absorb a greater quantity of visible light spectrum, which is beneficial for improving photoelectrocatalytic efficacy. The enhanced photon absorption of the heterojunction electrode ($FTO/WO_3/BiVO_4$) suggests that the electric interactions between $WO_3$ and $BiVO_4$ are functioned effectively, leading to improved photon absorption. Tauc diagrams were employed to ascertain the bandgap energies of the conductors, as illustrated in Figure 1(b). The bandgap values for FTO/ $WO_3$ are 2.6 eV, while those for FTO/ $BiVO_4$ are 2.4 eV, and $FTO/WO_3/BiVO_4$ is 2.3 eV(5). The $FTO/WO_3/BiVO_4$ heterojunction's lower bandgap energy suggests that the bandgap is narrowed by the combination of $WO_3$ and $BiVO_4$, which facilitates the formation of charge carriers when visible light interacts with the junction. The reduced bandgap enhances the photocatalytic activity, enabling the utilization of a greater amount of solar energy and the expansion of the wavelength range that can be absorbed. We noticed that $FTO/WO_3/BiVO_4$ exhibited improved bandgap reduction and light absorbance. The heterojunction effect is responsible for this, as it enables the separation of charges and reduces recombination losses. Combining $WO_3$ (a material with a profound conduction band) and $BiVO_4$ (a material with strong visible-light absorption qualities) results in the most optimal electronic structure, which maximizes charge transfer efficiency. This characteristic is especially important for photoelectrocatalytic applications, particularly those involving water oxidation and similar substances. The results suggest that the $WO_3/BiVO_4$ heterojunction significantly increases optical absorption while concurrently decreasing the bandgap energy. This makes it a potential electrode material for photoelectrochemical applications. It is possible that the improved optical properties could be advantageous for solar-driven water splitting and other photocatalytic processes that necessitate improved light absorption and charge separation.

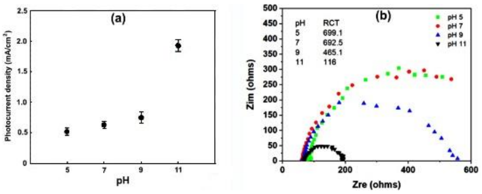


| Samples | Rct (Ohm) | CPE (F) |
|---|---|---|
| FTO/WO3 | $5.05 \times 10^{4}$ | $5.09 \times 10^{-6}$ |
| FTO/BiVO4 | 534.9 | $5.09 \times 10^{-6}$ |
| FTO/WO3/BiVO4 | 157.2 | $5.09 \times 10^{-6}$ |

**Figure 2** (a) Amperograms and (b) Nyquist plot of FTO/$WO_3$, FTO/$BiVO_4$, and FTO/$WO_3$/$BiVO_4$ electrodes in a 0.5 M NaCl solution at a potential of 1.0 V under visible light

The photocurrent density of FTO/$WO_3$, FTO/$BiVO_4$, and FTO/$WO_3$/$BiVO_4$ electrodes was investigated by under chopped illumination at 1.0 V vs. Ag/AgCl in a 0.5 M NaCl solution, as demonstrated in Figure 2(a). Compared to FTO/ $BiVO_4$ (blue line) and FTO/$WO_3$ (red line), the photocurrent reaction was greatest in the FTO/$WO_3$/$BiVO_4$ heterojunction electrode (black line). A heterojunction is created by $WO_3$ and $BiVO_4$, which facilitates the separation of charges and reduces the combination of electrons and holes. This is because either the charge carriers reassembled or the photoanode's surface deteriorated slightly due to improved exposure to light. However, the FTO/$WO_3$/$BiVO_4$ heterojunction exhibited significantly higher photocurrent levels than the other electrodes. The dimension of the half-circle in the Nyquist plot in Figure 2(b) is correlated with the charge transfer resistance (Rct) at the electrode/electrolyte contact. The electrode composed of FTO/$WO_3$/$BiVO_4$ exhibited the smallest half-circle, with a resistance of 157.2 Ω implies that it possessed the lowest charge transfer resistance. This demonstrates that the heterojunction between $WO_3$ and $BiVO_4$ is highly effective in reducing the resistance at the contact and facilitating the movement of electrons. The capacitance of the FTO/$WO_3$/$BiVO_4$ electrode is the highest, as evidenced by the constant phase element (CPE) values. This confirms that it has a greater active surface area for accumulating and transporting charges. The findings are consistent with the trends in photocurrent density displayed in Figure 2(a). These trends demonstrate that decreased resistance facilitates the transport of charges, thereby improving the functionality of PEC. The $WO_3$/$BiVO_4$ heterojunction exhibits significantly greater photoelectrochemical efficiency due to its ability to reduce charge transfer resistance and increase photocurrent density in the presence of visible light (6). Photoelectrocatalytic activities are well-suited to the heterojunction electrode, as it is capable of more effectively splitting charges and transferring electricity.

### 3.2 Effect of pH of precursor solution



| pH | RCT |
|---|---|
| 5 | 699.1 |
| 7 | 692.5 |
| 9 | 465.1 |
| 11 | 116 |

**Figure 3** (a) Photocurrent density and (b) Nyquist plots of FTO/$WO_3$/$BiVO_4$ electrodes prepared with various $WO_3$ precursor solution pH conditions of 5, 7, 9, and 11 in 0.5 M NaCl solution at an applied potential of 1.0 V under visible light

Figure 3(a) presents the effect of $WO_3$ precursor solution pH on the photocurrent density of the FTO/$WO_3$/$BiVO_4$ electrodes under visible light illumination. The results demonstrate a clear trend of increasing photocurrent density with rising pH, reaching a maximum of 1.91 $mA\,cm^{-2}$ at pH 11. These results suggest that higher pH conditions enhance charge separation and photoactivity. The photocurrent density significantly increases at pH 11, indicating that charge carriers are more effectively separated and oxidation reactions are more efficient. This is likely because the $WO_3$/$BiVO_4$ heterojunction's structure and electrical properties are optimal at this pH level. The electrode that was produced at pH 11 was more stable in terms of photoelectrocatalysis than the electrode that was produced at a lower pH. The results also showed a relative standard deviation (RSD) of 6.08% for a pH electrode optimized at pH = 11, indicating that it can be trusted to ensure high efficiency and consistency in the fabricating process. This indicates that it has the potential to be employed in oxidation processes for an extended period of time. The electrochemical resistance of the electrode was investigated using electrochemical impedance spectroscopy (EIS). The Nyquist diagrams are illustrated in Figure 3(b). The pH 11 electrode condition exhibited a charge transfer resistance

© 2025 Faculty of Science and Technology, RMUTT

that was significantly lower than that of the other electrode condition. In other words, the electrode produced with pH 11 is the most effective at conducting charges between interfacial electrode/electrolyte surfaces. It also demonstrates that it has a larger active surface area and can store charges more effectively, as evidenced by a constant phase element (CPE) value of $1.19 \times 10^{-5}$ F at pH 11. This supports the notion that it functions more effectively as a photoelectrocatalyst. The PEC's overall functionality and the separation of charges are significantly affected by the pH of the $WO_3$ precursor, as evidenced by the correlation between a high photocurrent reaction and a low Rct (12). The results indicate that the pH of the precursor solution significantly influences the electrochemical characteristics and PEC performance of the $WO_3/BiVO_4$ electrodes. The electrode produced at pH 11 was the most suitable for photoelectrocatalytic applications due to its superior photocurrent density and minimal resistance. The results demonstrate the crucial importance of increasing the pH of the precursor to facilitate improved light-induced oxidation and accelerate charge transfer.

The surface morphology of the $FTO/WO_3/BiVO_4$ electrodes, which were produced using $WO_3$ precursor solutions with pH values of 5, 7, 9, and 11, was examined using scanning electron microscopy (SEM).

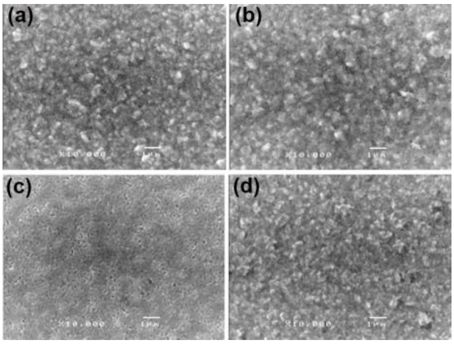


**Figure 4** SEM image of the $FTO/WO_3/BiVO_4$ electrode film prepared with $WO_3$ precursor solution pH conditions of (a) 5, (b) 7, (c) 9, and (d) 11

The microstructural variations between the films demonstrate the impact of the precursor solution's pH on the films' formation and the particles' dispersion. The electrode surfaces exhibited rough, non-uniform structures with large and irregularly shaped particulates when the pH was between 5 and 7 (Figures 4a and 4b). These characteristics indicate that the film is formed erratically due to unregulated growth and incomplete nucleation. At these lower pH levels, the larger particle sizes may facilitate a greater amount of charge recombination, as evidenced by the lower photocurrent reactions observed in previously conducted electrochemical studies. The surface appeared smoother at pH 9 (Figure 4c), with a thicker structure and smaller granules packed closer together. This change suggests a transition to improved nucleation and controlled growth, which could result in improved charge movement and separation. When the pH level was 11, the $FTO/WO_3/BiVO_4$ electrode exhibited the most uniform, smooth, and finely distributed particulates (Figure 4d). The film is more compact and free of defects due to the appropriate germination and growth conditions, as evidenced by the smaller particles and more even surface. The present study examines the impact of raising the pH of the $WO_3$ precursor solution on nucleation and particle growth, resulting in smoother, more uniform morphologies with a finer grain distribution at pH 11. This microstructural enhancement improves the interfacial contact between $WO_3$ and $BiVO_4$, facilitating more effective charge separation and transport. This well-defined geometry is associated with improved photoelectrocatalytic performance and reduced charge transfer resistance, as observed in previous studies (13). The smaller particles should enhance the relationship between the electrode and the electrolyte at pH 11, reducing the recombination effect and enhancing the charge transfer efficiency. The structure of the $WO_3/BiVO_4$ coatings is significantly influenced by the pH of the precursor solution, as demonstrated by the SEM study. The optimal pH level is 11. This directly enhances the efficiency of charge separation and transfer by ensuring that the surface is uniform, smooth, and uniformly distributed. Conversely, when the pH is lower (between 5 and 7), the shapes are irregular and rugged, resulting in increased recombination and reduced photocurrent generation. The findings indicate that the structural features of $FTO/WO_3/BiVO_4$ electrodes are significantly enhanced by altering the pH of the $WO_3$ precursor solution. The optimal surface characteristics is observed at pH 11, which is associated with improved photoelectrocatalytic activity, lower charge transfer resistance, and a higher photocurrent density. These results demonstrate the critical role of the pH of the precursor solution in modifying the electrode's properties to enhance its photoelectrochemical characteristics. The elemental composition analysis of the FTO/$WO_3$ electrode using EDX indicated that the tungsten (W) content peaked at pH 11, demonstrating enhanced adhesion of $WO_3$ to the electrode surface. Furthermore, the high pH environment results in enhanced incorporation of $WO_3$, as corroborated by EDX, which facilitates improved electronic coupling and conduction pathways at the heterojunction interface. These modifications combined yield a diminished charge transfer resistance and an increased photocurrent density. This result supports previous studies, demonstrating that pH 11 is the optimal condition for the preparation of $WO_3$ precursors.

## 4. Conclusions

This study emphasizes the significant impact of the pH of the $WO_3$ precursor solution on the structural, optical, and electrochemical characteristics of $WO_3/BiVO_4$ heterojunction photoanodes for photoelectrochemical (PEC) water oxidation. By systematically altering the precursor pH from 5 to 11, we exhibited substantial enhancements in photocatalytic performance, with pH 11 producing the most advantageous characteristics. Optimized photoanodes demonstrated improved light absorption ($\lambda = 576$ nm), a reduced bandgap (2.15 eV), and the highest photocurrent density (1.91 mA/cm$^2$ at 1.0 V vs. Ag/AgCl), more significant than electrodes produced at other pH levels. The developed $WO_3/BiVO_4$ photoanode exhibited a significantly higher photocurrent density of 1.91 mA cm$^{-2}$ compared to the reported value of 0.39 mA cm$^{-2}$ for the $TiO_2/Au/Cu_2O$ NRAs photoanode, indicating superior charge separation and photoelectrocatalytic performance (14). Electrochemical impedance spectroscopy (EIS) demonstrated that samples at pH 11 displayed the lowest charge transfer resistance (116 Ω), signifying enhanced charge transport, while morphological analysis validated a uniform and well-adhered film structure. These findings highlight precursor pH as a critical factor in enhancing $WO_3/BiVO_4$ heterojunction surfaces, significantly impacting charge separation and PEC efficiency. The enhanced performance at pH 11 indicates that meticulous regulation of synthesis conditions can optimize photoanode efficacy, providing an approach for further progress in solar-driven hydrogen generation. Future studies should concentrate on enhancing long-term stability, exploring alternate fabrication methods, and using co-catalysts to enhance PEC performance and scalability for practical applications. Future studies should address scalability challenges, particularly film uniformity and consistency during large-area or continuous production.

## Acknowledgements

The authors express sincere thanks to Princess Chulabhorn Science High School Pathum Thani and Rajamangala University of Technology Thanyaburi for their substantial help in granting access to modern equipment, which was crucial for the completion of this research. Their efforts have greatly enhanced the experimental work and data analysis. We express our appreciation to all persons and institutions who have offered guidance, technical support, and useful insights during this study.

## Declaration of Conflicting Interests

The authors declare they have no conflicts of interest for this article, and they alone are responsible for the content.

## References

1. Wang M, Nie T, She Y, Tao L, Luo X, Xu Q, et al. Study on the behavior of single oxygen bubble regulated by salt concentration in photoelectrochemical water splitting. Int J Hydrogen Energy. 2023;48(61):23387–401.
2. Tijani JO, Ugochukwu O, Fadipe LA, Bankole MT, Abdulkareem AS, Roos WD. One-step green synthesis of $WO_3$ nanoparticles using Spondias mombin aqueous extract: Effect of solution pH and calcination temperature. Appl Phys A. 2019;125(3):162.
3. Ghorbannejad B, Mahjoub A, Dalir N. Development and application of fluorine doped bismuth vanadate reduced graphene oxide Nafion composite electrode as an electrochemical sensor for 4-chlorophenol. Sci Rep. 2023;13:1.

4. Chatchai P, Murakami Y, Kishioka S-y, Nosaka AY, Nosaka Y. Efficient photocatalytic activity of water oxidation over $WO_3/BiVO_4$ composite under visible light irradiation. Electrochim Acta. 2009; 54(3):1147–52.
5. Ta CXM, Furusho Y, Amano F. Photoelectrochemical stability of $WO_3$/Mo-doped $BiVO_4$ heterojunctions on different conductive substrates in acidic and neutral media. Appl Surf Sci. 2021;548:149251.
6. Polo A, Nomellini C, Marra G, Selli E, Dozzi MV. $WO_3/BiVO_4$ heterojunction photoanodes: Optimized photoelectrochemical performance in relation to both oxides layer thickness. Catal Today. 2025;446:115137.
7. Shen H, Dawson G, Wu Y, Cao F, Cheng X. The photoelectrochemical properties of FTO/$WO_3/BiVO_4/TiO_2$ photoanode for water splitting. Chem Phys. 2025;588: 112457.
8. Tayyebi A, Soltani T, Lee B-K. Effect of pH on photocatalytic and photoelectrochemical (PEC) properties of monoclinic bismuth vanadate. J Colloid Interface Sci. 2019; 534:37–46.
9. Yang H, Li S, Yu S, Yu X, Zhao H, Wang C, et al. Strategies for enhancing the stability of $WO_3$ photoanodes for water splitting: A review. Chem Eng Sci. 2025;302:120894.
10. Lale A, Tsopela A, Civélas A, Salvagnac L, Launay J, Temple-Boyer P. Integration of tungsten layers for the mass fabrication of $WO_3$-based pH-sensitive potentiometric microsensors. Sens Actuators B Chem. 2015;206:152–8.
11. Madhavi V, Kondaiah P, Shaik H, Kumar KN, Kumar Naik TSS, Rao GM, et al. Fabrication of porous 1D $WO_3$ NRs and $WO_3/BiVO_4$ heterojunction photoanode for efficient photoelectrochemical water splitting. Mater Chem Phys. 2021;274: 125095.
12. Omrani N, Nezamzadeh-Ejhieh A. A comprehensive study on the enhanced photocatalytic activity of $Cu_2O/BiVO_4/WO_3$ nanoparticles. J Photochem Photobiol A Chem. 2020;389:112223.
13. Liaqat M, Munir RM, Maryam I, Iqbal T, Afsheen S, Nabi AG, et al. Synthesis and characterization of $WO_3/BiVO_4$/graphene ternary nanocomposites for the photodegradation of methylene blue and tetracycline. Mater Chem Phys. 2024;320: 129465.
14. Huang S, Liu X, Jiang M, Yao H, Wu L, Qin T, et al. Double plasmonic effect and step-like charge transport channel synergistically enhance bulk and surface charge separation efficiency of Au/$Cu_2O$-modified $TiO_2$ photoanode for efficient photoelectrochemical water splitting. Fuel. 2025;385:134179.