Received: January 28, 2024 | Revised: March 10, 2025 | Accepted: March 12, 2025

JOURNAL OF APPLIED RESEARCH ON SCIENCE AND TECHNOLOGY
INSTITUTE OF RESEARCH AND DEVELOPMENT
RAJAMANGALA UNIVERSITY OF TECHNOLOGY THANYABURI
JARST
ISSN ONLINE: 2773-9473
https://ph01.tci-thaijo.org/index.php/rmutt-journal

# Laser-assisted FTO/$WO_3$/$BiVO_4$ photoanode fabrication for enhanced photoelectrocatalytic performance and durability for organic dye degradation

**Watcharapong Nareejun[1], Chatchai Ponchio[1, 2*]**

[1]Department of Chemistry, Faculty of Science and Technology, Rajamangala University of Technology Thanyaburi, Pathum Thani 12120, THAILAND

[2]Advanced Photochemical and Electrochemical Materials (APEM) Research Unit, Faculty of Science and Technology, Rajamangala University of Technology Thanyaburi, Pathum Thani 12110, THAILAND

[*]Corresponding author: chatchai@rmutt.ac.th

## ABSTRACT

A significant challenge in the photoelectrocatalytic method for water oxidation and organic decomposition processes is the fabrication of scalable, durable, and efficient photoanodes. Several limitations, such as insufficient adhesion, uneven semiconductor coatings, and low durability, often lead to the unsatisfactory performance of the conventional FTO/$WO_3$/$BiVO_4$ photoanode. This study improves the surface properties of fluorine-doped tin oxide (FTO) substrates using a laser treatment process prior to the automated dip-coating of $WO_3$ and $BiVO_4$ semiconductor layers. The FTO substrate surface is textured and modified using laser induction as part of the fabrication process. Thereafter, $WO_3$ and $BiVO_4$ semiconductor layers are deposited in sequence. The laser treatment can promote surface homogeneity, semiconductor adhesion, and the active surface area of the fabricated FTO/$WO_3$/$BiVO_4$. The morphology, elemental composition, and electrochemical properties are analyzed using SEM, EDS, and EIS techniques. In that context, the laser-treated FTO/$WO_3$/$BiVO_4$ photoanode development significantly outperformed those without treatment. The FTO/$WO_3$/$BiVO_4$ photoanode that was treated with a laser had a lower energy band gap of 1.8 eV, a higher capacitance of $4.91 \times 10^{-6}$ F, and a higher photocurrent density of 5.5 mA/cm² compared to an electrode that was not treated with a laser at a bias potential of 1.0 V. The durability assessments demonstrated that the organic dye removal efficacy persisted after 1,000 hours. This study demonstrates that laser-treated FTO/$WO_3$/$BiVO_4$ photoanodes can overcome conventional fabrication method limitations. This successfully provides a scalable and effective alternative for various applications, including wastewater treatment and renewable energy. It is recommended that subsequent studies should focus on the evaluation of the applicability of this laser-assisted method to various kinds of environmental applications and photoelectrodes.

*Keywords:* Photoelectrocatalytic process, $WO_3$/$BiVO_4$, Laser treatment, Organic dye degradation

## INTRODUCTION

Increasing interest in efficient and sustainable alternative energy production and environmental management is contributing to extensive photoelectrocatalytic process research [1-3]. The FTO/$WO_3$/$BiVO_4$ photoanode is now recognized as an attractive alternative for water oxidation and organic dye degradation owing to its advantageous optical and electrical characteristics [4-6]. Conventional methods for fabricating these electrodes frequently yield limited efficiency, unsatisfactory durability, and insufficient reproducibility, principally due to difficulties in achieving homogenous semiconductor coatings and effective charge transfer at the electrode interface [7]. In order to improve the structural and functional features of photoelectrodes, recent breakthroughs have brought to light the significance of modifying the substrate. It has been demonstrated that roughening treatments, such as the use of a laser, can enhance surface adhesion, increase the degree of active surface area, and facilitate the absorption of light [8-10]. Furthermore, the long-term durability and scalability of these methods for practical applications have not yet been appropriately assessed in the context of FTO/$WO_3$/$BiVO_4$ systems. This study addresses those weaknesses through implementing a laser-assisted method for modifying FTO substrates before semiconductor immobilization through an automated dip-coating procedure. The suggested technology integrates laser-induced surface roughness with efficient material deposition to create a homogeneous, porous structure that improves light absorption, charge transfer, and overall photoelectrocatalytic efficacy. The study assesses the durability and reproducibility of the laser-treated electrodes, offering insights into their appropriateness for large-scale wastewater treatment and energy applications. This investigation





DOI: 10.60101/jarst.2024.260565

provides an alternative process for enhancing the performance of FTO/$WO_3$/$BiVO_4$ photoanodes. The methodology integrates efficient application with material design, resulting in the progression of sustainable technology.

## MATERIALS AND METHODS

### *3.1 Preparation of $WO_3$ and $BiVO_4$ precursor solutions*

A 0.1 M $WO_3$ precursor solution was prepared by dissolving tungstic acid (99%, $H_2WO_4$, Aldrich Chemistry) in an ammonium hydroxide (30%, $NH_4OH$, Panreac) solution. The solution was refluxed at 60°C for one hour with constant agitation. To maintain a consistent solution volume, incrementally introduce $NH_4OH$ while refluxing, continuously stirring the solution for one hour. The resultant solution, after one hour of stirring, will initially appear milky white and subsequently transition to a clear solution, without forming a suspension after settling for one night. A 0.05 M $BiVO_4$ solution was prepared by dissolving 0.1 M bismuth nitrate (≥98.0%, $Bi(NO_3)_3{\cdot}5H_2O$, Sigma-Aldrich) powder in acetic acid (99.8%, $CH_3COOH$, ACI Labscan) and stirring for 20 minutes. Concurrently, 0.1 M vanadyl acetyl acetonate (98.0%, $C_{10}H_{14}O_5V$, Sigma-Aldrich) powder was solubilized in an acetylacetone (99.5%, $CH_3COCH_2COCH_3$, Panreac) solution and agitated for 20 minutes. The two solutions were subsequently combined and agitated for 10 minutes, followed by ultrasonication for 120 minutes to achieve homogeneity, yielding a blue-green solution of 0.05 M $BiVO_4$.

### *3.2 Fabrication of FTO/$WO_3$/$BiVO_4$ photoanode*

Figure 1 illustrates the deposition process, emphasizing each step in the fabrication of FTO/$WO_3$/$BiVO_4$ electrodes. These electrodes have been developed for improved photoelectrocatalytic efficiency for water oxidation and the organic dyes degradation process.

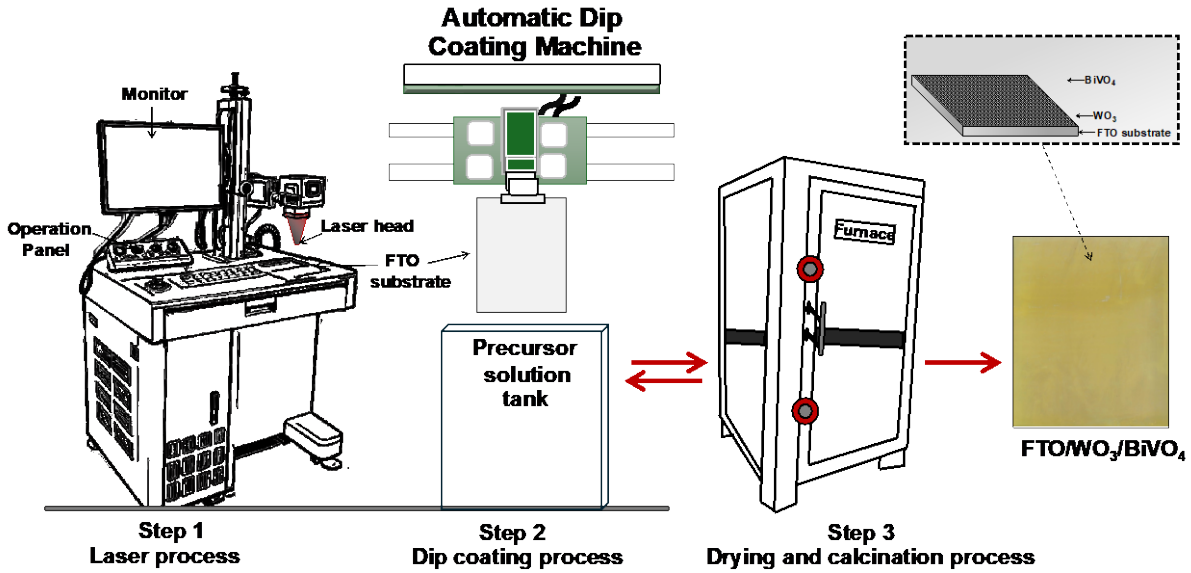


**Figure 1** The FTO/$WO_3$/$BiVO_4$ photoanode fabrication process using an automatic dip coating machine through the FTO substrate treatment using the laser process.

3.2.1 Substrate preparation and laser treatment

Fluorine-doped tin oxide (FTO) conductive glass substrates (21 x 32 cm) were cleaned to remove all contamination and provide suitable surface preparation. The cleaning procedure included a sequential wash using detergent, ethanol, and distilled water, with each step employing 15 minutes. The cleaned and dried FTO substrate surfaces were modified using laser treatments to create a surface with a rough texture that was favorable for the adhesion of precursor solutions. A 30-watt fiber laser (RAYCUS-30) with a wavelength of 1,064 nm was employed at a distance of 30 cm above the FTO surface to attain the requisite roughness while maintaining the substrate's electrical characteristics.

3.2.2 $WO_3$ Thin Film Deposition

The laser-treated FTO substrates were immersed in a 0.1 M $WO_3$ precursor solution using an automated dip-coating technique. Consistent dipping and pulling speeds were set at 2.0 cm/s to ensure a uniform coating. The coated substrates were subjected to drying at 150°C for 5 minutes and subsequently calcined at 500°C for 30 minutes. This approach produced FTO/$WO_3$ electrodes with a distinct semiconductor thin layer.

3.2.3 $BiVO_4$ thin film deposition

The FTO/$WO_3$ electrodes were subsequently coated with a 0.05 M $BiVO_4$ precursor solution employing the same automated dip-coating method. The electrodes were dipped at a velocity of 2.0 cm/s for 15 seconds and subsequently pulled at a lowered speed of 1.5 cm/s to ensure a consistent layer. The electrodes were heated at 150°C for 5 minutes, followed by calcination at 550°C for 1 hour. This procedure provided FTO/$WO_3$/$BiVO_4$ electrodes exhibiting improved structural and semiconductor characteristics.



DOI: 10.60101/jarst.2024.260565

JOURNAL OF APPLIED RESEARCH ON SCIENCE AND TECHNOLOGY

*3.3 FTO/$WO_3$/$BiVO_4$ photoanode characterization and photoelectrocatalytic activity study*

This study examined the impact of laser-treated and untreated FTO substrates on the photoelectrocatalytic performance of FTO/$WO_3$/$BiVO_4$ electrodes. We evaluated the impact of laser treatment on the developed FTO/$WO_3$/$BiVO_4$ photoanode through its characteristics and photoelectrocatalytic properties. The elemental composition and morphology of the fabricated electrodes were investigated using energy-dispersive X-ray spectroscopy (EDS; OXFORD, INCA-350) and scanning electron microscopy (SEM; JEOL, JSM-5410LV). The Shimadzu UV-2401PC spectrophotometer was employed to determine the spectrum of light that an electrode could absorb, with air serving as the baseline. The photoelectrocatalytic cell was provided with three electrodes: the working electrode was FTO/WO3/BiVO4, the counter electrode was platinum (Pt), and the reference electrode was Ag/AgCl (sat. KCl). For water oxidation experiments, the three electrodes were connected to a potentiostat (Princeton Applied Research, Inc., VersaSTAT3). The electrolyte solution was prepared using 0.1 M $Na_2SO_4$, which exhibited a conductivity of less than 5 µS/cm. A VersaSTAT3 potentiostat was employed to conduct electrochemical impedance spectroscopy (EIS) across a frequency spectrum of 100,000 to 0.1 Hz. The electrochemical cell is provided with a stainless steel cathode (21 x 32 cm), an FTO/$WO_3$/$BiVO_4$ anode (21 x 32 cm), and a controlled applied potential of 2.0 V. The research employed a 14.4-watt light-emitting diode (LED) as the visible light source for photoelectrocatalytic investigations at an intensity of 2,000 LUX. The cathode electrode was placed 4 cm from the anode electrode. In order to investigate the degradation of photoelectrocatalytic organic pigments, a 0.5 M NaCl solution was combined with 5 ppm of Orange Red. The reaction occurred in the presence of visible light from a 14.4-Watt LED source ($\lambda > 420$ nm) that was 26.47 mW/cm² bright and evenly dispersed the light. Over 1,000 hours of testing were conducted to determine the longevity of the dye, which was measured at 483 nm every 10 minutes for a maximum of an hour using a Shimadzu UV-2401PC spectrophotometer.

## RESULTS AND DISCUSSION

*4.1 Morphology and elemental composition*

Figure 2 illustrates the morphological examination of FTO and FTO/$WO_3$/$BiVO_4$ electrodes, both with and without laser treatment, as examined using SEM.

Laser-treated FTO substrates display significantly smaller particles owing to the optimum laser head distance of 30 cm, which enhances surface roughness without noticeably impacting electrical conductivity (Figure 2a-b). The rough, extremely porous surfaces of the laser-treated electrodes were characterized, increasing the active surface area of the coated $WO_3$ and $BiVO_4$ semiconductors on the FTO substrate, which is essential for oxidation reaction performance [11]. On the other hand, electrodes that have not been treated have fewer pores and a rougher surface, which makes them less catalytic (Figure 2c–d). The inset of the figure shows the photographs of each electrode to demonstrate the physical characteristics of the prepared electrodes. The FTO/$WO_3$/$BiVO_4$ electrodes show a distinct yellow color, which is consistent with the yellow color of $WO_3$ and $BiVO_4$, which confirming the existence of the two semiconductors. Figure 3 illustrates cross-sectional SEM images of bare FTO and FTO/$WO_3$/$BiVO_4$. The FTO layer thickness was probably 350 nm, while the $WO_3$ and $BiVO_4$ layers consolidated into an overall layer of approximately 400 nm subsequent calcination. These results demonstrate the effects of heterojunction formation on the structure.

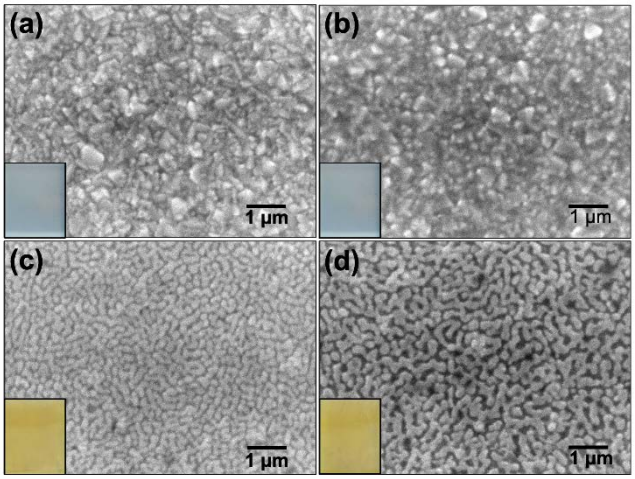


**Figure 2** Morphology of FTO electrodes; (a) untreated, (b) with laser-treatment, and (c) FTO/$WO_3$/$BiVO_4$ electrodes; untreated, (d) with laser-treatment; inset of image of each electrode.

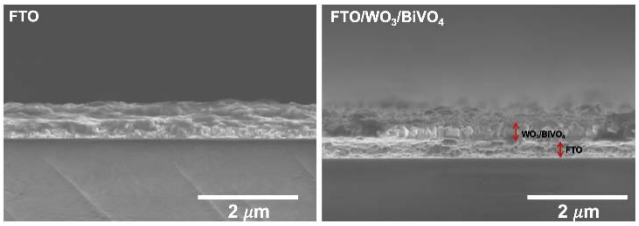


**Figure 3** FE-SEM image at the cross-sectional view of the FTO and FTO/ $WO_3$/ $BiVO_4$ (with laser-treatment)

The structure of bare FTO is compact and smooth, whereas the FTO/$WO_3$/$BiVO_4$ hybrid is well-defined and has numerous layers, resulting in a denser and rougher surface appearance.

The absorption of light and the separation of charges are enhanced when $WO_3$ and $BiVO_4$ layers are effectively combined, thereby reducing the recombination





DOI: 10.60101/jarst.2024.260565

loss. The coarser, more porous structure facilitates the movement of charges and provides a greater surface area for catalytic processes. This directly results in improved photoelectrocatalytic (PEC) performance. Additionally, the product's durability and stability are guaranteed by the robust interfacial bonding between layers. The laser-assisted fabrication method enhances the heterojunction characteristic, as evidenced by the shape and magnitude of these features. This clarifies the observed increases in photocurrent density and the efficiency of organic dye degradation.

**Table 1** Elemental composition analysis results using the EDX technique on FTO and FTO/$WO_3$/$BiVO_4$ electrodes effect with laser-treatment and untreated on the FTO substrate.

| Element | % Atomic | | | |
|---|---|---|---|---|
| | FTO | | FTO/$WO_3$/$BiVO_4$ | |
| | untreated | with laser- treatment | untreated | with laser- treatment |
| Si | 1.76 | 2.84 | 1.32 | 1.30 |
| Sn | 31.58 | 30.50 | 26.57 | 27.14 |
| W | - | - | 2.50 | 1.99 |
| Bi | - | - | 0.99 | 1.33 |
| V | - | - | 1.09 | 0.97 |
| O | 66.67 | 66.67 | 67.53 | 67.27 |

Table 1 shows the % elemental composition of FTO and FTO/$WO_3$/$BiVO_4$ electrodes with laser treatment and untreated electrodes. The laser treatment caused the FTO substrates to have higher Si content (2.84%) compared to untreated substrates (1.76%) indicating a higher surface roughness. On the other hand, the Sn content in laser- treated FTO (30.50%) was lower than that in untreated FTO (31.58%), which may suggest atomic redistribution. The laser treated FTO/$WO_3$/$BiVO_4$ electrodes had a higher Bi content of 1.33%, while the untreated samples had 0.99%. This indicates an improved $BiVO_4$ adhesion due to increased surface roughness. The tungsten content was slightly decreased in laser treated electrodes (1.99%) compared to untreated electrodes (2.50%). This indicates successful material incorporation on the new surface. Moreover, V content was slightly reduced in laser treated electrodes (0.97%) when compared to untreated electrodes (1.09%). With respect to the other samples, the oxygen content was consistent across all samples (~67%). This suggests that laser treatment did not significantly affect the oxidation state of the electrodes. These results imply that the laser treatment improves the uniformity of the $WO_3$ and $BiVO_4$ layer adherence and consequently the performance of the photoelectrodes.

X-ray diffraction (XRD) analysis, illustrated in Figure 4, verifies the phase composition of FTO/$WO_3$/$BiVO_4$ electrodes, encompassing both untreated and laser-treated variants. The diffraction peaks at 26.92°, 34.1°, 38.8°, and 52.0° are indicative of the tetragonal phase of $SnO_2$ in the FTO substrate. The $WO_3$ monoclinic phase is characterized by peaks at 23.6°, 24.44°, and 34.1°, whereas the $BiVO_4$ monoclinic phase is validated by diffraction peaks at 18.8°, 28.9°, and 30.6°. Laser-treated samples had sharper and more pronounced $BiVO_4$ peaks, signifying enhanced crystallinity and phase uniformity. This improvement is essential for eliminating defects and facilitating efficient charge transfer, hence decreasing recombination losses and optimizing photoelectrocatalytic efficacy.

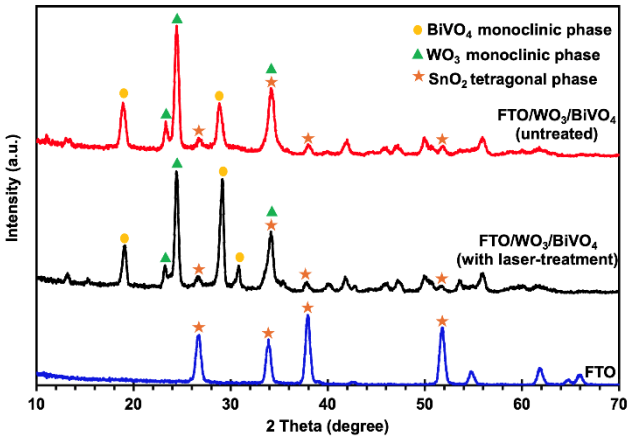


**Figure 4** The X-ray diffraction patterns of FTO substrate and FTO/$WO_3$/$BiVO_4$ electrodes, consequently treated with laser processing and untreated.

### *4.2 Optical characteristics*

Figure 5 shows the optical properties of the FTO/$WO_3$/$BiVO_4$ electrodes, with a focus on the effect of laser treatment on the FTO substrate. The laser-treated electrodes absorbed more visible light (Figure 5A). Because of the laser-induced surface roughness, the $WO_3$ and $BiVO_4$ layers adhere more strongly, resulting in a uniform coating [12]. Figure 5B shows the relationship between absorbance coefficient and energy band gap ($E_g$). The $E_g$ of laser-treated electrodes was 1.8 eV less than that of untreated samples. The reduced energy gap improves visible light absorption in photoelectrocatalytic applications. The optimum light harvesting on the



DOI: 10.60101/jarst.2024.260565

JOURNAL OF APPLIED RESEARCH ON SCIENCE AND TECHNOLOGY

electrode surface is accomplished through a uniform semiconductor coating on laser-treated substrates, which minimizes light reflection and eradicates interlayer gaps. The findings indicate that laser treatment enhances the optical properties of FTO/$WO_3$/$BiVO_4$ electrodes, demonstrating their potential for improving photoelectrocatalytic efficiency.

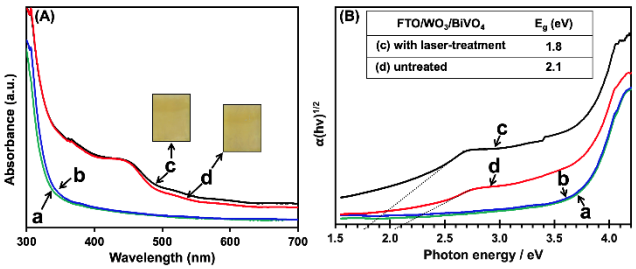


**Figure 5** (A) Absorbance spectra (B) the correlation between the absorption coefficient and energy band with effects laser treatment; (a) FTO (with laser-treatment), (b) FTO (untreated), (c) FTO/$WO_3$/$BiVO_4$ (with laser-treatment), and (d) FTO/$WO_3$/$BiVO_4$ (untreated).

In addition, the laser-treated electrodes demonstrate increased visible light absorption (Figure 5A) attributed to light scattering from surface roughness and higher semiconductor adherence, leading to a more uniform coating that reduces reflection and interlayer gaps. The lowering of the band gap from 2.1 eV (untreated) to 1.8 eV (laser-treated) (Figure 4B) is ascribed to structural and electronic alterations caused by laser irradiation. Band gap tuning can be accomplished through doping or alloying; however, structural alterations and defect states can also reduce the band gap, thereby improving visible light absorption and photoelectrocatalytic performance. These findings confirm that laser treatment enhances semiconductor interfacial contact and charge transport, offering it as an attractive option for enhancing PEC performance.

### *4.3 Photoelectrocatalytic activity*

Figure 6 shows the photoelectrocatalytic effectiveness of FTO/$WO_3$/$BiVO_4$ electrodes in a 0.1 M $Na_2SO_4$ solution at a potential of 1.0 V under visible light. Laser-treated FTO/$WO_3$/$BiVO_4$ electrodes showed enhanced photoelectrocatalytic performance, generating a current density of 5.5 mA/$cm^2$, in contrast to untreated electrodes, which provided 3.2 mA/$cm^2$. Laser-induced roughness on the FTO base made it easier for the $WO_3$ and $BiVO_4$ layers to bond together, increased the contact surface area, and let more solution through [13]. This modification made the oxidation reaction much more effective, demonstrating the advantageous effects of laser treatment before using the automatic dip-coating method to immobilize semiconductors.

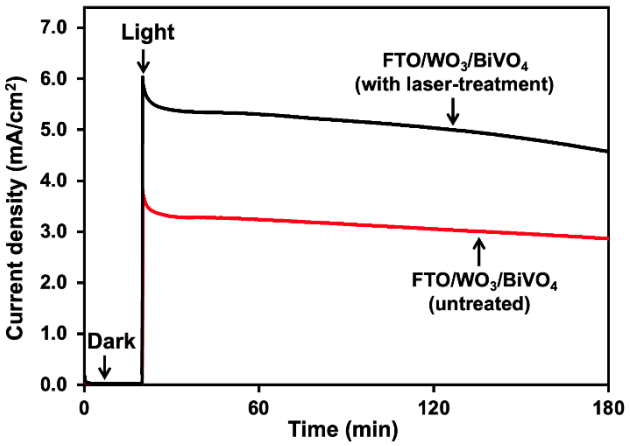


**Figure 6** Amperograms display the comparative results of the oxidation reaction current values in the aqueous solution of FTO/$WO_3$/$BiVO_4$ electrodes, highlighting the impact of laser treatment on the FTO substrate.

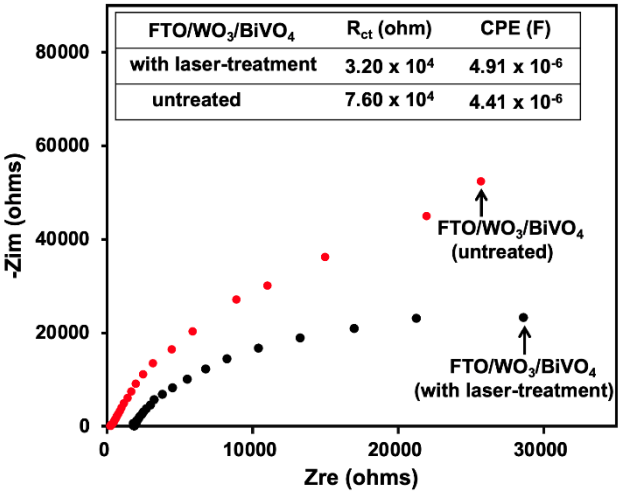


**Figure 7** Nyquist plots of FTO/$WO_3$/$BiVO_4$ electrodes: comparison of with laser-treatment and untreated FTO substrates with inset of charge transfer resistance ($R_{ct}$) and constant phase element (CPE).

### *4.4 Electrochemical resistance and capacitance properties*

Figure 7 demonstrates the electron transport characteristics between the electrode surface and the electrolyte, as a result of the electrochemical impedance spectroscopy (EIS) investigation of FTO/$WO_3$/$BiVO_4$ electrodes. The electron transfer efficiency in water oxidation reactions is improved by laser-treated FTO/$WO_3$/$BiVO_4$ electrodes, which have the smallest semicircle radius in the Nyquist plot. This represents a low charge transfer resistance ($R_{ct}$) and negligible electron transfer resistance. These results are consistent with the current density values depicted in Figure 6. Furthermore, the inset table illustrates that laser-treated electrodes have a higher constant phase element (CPE) value (4.91 x $10^{-6}$ F), which suggesting that the surface is more porous and rugged. This increases the surface area of the





DOI: 10.60101/jarst.2024.260565

JOURNAL OF APPLIED RESEARCH ON SCIENCE AND TECHNOLOGY

electrode and its ability to maintain charge, as demonstrated in Figure 2 by SEM. The results show that laser treatment proceeds prior to the immobilization of $WO_3$ and $BiVO_4$, resulting in the development of thin coatings with improved electron transfer efficiency during water oxidation at the interfacial electrode/electrolyte.

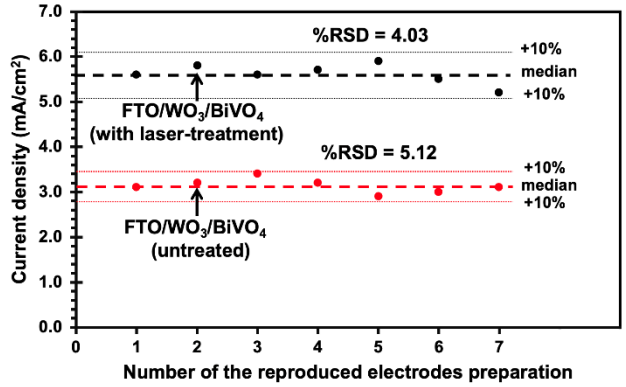


**Figure 8** Comparison of photocurrent from water oxidation: reproducibility of $FTO/WO_3/BiVO_4$ electrodes with laser- treatment and untreated.

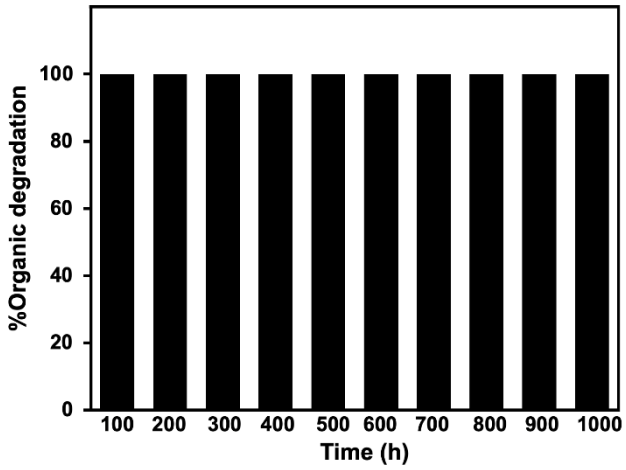


**Figure 9** Durability of laser-treated $FTO/WO_3/BiVO_4$ photoanode for orange red dye removal via photoelectrocatalytic process.

*4.5 The reproducibility performance*

Figure 8 demonstrates the repeatability investigation of $FTO/WO_3/BiVO_4$ photoanode fabrication, emphasizing the impact of laser treatment on the FTO substrate prior to automated dipping in $WO_3$ and $BiVO_4$ solutions. Seven electrodes were produced under comparable settings to test consistency. The investigation found that laser-treated $FTO/WO_3/BiVO_4$ electrodes had higher photocurrent density than untreated electrodes, with a %RSD of less than 5%, indicating high reproducibility. Laser-induced porosity and homogeneous areas reduce variability, improving electrode production uniformity. The uniform features of the electrodes are provided by the improved adhesion of the coating solution, resulting in a homogeneous surface structure [14]. The findings indicate that the uniformity of the electrode production process is significantly improved by the laser treatment of FTO substrates before semiconductor immobilization.

*4.6 The durability performance*

Figure 9 demonstrates the durability of the $FTO/WO_3/BiVO_4$ photoanode, fabricated by laser treatment of the FTO substrate before semiconductor immobilization. The electrodes were utilized to decompose organic dye by applying the bias potential and subjecting them to visible light for 1,000 hours. The laser-treated electrodes maintained 100% removal efficiency throughout testing, demonstrating no performance loss. Laser-treated $FTO/WO_3/BiVO_4$ electrodes degrade organic dyes by photoelectrocatalytic reactions, resulting in a longer operational lifetime [15]. Figure 10 illustrates the schematic representation of the fabrication of the laser-treated $FTO/WO_3/BiVO_4$ photoanode, highlighting enhancements in surface roughness, charge storage capacity, and photoelectrocatalytic performance. Laser-treated $FTO/WO_3/BiVO_4$ photoanodes enable scalable wastewater treatment and sustainable energy applications, according to this study. The findings support further research on laser-assisted fabrication of improved photoelectrocatalytic materials.

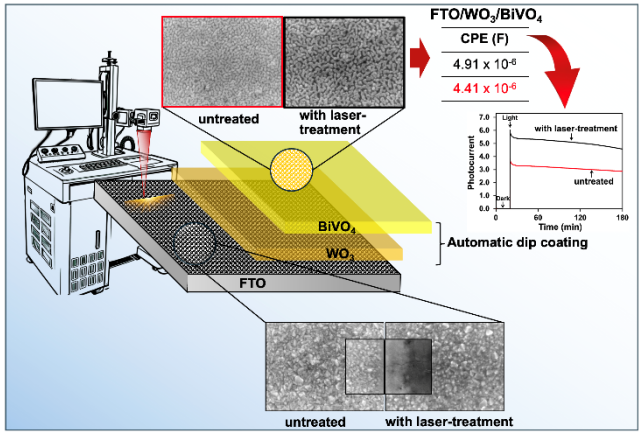


**Figure 10** Schematic diagram of laser-treated $FTO/WO_3/BiVO_4$ photoanode fabrication.

This study describes an alternative way for increasing the efficiency and durability of $FTO/WO_3/BiVO_4$ photoanodes used in photoelectrocatalytic applications such as water oxidation and organic dye degradation. Several experimental assessments show that applying laser treatment to FTO substrates prior to semiconductor deposition improves electrode properties significantly. The laser-treated electrodes have a rough surface that enhances the adherence and homogeneity of $WO_3$ and $BiVO_4$ layers, improving their structural and functional properties. The fabrication process affects the performance of photoanode photoelectrocatalytic (PEC) technology. The laser-assisted $FTO/WO_3/BiVO_4$ photoanode exceeded alternative techniques, attaining a photocurrent density of 5,500 µA/cm² at 1.00 V vs. Ag/AgCl, and 100% degradation





DOI: 10.60101/jarst.2024.260565

of methylene blue (MB) within 40 minutes (Table 2). Laser-induced surface structures promote charge separation, enhance light absorption, and maintain electrochemical stability. In contrast, the normal dip coating exhibited a decreased current density (250 μA/cm²) and needed 180 minutes to remove 94% of the MB, signifying ineffective charge redistribution. The spin coating technique exhibited slight photocurrents (1,500-2,243 μA/cm²) and degradation rates (61% for coumarin, 98% for MB) under all conditions. These improvements demonstrate that the characteristics of electrolytes and contaminants substantially affect the effectiveness of PEC. The hydrothermal approach ($FTO/CdS/TiO_2$) had the lowest current density (84.25 μA/cm²) and the moderate degradation of methylene blue (82% in 180 minutes), indicating insufficient charge transport. Laser-assisted $FTO/WO_3/BiVO_4$ fabrication improves conventional methods in photoelectrochemical efficiency, durability, and organic dye degradation.

**Table 2** Comparison of current densities and organic degradation efficiency for photoanodes by different fabrication methods.

| Materials | Fabrication method | Electrolyte solution / Light source | Current density | Pollutants / Electrolyte / Degradation efficiency | References |
|---|---|---|---|---|---|
| $FTO/WO_3/BiVO_4$ | Laser treatment combined Automatic dipping machine | 0.1M $Na_2SO_4$ / 14.4-Watt light-emitting diode (LED) | 5,500 μA/cm$^{-2}$ at 1.00 V vs Ag/AgCl | 5 ppm MB / 0.5M NaCl / 100% for 40 min | This work |
| $FTO/WO_3/BiVO_4$ | Dip coating | 0.1M $Na_2SO_4$ / 20-watt visible light irradiation | 250 μA/cm$^{-2}$ at 1.00 V vs Ag/AgCl | 5 ppm MB / 0.1M $Na_2SO_4$ / 94% for 180 min | [16] |
| $FTO/WO_3/BiVO_4$ | Spin coating | 0.5M NaCl / 320-watt light source | 1,500 μA/cm$^{-2}$ at 1.23 V vs RHE | coumarin / 0.5M NaCl / 61% for 90 min | [17] |
| $FTO/WO_3/BiVO_4$ | Spin coating | 0.1M $Na_2SO_4$ / 300-watt light source | 2,243 μA/cm$^{-2}$ at 1.28 V vs RHE | 10 ppm MB / 0.1M $Na_2SO_4$ / 98% for 180 min | [18] |
| $FTO/CdS/TiO_2$ | Hydrothermal | 0.1M NaCl / 300-Watt Xe arc lamp irradiation | 84.25 μA/cm$^{-2}$ at 1.0 V vs Ag/AgCl | 5 ppm MB / 0.1M NaCl / 82% for 180 min | [19] |

## CONCLUSIONS

This research demonstrates that laser-treated $FTO/WO_3/BiVO_4$ photoanodes exhibit outstanding performance in degrading organic dyes compared to conventional production techniques. The laser method increased the roughness of the substrate, enhancing semiconductor adhesion and promoting structural uniformity. The developed $FTO/WO_3/BiVO_4$ photoanode exhibited a narrower energy band gap (1.8 eV), increased photocurrent density (5.5 mA/cm² at 1.0 V in 0.1 M $Na_2SO_4$), and reduced charge transfer resistance. Robustness studies demonstrated complete dye removal efficacy for 1,000 hours without performance loss, highlighting the durability and scalability of the modified electrodes for practical applications. These findings emphasize the promise of laser-treated $FTO/WO_3/BiVO_4$ photoanodes for wastewater treatment and renewable energy production applications. Future research may concentrate on refining laser settings for other materials and broadening applications to various photoelectrocatalytic processes.

## ACKNOWLEDGEMENT

This research received funding from the Research and Researchers for Industries (RRI) project and Eagle Dream Co., Ltd. (N41A650408).

## REFERENCES

1. Zeng Q, Lyu L, Gao Y, Chang S, Hu C. A self-sustaining monolithic photoelectrocatalytic/photovoltaic system based on a $WO_3/BiVO_4$ photoanode and Si PVC for efficiently producing clean energy from refractory organics degradation. Appl Catal B: Environ. 2018;238:309-17.
2. Liu J, Zhang S, Wang W, Zhang H. Photoelectrocatalytic principles for meaningfully studying photocatalyst properties and photocatalysis processes: From



DOI: 10.60101/jarst.2024.260565

fundamental theory to environmental applications. J Energy Chem. 2023;86:84-117.

3. Potipat J, Somnuek C, Mekprayoon S. Water pollution influencing contamination of Vibrio bacteria in the coastal aquaculture area of Chanthaburi and Trat Provinces. J Appl Res Sci Tech [internet]. 2024;23(3):255295. Available from: https://doi.org/10.60101/jarst.2023.255295.
4. Kangkun N, Ponchio C. Photoelectrodeposition of $BiVO_4$ layer on FTO/$WO_3$ photoanodes for highly efficient photoelectrocatalytic chemical oxygen demand sensor applications. Appl Surf Sci. 2020;526:146686.
5. Wei P, Wen Y, Lin K, Li X. 2D/3D $WO_3$/$BiVO_4$ heterostructures for efficient photoelectrocatalytic water splitting. Int J Hydrog Energy. 2021;46(54): 27506-15.
6. Uttayanil T, Ponchio C. $WO_3$/$Bi_2WO_6$ photoanode enhancement for photoelectrocatalytic water oxidation; scan rate effect optimization in the cyclic voltammetry deposition method. J Appl Res Sci Tech [internet]. 2023;23(1):253891. Available from: https://doi.org/10.60101/jarst.2023.253891.
7. Nareejun W, Ponchio C. Novel photoelectrocatalytic/ solar cell improvement for organic dye degradation based on simple dip coating $WO_3$/$BiVO_4$ photoanode electrode. Sol Energy Mater Sol Cells. 2020;212: 110556.
8. Du X, Ning X. Heteroepitaxial growth of PMN-PT thin films on $SrTiO_3$ buffered III-V semiconductor GaAs by pulsed laser deposition. J Cryst Growth. 2025;653:128070.
9. Lamichhane S, Tomar M, Chowdhuri A, Sharma S. Role of laser energy variation on energy storage capacity of bilayer BFO/$WO_3$ thin film structure. Mater Sci Semicond Process. 2025;188:109218.
10. Hacini A, Ali AH, Harkat L, Nayan N, Adnan NN, Azali MM, et al. Effect of laser fluence on the ITO/ Mo-Ag/ITO multilayer thin film for a-Si(n)/c-Si(p)/ a-Si(p)/Al heterojunction solar cells. Sol Energy. 2024;284:113042.
11. Rodríguez-Rosales K, Cruz-Gómez J, Santos Cruz J, Guillén-Cervantes A, de Moure-Flores F, Villagrán-Muniz M. Plasma emission spectroscopy for studying $Bi_2S_3$ produced by pulsed laser deposition and effects of substrate temperature on structural, morphological, and optical properties of thin films. Mater Sci Eng B 2025;312:117867.
12. Majumder M, Batista-Pessoa W, Bottin N, Constantinescu C, Koudia M, Petroni E, et al. Optically inducing and probing the local crystallization of ultra-thin GeSbTe films by single-pulse laser irradiations. Surf Interfaces. 2025;56:105664.
13. Divya J, Shivaramu NJ, Swart HC. Structural and optical characteristics of α-$Bi_2O_3$/ $Bi_2O(3\text{-}x)$:$HO^{3+}$ thin films deposited by pulsed laser deposition for improved green and near-infrared emissions and photocatalytic activity. Heliyon. 2024;10(1): e23200.
14. Mishra G, Tiwari A. Pulsed laser deposition of Nd-doped $BaSnO_3$ thin films on c-plane sapphire substrate for transparent sensors. Mater Sci Eng B. 2024;310:117768.
15. Velmurugan R, Aishwarya M, Balamurugan K, Nivedha K, Subramanian B. Influencing In situ tuned nanostructures of pulsed laser ablated $Co_3O_4$ & $WO_3$ thin film electrodes for binder free flexible operando hybrid supercapacitor devices. Electrochim Acta. 2022;419:140371.
16. Nareejun W, Ponchio C. Novel photoelectrocatalytic/ solar cell improvement for organic dye degradation based on simple dip coating $WO_3$/$BiVO_4$ photoanode electrode. Sol Energy Mater Sol Cells. 2020;212:110556.
17. Zeng Q, Lyu L, Gao Y, Chang S, Hu C. A self-sustaining monolithic photoelectrocatalytic/ photovoltaic system based on a $WO_3$/$BiVO_4$ photoanode and Si PVC for efficiently producing clean energy from refractory organics degradation. Appl Catal B: Environ. 2018;238:309-17.
18. Zeng Q, Lyu L, Gao Y, Chang S, Hu C. A self-sustaining monolithic photoelectrocatalytic/ photovoltaic system based on a $WO_3$/$BiVO_4$ photoanode and Si PVC for efficiently producing clean energy from refractory organics degradation. Appl Catal B: Environ. 2018;238: 309-17.
19. Wu YH, Wu T, Lin YW. Photoelectrocatalytic degradation of methylene blue on cadmium sulfide-sensitized titanium dioxide film. Mater Res Bull. 2019;118:110500.





DOI: 10.60101/jarst.2024.260565