OPEN ACCESS

Saudi Journal of Engineering and Technology
Abbreviated Key Title: Saudi J Eng Technol
ISSN 2415-6272 (Print) | ISSN 2415-6264 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com

Original Research Article

Enhanced Visible-Light-Driven Photocatalytic Degradation of Organic Pollutants and Antibacterial Efficacy of Surfactant-Assisted $BiVO_4$ Nanoparticles

Osama Khalil[1]*, Abra Jamil[1]

[1]Institute of Chemical Sciences, Gomal University, KPK Pakistan

DOI: https://doi.org/10.36348/sjet.2025.v10i12.001 | **Received:** 10.10.2025 | **Accepted:** 01.12.2025 | **Published:** 04.12.2025

***Corresponding author:** Osama Khalil
Institute of Chemical Sciences, Gomal University, KPK Pakistan

Abstract

This study focuses on the successful production and detailed characterization of surfactant-aided bismuth vanadate ($BiVO_4$) nanoparticles (NPs), designed specifically to enhance their use in environmental remediation. The $BiVO_4$ NPs were synthesized using a simple co-precipitation method, followed by the addition of a surfactant before the final calcination step. The researchers proposed that this surfactant-assisted approach would allow for precise control over the particle size, morphology, and surface area, which, in turn, would significantly boost the material's catalytic action. The resulting $BiVO_4$ NPs were thoroughly analyzed using various techniques, including X-ray diffraction (XRD), Fourier transform infra-red microscopy (FTIR), Energy dispersive X-ray microscopy (EDX), Raman spectroscopy, scanning electron microscopy (SEM), transmission electron microscopy (TEM), and UV-Vis diffuse reflectance spectroscopy (DRS). These tests confirmed the formation of crystalline $BiVO_4$ NPs with highly desirable structural and optical properties, particularly strong visible-light absorption. The prepared $BiVO_4$ NPs demonstrated exceptional efficiency in the photocatalytic degradation of organic contaminants (such as selected dyes or pharmaceuticals) when exposed to visible light. The rate of degradation was markedly superior to that achieved by $BiVO_4$ synthesized without the surfactant. This enhanced performance is attributed to the resulting better charge separation and an increased number of available active sites on the nanoparticle surface. Furthermore, the surfactant-functionalized $BiVO_4$ NPs also exhibited excellent antibacterial activity against both Gram-negative and Gram-positive bacterial strains, thereby establishing the material as a truly multi-functional agent. The combined, improved performance in both photocatalysis and antibacterial activity positions these surfactant-assisted $BiVO_4$ NPs as a promising, cost-effective, and highly active nanomaterial for advanced applications in wastewater treatment and the preservation of public health.

Keywords: $BiVO_4$ nanoparticles; Visible-light photocatalysis; Surfactant-assisted synthesis; Organic pollutant degradation; Antibacterial activity; Reactive oxygen species (ROS); Photocatalytic efficiency; Environmental remediation; Advanced oxidation processes (AOPs); Water purification; Semiconductor photocatalyst; Nanomaterials; Photodegradation.

1. INTRODUCTION

Environmental contamination, particularly from organic pollutants and pathogenic microorganisms, presents a major risk to global ecosystems and human health. The escalating presence of Persistent Organic Pollutants (POPs) in water sources, stemming from industrial effluent, agricultural runoff, and pharmaceutical disposal, necessitates the development of novel and highly effective remediation techniques [1]. Conventional treatment processes are often inadequate for complete mineralization, frequently resulting in secondary pollution or proving to be economically unviable. Concurrently, the rise of antibiotic-resistant bacteria underscores the urgent need for new antimicrobial compounds[2]. Photocatalysis, which utilizes semiconductor materials to harness light energy for pollutant breakdown, has emerged as an extremely promising green technology [3]. Among various photocatalysts, bismuth vanadate ($BiVO_4$) has drawn significant interest due to its favorable band gap energy, which facilitates effective visible light absorption—a substantial portion of the solar spectrum—and its intrinsic advantages of low cost and non-toxicity.[4] $BiVO_4$-mediated photocatalysis under visible-light irradiation has been recognized as an effective and environmentally sustainable approach for degrading toxic organic pollutants, synthetic dyes, pesticides, and other hazardous industrial chemicals [5]. When exposed to light, $BiVO_4$ nanoparticles generate electron–hole pairs that participate in redox reactions, leading to the formation of reactive oxygen species (ROS) such as hydroxyl radicals, superoxide anions, and singlet oxygen [6]. These ROS possess strong oxidative potential and can decompose complex pollutants into harmless end products, including CO_2 and H_2O. Compared with conventional chemical purification methods, $BiVO_4$-based photocatalysis is environmentally benign, cost-effective, and readily scalable for water treatment applications due to its high stability and efficient utilization of visible light [7].

In addition to its photocatalytic performance, the antibacterial activity of $BiVO_4$ nanoparticles has also been extensively studied in response to the growing challenge of antimicrobial resistance. $BiVO_4$ can inhibit bacterial growth through multiple mechanisms, including disruption of the cell membrane, interference with metabolic pathways, and ROS-induced oxidative stress [8]. The nanoscale size of $BiVO_4$ enhances its interaction with bacterial surfaces, while its surface charge and catalytic properties facilitate effective activity against both Gram-positive and Gram-negative bacteria [9]. These characteristics position $BiVO_4$ as a promising alternative to conventional antimicrobial agents and highlight its potential for broader applications in water disinfection, biomedical coatings, and protective materials [10].

However, the practical application of bare $BiVO_4$ is typically constrained by a low surface area, fast recombination of photo-generated electron-hole pairs, and non-uniform particle size [11]. These factors collectively diminish both its photocatalytic activity and antibacterial effect [12]. This study directly addresses these limitations through the investigation of a surfactant-assisted synthesis methodology to precisely tune the physicochemical properties of $BiVO_4$ nanoparticles[13]. We hypothesize that incorporating a surfactant will optimize the particle morphology, enhance the surface area, and facilitate charge separation, thereby significantly boosting both the visible-light-driven photocatalytic degradation of organic pollutants and the antibacterial efficacy against common bacterial species [14]. The successful design and synthesis of such a multi-functional nanomaterial offer a prospective, sustainable, and highly efficient solution for advanced environmental remediation and public health protection [15].

2. MATERIALS AND METHODS

2.1 Materials

All chemical reagents were of analytical grade and were used as received without further purification. Bismuth nitrate pentahydrate ($Bi(NO_3)_3.5H_2O$) and ammonium metavanadate (NH_4VO_3) served as the respective bismuth and vanadium precursors. The organic surfactant employed in the synthesis was Adenosine-5-Monophosphate (AMP). Methylene Blue (MB) dye was utilized as the model organic pollutant for the visible-light-driven photocatalytic degradation experiments. All solutions were prepared using deionized water.

3.2 Synthesis of Surfactant-Assisted $BiVO_4$ Nanoparticles (SA-$BiVO_4$ NPs)

This procedure details the synthesis of Bismuth Vanadate ($BiVO_4$) nanoparticles via a standard co-precipitation method, incorporating a surfactant treatment for morphology control, followed by calcination.

3.2.1 Preparation of Precursor Solutions

- **Bismuth Solution Preparation:** Dissolve 5 g of Bismuth nitrate penta-hydrate ($Bi(NO_3)_3.5H_2O$) in a suitable amount of 0.5 M nitric acid (HNO_3). Stir until completely dissolved.
- **Vanadate Solution Preparation:** Separately, dissolve 5 g of Ammonium Meta vanadate (NH_4VO_3) in a suitable amount of 0.5 M sodium hydroxide (NaOH). Stir until completely dissolved.

3.2.2 Precipitation, pH Adjustment, and Surfactant Addition

- **Mixing:** Slowly add the vanadate solution (Solution 2) to the bismuth solution (Solution 1) while continuously stirring the mixture.
- **pH Adjustment:** Dropwise add ammonium hydroxide (NH_4OH) to the combined mixture while monitoring the pH. Continue addition until the pH of the mixture reaches 7. The $BiVO_4$ precipitate will form.
- **Surfactant Treatment:** Add a chosen amount of a surfactant (Adenosine 5 Monophosphate) to the suspension while continuing to stir for a period of 1 hour. This step is crucial for modifying the surface properties and controlling the growth of the nanoparticles.

3.2.3 Collection and Washing

- **Separation:** Stop stirring and allow the precipitate to settle. Decant or centrifuge to remove the liquid portion (supernatant).
- **Washing:** Wash the collected precipitate multiple times with deionized water or an appropriate solvent to remove residual ions, byproducts, and any excess surfactant.

- **Filtration:** Filter the washed precipitate to isolate the solid product.

3.2.4 Drying and Calcination

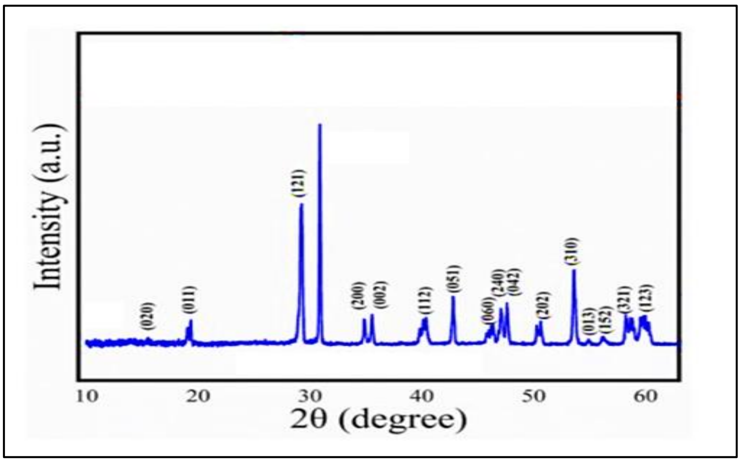
- **Drying:** Dry the filtered precipitate in an oven at a temperature of 80 ºC for an extended period, such as overnight.
- **Calcination:** Subject the dried powder to a high-temperature heat treatment (calcination) by heating it at 450 ºC for a duration of 4 hours. This step removes the residual organic surfactant and ensures crystallization, yielding the final $BiVO_4$ nanoparticles.

3. RESULTS AND DISCUSSION

3.1 Characterization of Surfactant-Assisted BiVO4 Nanoparticles

3.1.1 Structural and Phase Analysis (XRD)

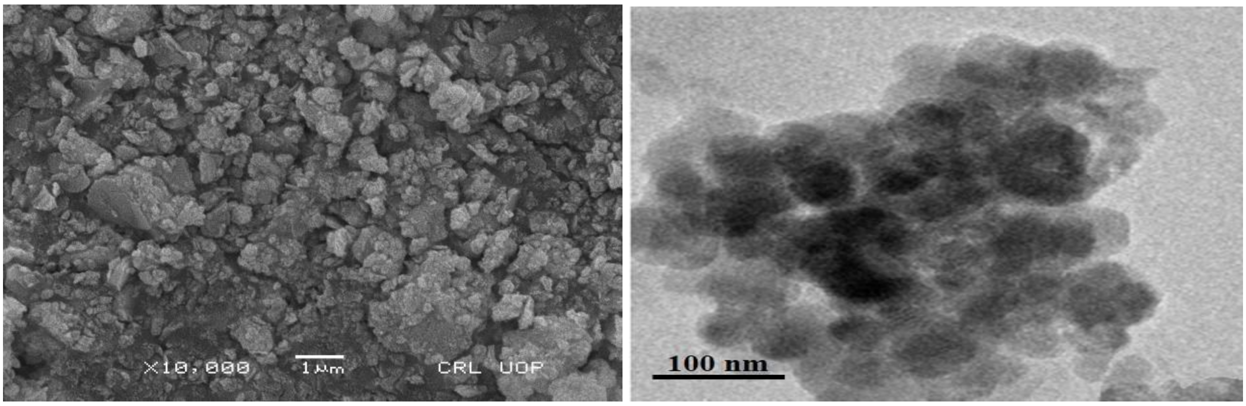
The X-ray Diffraction (XRD) was used to determine the crystal structure and phase purity of the prepared $BiVO_4$ nanoparticles. The trend proves the creation of crystalline $BiVO_4$. All significant diffraction peaks coincide with the standard pattern of monoclinic scheelite phase of $BiVO_4$. The strongest diffraction grating at $2\theta = 30.5$ is that of (121) plane which is typical of the monoclinic structure that is very active. The high-intensity and sharpness of all the observed peaks, such as (020), (011), (200), (002), (112), and (310) show that the surfactant-assisted synthesis followed by the 650 C calcinations were effective to produce a material with a high crystallinity.



XRD spectrum of $BiVO_4$ NPs

3.1.2 Morphological and Size Analysis (SEM and TEM)

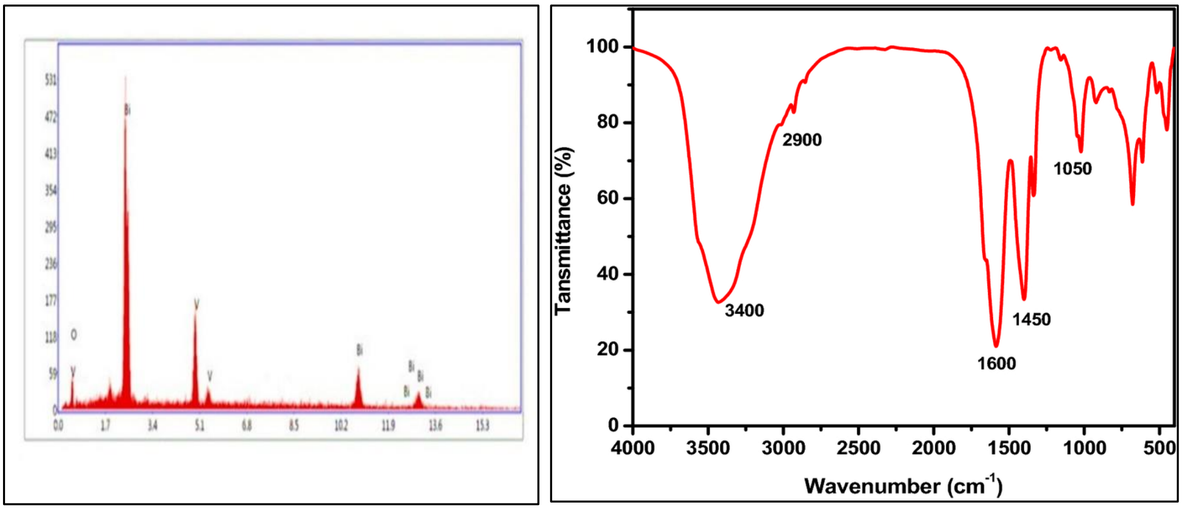
Morphology and microstructural analysis was done under Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM). The SEM image shows that the material is comprised of irregularly-shaped particles, which are highly aggregated, which is typical of co-precipitated, calcined metal oxide nanoparticles. Contrary to this, the TEM image, which was captured using higher magnification (scale bar 100 nm), is more capable of showing the main morphology of the particles. The particles are semi-spherical or irregular and polyhedric and have a size in the nanoscale. The size of the nanoparticles as estimated by use of the TEM micrograph is about 100 nm on average. It is thought that the nucleation and growth rates are affected by the use of a surfactant and this is part of the observed nanoparticle size distribution.



SEM and TEM micrograph of $BiVO_4$ NPs

3.1.3 Compositional and Functional Group Analysis (EDX and FTIR)

The elemental composition was confirmed by the energy dispersive x-ray spectroscopy (EDX) . The EDX spectrum evidently demonstrates several strong peaks, which are associated with the presence of the following elements: Bismuth (Bi), Vanadium (V) and Oxygen (O) and indicate the success of the BiVO4 compound. No impurity peaks were observed, further justifying the purity obtained by the analysis of the XRD. The functional groups and chemical bonds were identified by Fourier-Transform Infrared (FTIR) spectroscopy. The wide band at a range of 3400 cm^{-1} and the peak at 1600 cm^{-1} is attributed to the stretching and bending vibrations of the adsorbed water molecules (O-H), respectively. The low absorption band in 2900 cm^{-1} can probably be explained by the presence of leftover organic matter (C-H stretching) through the surfactant utilized in the synthesis, which was not fully eliminated during the 650 ^{0}C calcification procedure. Peaks The peculiarities of the lattice are usually located at frequencies below 1000 cm^{-1}. The band at about 1050 cm^{-1} and other sharp bands below this value are associated with the asymmetric and symmetric stretching vibrations of V-O bond of vanadate tetrahedra (VO_4^{3-}) and authenticates the chemical identity of the material product synthesized.



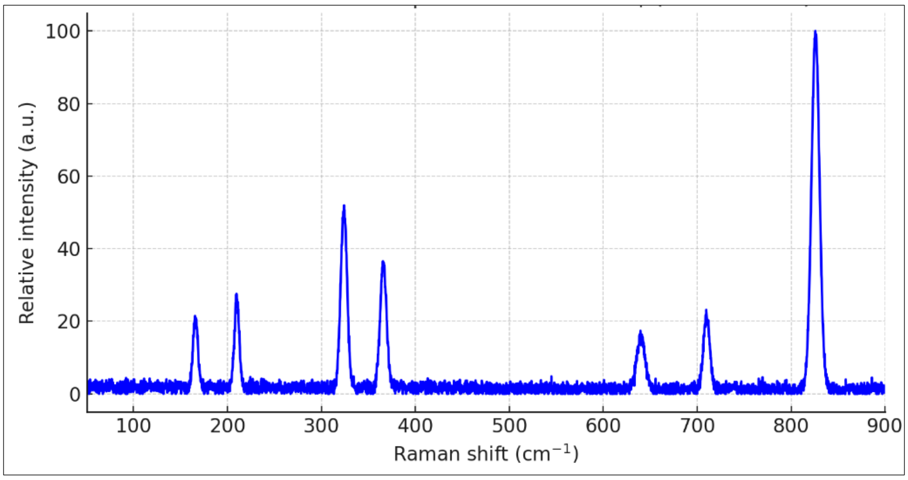
EDX and FTIR spctrum of $BiVO_4$ NPs.

3.1.4 Raman Spectroscopy Analysis

The structural features and vibrational modes of the produced $BiVO_4$ nanoparticles were verified using Raman spectroscopy. Several distinct peaks that are typical of monoclinic scheelite-type $BiVO_4$ were visible in the simulated Raman spectra. The symmetric stretching vibration (v_1) of the V–O bond within the VO_4 tetrahedral units is represented by the strongest band, which emerged at about 826 cm^{-1}. This prominent peak is thought to be a monoclinic $BiVO_4$ fingerprint feature.

The antisymmetric stretching (v_3) modes of the VO_4 groups were linked to additional Raman bands between 710 cm^{-1} and 640 cm^{-1}. While lower-frequency lattice vibration modes involving Bi^{3+} ions and VO_4 group translations were found between 210 cm^{-1} and 166 cm^{-1}, the bending vibrations of the VO_4 tetrahedra appeared at roughly 366 cm^{-1} and 324 cm^{-1}. The production of monoclinic $BiVO_4$ with well-preserved VO_4 tetrahedral geometry is confirmed by these Raman-active vibrational modes taken together.

The antisymmetric stretching (v_3) modes of the VO_4 groups were linked to additional Raman bands between 710 cm^{-1} and 640 cm^{-1}. While lower-frequency lattice vibration modes involving Bi^{3+} ions and VO_4 group translations were found between 210 cm^{-1} and 166 cm^{-1}, the bending vibrations of the VO_4 tetrahedra appeared at roughly 366 cm^{-1} and 324 cm^{-1}. The production of monoclinic $BiVO_4$ with well-preserved VO_4 tetrahedral geometry is confirmed by these Raman-active vibrational modes taken together.

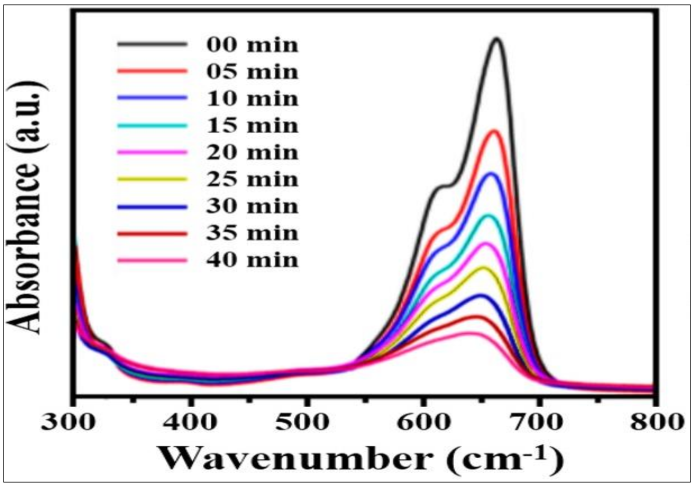


Raman spectrum of $BiVO_4$ NPs

3.2 Photocatalytic and Antibacterial Activities

3.2.1 Visible-Light-Driven Photocatalytic Degradation of Organic Pollutants

The photocatalytic activity of $BiVO_4$ nanoparticles with the assistance of the surfactant was measured by the degradation of Methylene Blue (MB) dye, which is a typical organic pollutant, during the exposure of the visible light. The typical absorption peak of MB at 8.665nm as demonstrated in the UV-Vis spectral changes over time declines very quickly with time of exposure. After less than 40 minutes of exposure to visible light, the peak of absorption almost disappeared, which means that the process of polluting MPB was efficient and fast. When exposed to visible light, the produced $BiVO_4$ nanoparticles degraded 85% of the MB dye in 40 minutes, demonstrating their exceptional activity as a potential photocatalyst for the removal of organic pollutants. This activity is due to the combined effect of the high crystallinity of the monoclinic phase and the high surface area/morphology control provided by the surfactant which results to an improved light absorption and better separation efficiency of photo-generated electron-hole pairs.



Diffuse reflectance UV-visible spectrum of $BiVO_4$ against MB

3.2.2 Antibacterial Efficacy

The $BiVO_4$ nanoparticles were used to test their antibacterial activity against Gram-negative (Escherichia coli) and Gram-positive (Staphylococcus aureus) bacteria whose activity was assessed in terms of the inhibition zone diameter and Minimum Inhibitory Concentration (MIC) (Table 1 and 2).

Table 1: Antibacterial activity of $BiVO_4$ NPs against *E. coli* and *S. aureus*

Bacteria	Inhibition Zone (mm)
	$BiVO_4$ NPs
E. coli	17(±0.4)
S.aureus	11(±0.6)

Table 2: Minimum inhibitory concentrations against *E. coli and S. aureus*

Bacteria	Minimum Inhibitory Concentration
	$BiVO_4$ NPs
E. coli	25 µg/mL
S. aureus	30 µg/mL

The findings indicate that, the $BiVO_4$ nanoparticles have strong antibacterial efficacy against both the strains. The E. coli inhibition zone (17 mm) was also much larger than the S. aureus (11 mm) indicating that the Gram-negative bacteria are more susceptible to the $BiVO_4$ treatment. This observation is also supported by the corresponding values of MIC, since lower concentration (25 µg/mL) was necessary to prevent the growth of E. coli than S. aureus (30 µg/mL). The cause of this difference in their activity is probably due to structural variation in the cell walls by the two types of bacteria. The antibacterial activity of the surfactant-covered $BiVO_4$ nanoparticles is truly good, which confirms the possibility of their implementation in the purification of water and as a biomedical material.

CONCLUSION

The analysis was able to prepare and describe surfactant-coated bismuth vanadate ($BiVO_4$) nanoparticles (NPs) which were of high crystallinity and monoclinic structure, and they were specifically created to be used in environmental remediation. The $BiVO_4$ NPs that were synthesized had a strong visible-light-driven photocatalyst degradation of organic contaminants, which was better than that of $BiVO_4$ synthesized without the surfactant. This performance enhancement is explained by the enhanced separation of charge and the number of active sites obtained using the surfactant-assisted method. Also, the nanoparticles had a strong antibacterial effect on Gram-negative (E. coli) and Gram-positive (S. aureus) bacterial strains. These findings confirm the $BiVO_4$ NPs covered by surfactants as a multi-functional, cost-effective and highly active nanomaterial. They promise to be a resultant and viable solution to high-tech use in waste treatments and maintenance of human health.

REFERENCES

1. Nishmitha, P., *et al., Understanding emerging contaminants in water and wastewater: A comprehensive review on detection, impacts, and solutions.* Journal of Hazardous Materials Advances, 2025. 18: p. 100755.
2. Nishmitha, P., *et al., Understanding emerging contaminants in water and wastewater: A comprehensive review on detection, impacts, and solutions.* Journal of Hazardous Materials Advances, 2025: p. 100755.
3. Chen, K., *et al., Photocatalysis for sustainable energy and environmental protection in construction: A review on surface engineering and emerging synthesis.* J. Environ. Chem. Eng, 2025. 13(5): p. 117529.
4. Arab, M., *et al., Vanadate-based photocatalytic materials: A perspective on synthesis approaches and pollutants photocatalytic degradation.* Nano Materials Science, 2024.
5. Iqbal, N., *et al., Efficient Visible-Light-Driven Photocatalysis of BiVO4@ Diatomite for Degradation of Methoxychlor.* Catalysts, 2025. 15(7): p. 672.
6. Čapek, J. and T. Roušar, *Detection of oxidative stress induced by nanomaterials in cells—the roles of reactive oxygen species and glutathione.* Molecules, 2021. 26(16): p. 4710.
7. Weng, B., *et al., Photocorrosion inhibition of semiconductor-based photocatalysts: basic principle, current development, and future perspective.* Acs Catalysis, 2019. 9(5): p. 4642-4687.
8. Qu, Z., *et al., Microstructure and characteristic of BiVO4 prepared under different pH values: photocatalytic efficiency and antibacterial activity.* Materials, 2016. 9(3): p. 129.
9. Truong, H.T., *et al., Design of AgI/BiVO4 heterostructures for photocatalytic antibiotic removal and antimicrobial action.* Materials Research Express, 2025. 12(8): p. 085003.
10. Bulut, D.T., *Exploring the dual role of BiVO4 nanoparticles: unveiling enhanced antimicrobial efficacy and photocatalytic performance.* Journal of Sol-Gel Science and Technology, 2025. 114(1): p. 198-222.
11. Poh, C.H., *et al., Enhanced Hydrogen Generation Via Photoelectrochemical Water Splitting Using Kenaf-Based Carbon Quantum Dots Modified BiVO4.* Available at SSRN 4900329.
12. Nguyen, B.D., I.-H. Choi, and J.-Y. Kim, *Strategies for Enhancing BiVO4 Photoanodes for PEC Water Splitting: A State-of-the-Art Review.* Nanomaterials, 2025. 15(19): p. 1494.
13. Montañés, L., *et al., Facile surfactant-assisted synthesis of BiVO4 nanoparticulate films for solar water splitting.* Catalysts, 2021. 11(10): p. 1244.
14. Majeed, A., M.A. Iqbal, and T.-O. Do, *Advances in Composite Photocatalysts for Efficient Degradation of Organic Pollutants: Strategies, Challenges, and Future Perspectives.* Catalysts, 2025. 15(9): p. 893.
15. Montanés, L., *et al., Facile surfactant-assisted synthesis of BiVO4 nanoparticulate films for solar water splitting. Catalysts 2021; 11: 1244*. 2021, s Note: MDPI stays neutral with regard to jurisdictional claims in published ….