

Biomedical Applications of Bismuth Vanadate Nanoparticles: A Review

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ABSTRACT

Bismuth vanadate (BiVO_4) nanoparticles have recently emerged as promising multifunctional materials in biomedical applications due to their excellent optical properties, chemical stability, and biocompatibility. This review systematically summarizes current advancements in the synthesis methods, properties, and biomedical applications of BiVO_4 nanoparticles, emphasizing their use in bioimaging, photodynamic therapy, antibacterial treatments, and cancer therapeutics. Furthermore, critical challenges and future perspectives are discussed to advance their clinical translation.

Keywords: Bismuth Vanadate; Nanoparticles; Biomedical Applications; Bioimaging; Photodynamic Therapy; Antibacterial; Cancer Therapy

Abbreviations: CT: Computed Tomography; TEM: Transmission Electron Microscopy; SEM: Scanning Electron Microscopy; XRD: X-ray Diffraction; FTIR: Fourier Transform Infrared Spectroscopy; UV-VIS: UV-Visible Spectroscopy; DLS: Dynamic Light Scattering; TGA: Thermogravimetric Analysis; PDT: Photodynamic Therapy; PTT: Photothermal Therapy; EPR: Enhanced Permeability and Retention

Introduction

Nanotechnology, characterized by the manipulation and application of materials at nanoscale dimensions (approximately 1–100 nm), has significantly influenced the advancement of biomedical sciences over the past two decades. At this scale, materials often exhibit exceptional physical, chemical, electronic, optical, and biological properties distinct from their bulk counterparts. This paradigm shift has empowered scientists and clinicians to develop innovative diagnostic techniques, advanced therapeutic strategies, and multifunctional materials for personalized medicine. Nanoparticles, due to their high surface-area-to-volume ratio, tunable morphology, and capability for surface functionalization, offer enhanced interactions with biological systems, rendering them invaluable tools for biomedical applica-

tions [1]. Among emerging nanomaterials, bismuth vanadate (BiVO_4) nanoparticles have garnered considerable interest, primarily due to their unique physicochemical attributes such as excellent photocatalytic efficiency, superior photostability, favorable biocompatibility, and low toxicity. Structurally, BiVO_4 nanoparticles commonly crystallize into scheelite or monoclinic phases, which influence their optical absorption capabilities, extending well into the visible spectrum.

This intrinsic ability to absorb visible light efficiently enables applications not only in photocatalysis and environmental remediation but increasingly within biomedical contexts, especially in bioimaging, drug delivery systems, photothermal therapy, and photodynamic therapy [2]. The biomedical significance of BiVO_4 nanoparticles is further highlighted by their multifunctional capacities—specifically their dual diagnostic and therapeutic (“theranostic”) potential. The

promising biocompatibility, stability, ease of surface modification, and controllable morphology make BiVO₄ nanoparticles appealing candidates for theranostics [3]. Their enhanced photostability and photo-induced reactive oxygen species generation capabilities are particularly valuable for photodynamic therapies targeting cancerous tissues, while their inherent heavy-metal components enable applications in contrast-enhanced imaging techniques such as computed tomography (CT) and X-ray imaging. Despite these remarkable advantages, comprehensive biomedical adoption of BiVO₄ nanoparticles is still in nascent stages [4]. There remain numerous critical challenges, such as standardized and scalable synthesis protocols, thorough cytotoxicity evaluations, long-term biocompatibility assessments, detailed understanding of bio-nano interactions, pharmacokinetics, and

precise targeting mechanisms. Addressing these challenges is pivotal for the seamless translation of BiVO₄ nanoparticles from laboratory settings into clinical practice [5].

The present review systematically explores the biomedical potentials of BiVO₄ nanoparticles, synthesizing existing knowledge from recent literature. The article elaborates on their physicochemical properties, synthesis methodologies, surface functionalization strategies, specific biomedical applications, safety concerns, and regulatory considerations [6-10]. Ultimately, this comprehensive analysis aims to underscore current advancements, elucidate potential applications, identify critical research gaps, and pave the way for future clinical translation of BiVO₄ nanoparticles in personalized healthcare paradigms [11-13] (Table 1).

Table 1: Summary of recent developments in biomedical applications of bismuth vanadate (BiVO₄) nanoparticles.

Synthesis Method	Surface Functionalization	Biomedical Application	Functional Role	Key Outcomes	References
Hydrothermal	Polyethylene glycol (PEG)	Photothermal therapy	Light-to-heat conversion agent	High photothermal efficiency; effective tumor ablation <i>in vitro</i> and <i>in vivo</i>	[6]
Sol-gel	Folic acid conjugation	Targeted drug delivery	Ligand-targeted delivery of anti-cancer drugs	Enhanced uptake by cancer cells; reduced off-target toxicity	[7]
Co-precipitation	None	CT imaging	Contrast enhancement	Strong X-ray attenuation; clear anatomical visualization	[8]
Microwave-assisted	Graphene oxide hybridization	Photoacoustic imaging	Acoustic signal amplifier	Enhanced imaging depth and resolution in biological tissues	[9]
Green synthesis (plant extract)	Chitosan coating	Antibacterial applications	Membrane disruption and ROS generation	Broad-spectrum antibacterial activity; biocompatibility confirmed	[10]
Electrospinning	PVA blending	Wound healing scaffolds	Structural support and antibacterial activity	Accelerated wound closure; reduced bacterial load	[11]
Sonochemical	BSA stabilization	Drug delivery and imaging	Dual-mode delivery and imaging carrier	Stable dispersion; improved biodistribution	[12]
Thermal decomposition	Dextran coating	MRI contrast enhancement	Magnetic resonance signal booster	Improved contrast in T1-weighted imaging sequences	[13]

Synthesis and Characterization of Bismuth Vanadate Nanoparticles

Bismuth vanadate (BiVO₄) nanoparticles have emerged as promising biomedical nanomaterials due to their distinct physicochemical attributes. However, their effective biomedical application strongly depends on precisely controlled synthesis and rigorous characterization to ensure reproducible properties and high biocompatibility [14].

Chemical Synthesis Methods

BiVO₄ nanoparticles can be synthesized by various chemical methods, among which sol-gel, hydrothermal, and microwave-assist-

ed methods are the most frequently employed. Each method presents unique advantages, influencing particle size, morphology, purity, and structural characteristics.

Sol-Gel Method: The sol-gel synthesis is a popular, versatile, and widely used chemical method due to its simplicity and excellent control over the size and morphology of nanoparticles [15]. Typically, soluble precursors such as bismuth nitrate (Bi(NO₃)₃) and ammonium metavanadate (NH₄VO₃) are dissolved separately in appropriate solvents (often water, ethanol, or ethylene glycol). Upon mixing, hydrolysis and condensation reactions occur, leading to the formation of a homogeneous sol. Subsequent aging of this sol promotes gelation, creating a three-dimensional porous network. Finally, controlled calcination at elevated temperatures (300–600 °C) induces crystalliza-

tion and removes organic contaminants, yielding highly crystalline BiVO_4 nanoparticles. Advantages include uniform particle distribution, tunable porosity, and adjustable surface chemistry, essential for biological applications [16].

Hydrothermal Method: The hydrothermal synthesis technique involves crystallization of nanoparticles at elevated temperatures (typically 120–250 °C) under high-pressure conditions within a sealed autoclave. This method effectively controls crystallinity, particle size, shape, and phase purity by adjusting parameters such as temperature, reaction duration, precursor concentration, solvent composition, and pH of the reaction mixture [17]. Hydrothermal synthesis is particularly advantageous in producing nanoparticles with uniform size and shape (e.g., spheres, rods, sheets) and enhanced crystallinity. Notably, this method is frequently preferred when well-defined crystal phases (monoclinic or scheelite tetragonal) are required, im-

pacting optical and catalytic properties essential for biomedical applications, including theranostic and imaging agents [18].

Microwave-Assisted Method: Microwave-assisted synthesis has gained attention for its efficiency, rapid processing time, uniform heating, and low energy consumption. In this approach, BiVO_4 nanoparticles are formed by irradiating a precursor solution containing $\text{Bi}(\text{NO}_3)_3$ and NH_4VO_3 or other suitable salts using microwave energy [19]. Rapid and localized heating due to microwave irradiation accelerates nucleation and crystallization, resulting in nanoparticles with smaller sizes, uniform morphology, fewer defects, and higher phase purity compared to conventional heating methods. Additionally, microwave synthesis can significantly reduce reaction times from hours to minutes, enabling scalable and cost-effective manufacturing for biomedical purposes [20] (Figure 1).

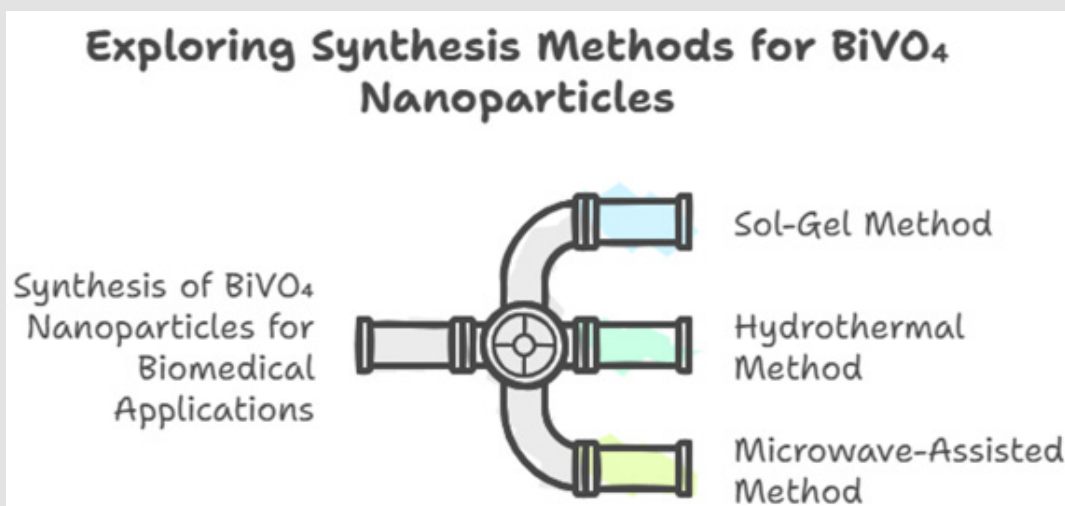


Figure 1.

Physical and Chemical Characterization Techniques

The precise physicochemical characterization of synthesized BiVO_4 nanoparticles is crucial to confirm their structural, optical, and surface properties, ensuring their suitability and consistency for biomedical use. A comprehensive set of analytical techniques is routinely employed to thoroughly understand nanoparticle characteristics.

Transmission Electron Microscopy (TEM): TEM provides detailed nanoscale information on particle size, shape, crystallinity, morphology, and agglomeration state. TEM imaging can precisely measure particle size distributions and crystal lattice structures, essential in correlating nanoparticle features with their biomedical performance, especially interactions at the cellular level and biodistribution profiles [21].

Scanning Electron Microscopy (SEM): SEM complements TEM by offering high-resolution topographic and morphological surface characterization. It helps visualize particle uniformity, aggregation tendencies, surface texture, and overall distribution. SEM data is critical to understanding the nanoparticle's stability, surface roughness, and suitability for biomedical applications, especially drug delivery and therapeutic coatings [22].

X-ray Diffraction (XRD): XRD is a fundamental technique for determining crystal structure, phase purity, crystallite size, and lattice parameters of BiVO_4 nanoparticles. XRD helps distinguish different polymorphs (monoclinic, tetragonal, scheelite), each exhibiting distinct optical and photocatalytic properties, thereby guiding optimal synthesis routes for targeted biomedical functions [23].

Fourier Transform Infrared Spectroscopy (FTIR): FTIR spectroscopy provides insight into chemical bonding, functional groups, surface modification, and potential impurities in synthesized nanoparticles. It confirms the presence of characteristic Bi–O and V–O bonds, verifies successful synthesis, identifies residual organic groups, and guides effective surface functionalization, crucial for enhancing biocompatibility and ensuring nanoparticle stability in biological environments [24].

UV-Visible Spectroscopy (UV-Vis): UV-Vis spectroscopy characterizes the optical properties, including absorption bands, optical band gap energies, and photocatalytic capabilities. The band gap energy, typically between 2.4–2.7 eV for BiVO₄, directly relates to visible-light absorption efficiency, influencing phototherapy effectiveness (photothermal and photodynamic therapies) and diagnostic imaging capabilities [25].

Dynamic Light Scattering (DLS) and Zeta Potential Analysis: Dynamic light scattering is essential for measuring nanoparticle hydrodynamic size distribution in suspension, critical for assessing colloidal stability and particle behavior in biological fluids. Zeta potential measurements determine surface charge, which affects nanoparticle dispersion stability, cellular uptake efficiency, and interaction with biomolecules, essential in therapeutic and diagnostic applications [26].

Raman Spectroscopy: Raman spectroscopy provides complementary structural information through vibrational modes, particularly valuable for confirming crystal structures, detecting defects, and ensuring phase purity. Such information helps optimize optical and photocatalytic properties for targeted biomedical use [27].

Thermogravimetric Analysis (TGA): TGA evaluates nanoparticle thermal stability and surface functionalization efficiency by monitoring weight changes during controlled heating. This is particularly useful in confirming the successful attachment of biological or therapeutic molecules to the nanoparticle surface, which is critical for biomedical efficacy [28].

Biomedical Applications

Bioimaging

Medical imaging technologies have significantly advanced diagnostics, therapy monitoring, and understanding biological mechanisms at the cellular and molecular scales. Traditional imaging agents, such as organic dyes and quantum dots, frequently suffer from limitations including poor photostability, cytotoxicity, limited penetration depth, and rapid photobleaching, constraining their clinical utility [29]. Recent progress in nanoparticle-based technologies has paved the way for multifunctional imaging probes. Bismuth vanadate (BiVO₄) nanoparticles, in particular, exhibit exceptional promise for bioimaging applications due to their unique optical properties, high biocompatibility, and versatile imaging functionalities [2]. BiVO₄

nanoparticles demonstrate remarkable optical attributes due to their narrow band gap (approximately 2.4–2.7 eV), facilitating strong absorption in the visible to near-infrared (NIR) range. This efficient optical absorption allows deeper tissue penetration and enhanced contrast in imaging biological tissues compared to traditional agents. Moreover, these nanoparticles exhibit superior photostability, which is crucial for maintaining imaging signal quality over extended periods. Such optical robustness ensures reliable and accurate imaging results, making BiVO₄ nanoparticles suitable for long-term monitoring of disease progression and therapeutic outcomes [30]. Fluorescence imaging is widely utilized in biomedical research for real-time visualization of biological processes owing to its high sensitivity and spatial resolution.

BiVO₄ nanoparticles either exhibit intrinsic fluorescence or can be easily conjugated with fluorescent dyes or molecules, providing clear visualization and precise tracking of cellular events, tumor tissues, or biomarkers. The nanoparticles can be further functionalized with targeting ligands such as antibodies, peptides, or aptamers, enabling specific imaging of pathological sites including tumors and inflammatory tissues [31]. Photoacoustic imaging, an innovative imaging modality combining optical excitation and ultrasonic detection, provides superior deep-tissue imaging capabilities compared to conventional fluorescence techniques. BiVO₄ nanoparticles are particularly effective in photoacoustic imaging due to their strong optical absorption and high photothermal conversion efficiency. Upon pulsed-laser excitation, absorbed optical energy generates acoustic waves detectable as high-resolution images. The intrinsic heavy-metal component, bismuth, significantly enhances image contrast, thereby improving the sensitivity and resolution of deep-tissue and tumor imaging [32]. Compared to conventional imaging agents, BiVO₄ nanoparticles offer numerous advantages, including enhanced biocompatibility, reduced cytotoxicity, and outstanding photostability. Unlike heavy-metal-based quantum dots, which are typically toxic (e.g., cadmium-based nanoparticles), BiVO₄ nanoparticles exhibit low toxicity, promoting safer clinical translation.

Additionally, their robust photostability circumvents rapid photobleaching issues characteristic of traditional fluorescent dyes, enabling continuous imaging over extended periods [33]. A distinctive advantage of BiVO₄ nanoparticles is their multimodal imaging potential. Due to their heavy-metal bismuth composition, they can simultaneously serve as agents for fluorescence, photoacoustic imaging, computed tomography (CT), and X-ray imaging, allowing integrated diagnostic approaches. Furthermore, their surface can be easily modified with various targeting molecules, therapeutic drugs, or functional imaging labels, enhancing their precision and efficacy in theranostic (therapeutic and diagnostic) applications [34]. Despite their impressive bioimaging potential, translating BiVO₄ nanoparticles to clinical settings involves addressing several challenges, such as comprehensive long-term biocompatibility studies, pharmacokinetics, standardized synthesis protocols, and regulatory considerations. Fur-

ther research is required to explore targeted functionalization strategies, optimize nanoparticle size and morphology, and deepen understanding of biological interactions. Integration of advanced imaging modalities with therapeutic capabilities, particularly in theranostics, represents an exciting future direction, potentially revolutionizing personalized medicine and diagnostic accuracy.

Photodynamic Therapy (PDT)

Photodynamic therapy (PDT) has emerged as a promising minimally invasive therapeutic approach, particularly effective for cancer treatment and microbial infections. It utilizes photosensitizing agents activated by specific wavelengths of light to generate cytotoxic reactive oxygen species (ROS), including singlet oxygen (1O_2), hydroxyl radicals ($\bullet OH$), and superoxide ions ($O_2^{\bullet -}$). These ROS subsequently induce oxidative damage to cellular components, such as proteins, lipids, and DNA, ultimately triggering cell apoptosis or necrosis. Recent research highlights the potential of bismuth vanadate ($BiVO_4$) nanoparticles as innovative photosensitizing agents due to their intrinsic photocatalytic properties and effective ROS generation capabilities under visible-light irradiation [35]. $BiVO_4$ nanoparticles act as efficient photosensitizers primarily because of their narrow band gap (around 2.4–2.7 eV), enabling strong visible-light absorption. Upon exposure to suitable irradiation, electron-hole pairs are generated, promoting electron transfer reactions with molecular oxygen or water molecules in the surrounding medium to produce highly reactive oxygen species. The photocatalytic mechanism involves valence band holes (h^+) and conduction band electrons (e^-), which effectively oxidize water or biomolecules, leading to the sustained production of cytotoxic ROS.

The high stability, excellent photostability, and effective electron-hole separation efficiency of $BiVO_4$ nanoparticles substantially enhance the PDT efficacy compared to traditional organic photosensitizers, which often suffer from rapid photobleaching, poor aqueous solubility, and reduced ROS production [36].

The phototoxicity of $BiVO_4$ nanoparticles can be further enhanced through strategic modifications such as doping, surface functionalization, and the formation of hybrid composites. Metal or non-metal doping (e.g., doping with lanthanides, silver, or carbon elements) optimizes band-gap energies, promotes charge separation efficiency, and thus significantly amplifies ROS generation. Similarly, surface functionalization with targeting ligands, antibodies, peptides, or other therapeutic molecules ensures selective accumulation at disease sites, enabling targeted PDT with reduced off-target toxicity. Additionally, combining $BiVO_4$ nanoparticles with other photosensitizers or nanomaterials (e.g., graphene oxide, gold nanoparticles, or carbon dots) creates synergistic effects, greatly improving their therapeutic efficiency and expanding their application potential [37]. Numerous *in vitro* and *in vivo* studies have demonstrated the promising potential of $BiVO_4$ nanoparticles in PDT. *In vitro* studies using various cancer cell lines, such as breast, lung, liver, and cervical cancer cells, consistently

show significant phototoxic effects upon irradiation with visible or near-infrared light, characterized by enhanced apoptosis and reduced cellular viability.

These studies highlight the dose-dependent cytotoxicity of $BiVO_4$ nanoparticles, emphasizing the importance of optimizing nanoparticle concentration, exposure time, and irradiation conditions. Furthermore, *in vivo* investigations, primarily conducted using mouse xenograft tumor models, revealed remarkable tumor regression, decreased tumor growth rates, and enhanced survival rates following PDT with $BiVO_4$ nanoparticles. These studies underscore not only the therapeutic effectiveness but also the nanoparticles' favorable biocompatibility, minimal systemic toxicity, and reduced adverse side effects, underscoring their clinical potential [38]. Despite these encouraging findings, the clinical translation of $BiVO_4$ nanoparticle-based PDT requires addressing critical challenges, including comprehensive safety evaluations, precise control of dosage and irradiation parameters, long-term biodistribution studies, and regulatory approvals. Future research should focus on optimizing synthesis strategies, improving specificity and targeted delivery, and exploring combination therapies integrating PDT with chemotherapy, immunotherapy, or photothermal therapy. Addressing these considerations will significantly enhance the effectiveness and clinical acceptance of $BiVO_4$ -based photodynamic therapies.

Antibacterial Applications

The emergence and spread of antibiotic-resistant bacteria present significant challenges to global public health, underscoring the urgent need for novel antimicrobial agents. Nanomaterials have attracted considerable attention in this regard due to their unique antibacterial mechanisms, which differ fundamentally from conventional antibiotics. Among emerging nanomaterials, Bismuth Vanadate ($BiVO_4$) nanoparticles have demonstrated notable antibacterial properties attributed primarily to their robust photocatalytic activity and effective generation of reactive oxygen species (ROS) [39]. The antibacterial mechanisms of $BiVO_4$ nanoparticles involve multiple pathways, primarily through the photocatalytic generation of reactive oxygen species, including hydroxyl radicals ($\bullet OH$), superoxide ions ($O_2^{\bullet -}$), and singlet oxygen (1O_2), upon visible-light irradiation. These ROS exhibit strong oxidative potentials capable of disrupting bacterial cell membranes, oxidizing essential biomolecules such as DNA, proteins, and lipids, and ultimately inducing bacterial cell death. Additionally, $BiVO_4$ nanoparticles may cause physical disruptions to bacterial cells due to their nanoscale size and surface interactions, facilitating enhanced uptake and intracellular damage, further amplifying their antibacterial effects [40].

$BiVO_4$ nanoparticles exhibit considerable efficacy against various pathogenic bacteria, including drug-resistant strains such as Methicillin-resistant *Staphylococcus aureus* (MRSA), multidrug-resistant (MDR) *Escherichia coli*, and *Pseudomonas aeruginosa*. *In vitro* studies have demonstrated significant reductions in bacterial viability under

visible or near-infrared light irradiation, illustrating their potential as an alternative or adjunctive approach to traditional antibiotics. These studies highlight not only the broad-spectrum antibacterial activity but also the ability to mitigate the rapid development of bacterial resistance due to the multi-target oxidative stress mechanisms involved [41]. Furthermore, BiVO₄ nanoparticles show promising potential in wound healing applications. Chronic and infected wounds, particularly those complicated by antibiotic-resistant bacteria, represent significant clinical challenges. BiVO₄ nanoparticles have been explored as topical antibacterial agents in wound dressings or as part of bioactive nanocomposite materials. Their capacity to generate ROS effectively under light irradiation can reduce bacterial load, suppress biofilm formation, and prevent infections, thereby accelerating wound healing processes. Additionally, these nanoparticles can stimulate tissue regeneration indirectly through ROS-mediated modulation of inflammatory responses and promoting the proliferation of skin cells, fibroblasts, and endothelial cells. Preliminary *in vivo* studies using animal wound models support these observations, indicating accelerated wound closure, reduced inflammation, and enhanced tissue regeneration when BiVO₄ nanoparticles are incorporated into wound dressings [42].

Despite these promising antibacterial properties, several challenges need addressing before clinical translation. Comprehensive evaluation of potential cytotoxicity to human cells, precise control of ROS generation to minimize off-target effects, and optimization of nanoparticle stability in physiological environments are necessary. Long-term biocompatibility, detailed pharmacokinetic analyses, and regulatory approval processes also remain crucial steps. Future research directions should include developing robust, targeted delivery systems, combining BiVO₄ nanoparticles with conventional antibiotics or antimicrobial peptides for synergistic efficacy, and designing smart nanoparticle-based antimicrobial platforms responsive to specific environmental triggers.

Cancer Therapeutics

Cancer remains one of the leading causes of mortality globally, demanding novel and effective therapeutic strategies. Nanotechnology has significantly expanded the potential for cancer treatment through innovative therapeutic approaches such as targeted drug delivery, photodynamic therapy (PDT), photothermal therapy (PTT), and combined therapy modalities. Among emerging nanomaterials, bismuth vanadate (BiVO₄) nanoparticles have demonstrated significant promise in cancer therapeutics, leveraging their unique physicochemical properties and versatile therapeutic potential [43]. Effective targeting of nanoparticles to tumor sites is crucial for enhanced therapeutic outcomes. BiVO₄ nanoparticles can be effectively modified with specific targeting ligands such as antibodies, peptides, folic acid, aptamers, or small molecules to facilitate selective accumulation in cancer cells expressing specific surface receptors. For instance, folic

acid-functionalized BiVO₄ nanoparticles efficiently target folate receptor-overexpressing cancer cells, increasing internalization and intracellular accumulation, thereby significantly enhancing therapeutic efficiency while minimizing toxicity to normal tissues [44].

Additionally, BiVO₄ nanoparticles leverage the enhanced permeability and retention (EPR) effect for passive tumor targeting. Tumor vasculature is characterized by abnormal structure, including leaky endothelial junctions and poor lymphatic drainage, facilitating passive nanoparticle accumulation in tumor tissues. The nanoscale dimensions of BiVO₄ particles enable effective extravasation through these defective tumor vessels, leading to increased local concentration and retention within tumors. Exploiting the EPR effect improves the selective delivery and concentration of therapeutic agents, enhancing anticancer efficacy while reducing off-target effects [45]. BiVO₄ nanoparticles have been increasingly utilized in combined therapeutic strategies, particularly integrating photodynamic therapy (PDT) with chemotherapy, thereby achieving synergistic anticancer effects. PDT involves light-activated generation of reactive oxygen species (ROS), which induce oxidative damage and apoptosis in cancer cells. BiVO₄ nanoparticles, with excellent visible-light absorption properties, effectively mediate PDT through robust ROS generation [46]. When combined with chemotherapeutic drugs such as doxorubicin, cisplatin, or paclitaxel, these nanoparticles can enhance chemotherapy efficacy by facilitating drug delivery, controlled release, and increasing sensitivity of cancer cells through oxidative stress-induced cell damage.

This dual therapeutic approach has been demonstrated in several preclinical studies to significantly improve treatment outcomes, reduce tumor volume, and inhibit tumor recurrence more effectively than single-modality treatments [47]. Preclinical *in vitro* and *in vivo* studies underscore the promising therapeutic potential of BiVO₄ nanoparticles. *In vitro* evaluations have demonstrated significant cytotoxicity toward various cancer cell lines, including breast, lung, colon, liver, and cervical cancer cells, especially when combining PDT and chemotherapy. *In vivo* studies, utilizing mouse xenograft models, have shown substantial tumor growth inhibition, tumor regression, and enhanced survival rates with minimal systemic toxicity. These findings validate the potential of BiVO₄ nanoparticles as a versatile cancer therapeutic platform, integrating multiple modalities for enhanced treatment efficacy [48]. However, translating BiVO₄ nanoparticles into clinical oncology practice requires addressing critical challenges. Comprehensive biocompatibility assessments, detailed pharmacokinetics, biodistribution studies, long-term safety evaluation, and precise dosage control are necessary. Additionally, developing standardized protocols for nanoparticle synthesis, optimization of targeting efficiency, and integration with existing clinical cancer therapies remain vital areas of future research. Exploring combination therapies with immunotherapy or radiotherapy might also expand therapeutic applications and enhance clinical efficacy.

Toxicity and Biocompatibility

The clinical translation of any nanomaterial-based biomedical application hinges on a thorough understanding of its toxicity profile and biocompatibility. While bismuth vanadate (BiVO_4) nanoparticles demonstrate promising diagnostic and therapeutic properties, ensuring their safety in biological systems is paramount. Evaluating cytotoxicity, *in vivo* responses, and compliance with regulatory frameworks is essential for their responsible and effective use in clinical settings [6]. Numerous cytotoxicity studies have been conducted to evaluate the interaction of BiVO_4 nanoparticles with various cell lines. *In vitro* assays such as MTT, LDH leakage, live/dead staining, and ROS generation tests have shown that BiVO_4 nanoparticles exhibit dose-dependent cytotoxicity. At lower concentrations (typically $<50 \mu\text{g/mL}$), the nanoparticles generally show minimal toxicity toward normal human cell lines, such as fibroblasts and epithelial cells. However, higher concentrations or prolonged exposure may induce oxidative stress, mitochondrial dysfunction, and membrane disruption due to excessive ROS production. Importantly, surface modification of BiVO_4 nanoparticles with biocompatible polymers (e.g., PEG, PVP, chitosan) or targeting ligands can significantly reduce non-specific toxicity, improving their overall safety profile. These findings indicate that controlled dosing, appropriate surface engineering, and delivery strategies are critical for minimizing cytotoxic effects [49].

In vivo studies using animal models provide crucial insights into the systemic behavior, organ distribution, metabolism, and clearance of BiVO_4 nanoparticles. Studies in mice and rats have demonstrated that intravenously or topically administered BiVO_4 nanoparticles generally exhibit favorable biocompatibility, with limited accumulation in major organs such as the liver, spleen, lungs, and kidneys. Histopathological examinations often reveal no significant tissue damage or inflammation at therapeutic doses. Additionally, blood chemistry, hematological analysis, and behavioral assessments typically show no acute toxicity. However, the long-term effects, including chronic exposure and biodegradation kinetics, remain insufficiently understood and warrant further investigation. The route of administration, particle size, surface charge, and aggregation tendencies are all factors that can influence toxicity and clearance behavior *in vivo* [50]. From a regulatory standpoint, BiVO_4 nanoparticles are still in the early stages of biomedical development, and no BiVO_4 -based formulations have yet received clinical approval. Regulatory agencies such as the U.S. Food and Drug Administration (FDA), European Medicines Agency (EMA), and ISO standards require comprehensive evaluation of nanomaterials' pharmacokinetics, immunogenicity, genotoxicity, and long-term safety before approval for clinical use.

This includes rigorous good manufacturing practice (GMP) compliance, detailed nanoparticle characterization, batch-to-batch consistency, and toxicological profiling under standardized protocols. Furthermore, potential environmental and ecological impacts of

BiVO_4 nanoparticle disposal must also be considered, especially given their metal oxide nature. In summary, while BiVO_4 nanoparticles demonstrate encouraging biocompatibility and relatively low toxicity under controlled conditions, their safe integration into clinical practice requires deeper and more standardized safety evaluations. Future research should focus on establishing detailed toxicological datasets, understanding long-term biological responses, and aligning development with international regulatory requirements. Addressing these aspects will be vital to unlocking the full potential of BiVO_4 nanoparticles in safe and effective biomedical applications.

Future Perspectives

The future of bismuth vanadate (BiVO_4) nanoparticles in biomedicine is promising but hinges on overcoming several scientific and translational barriers. With their unique optical, electronic, and catalytic properties, BiVO_4 -based systems have strong potential in areas such as photothermal therapy, photoacoustic imaging, and targeted drug delivery. Future research will likely concentrate on making these nanoparticles more intelligent, biocompatible, and multifunctional. One key direction is the development of stimuli-responsive BiVO_4 nanostructures—platforms that activate selectively under specific biological triggers such as pH, redox gradients, or enzymatic activity. This would enable more precise drug delivery and reduce systemic toxicity. Advances in materials engineering could also lead to biodegradable or renal-clearable BiVO_4 formulations, which would improve their safety profile and facilitate clinical translation. Another avenue lies in hybrid nanoplateforms, where BiVO_4 is combined with materials like gold, graphene oxide, or polymers to enhance properties like photothermal efficiency, drug loading capacity, or targeting specificity. These combinations open the door to multimodal theranostics, where diagnosis and treatment are integrated into a single, compact system.

The integration of machine learning and AI is also expected to influence the design and optimization of BiVO_4 nanoparticles. Predictive modeling of particle-biological interactions could accelerate the development of safer and more effective formulations by reducing trial-and-error experimentation. From a clinical perspective, future success will depend on meeting regulatory standards and establishing standardized protocols for synthesis, functionalization, and safety assessment. Interdisciplinary collaboration—linking materials science, biomedicine, pharmacology, and clinical research—will be essential for translating laboratory findings into real-world medical solutions. In the long term, BiVO_4 nanoparticles could be part of next-generation precision medicine tools, offering targeted, image-guided, and minimally invasive therapies tailored to individual patients. As fabrication techniques mature and biological understanding deepens, these nanoparticles may transition from experimental tools to clinical mainstays.

Conclusion

Bismuth vanadate (BiVO_4) nanoparticles have emerged as a promising class of nanomaterials with versatile applications in biomedicine, particularly in imaging, therapy, and drug delivery. Recent advancements have demonstrated their ability to serve as photothermal agents, photoacoustic contrast enhancers, and multifunctional theranostic platforms. Modifications in particle synthesis, surface engineering, and hybridization with other nanomaterials have significantly improved their performance and expanded their functional scope. The potential impact of BiVO_4 nanoparticles on healthcare is considerable. Their unique physicochemical properties, combined with tunable biocompatibility, make them strong candidates for non-invasive, targeted, and image-guided therapies. If translated successfully, these nanomaterials could contribute to more accurate diagnostics, personalized treatment regimens, and reduced side effects—addressing critical gaps in current clinical practice. Looking ahead, the focus must shift toward addressing key translational challenges such as long-term safety, standardization, and regulatory approval. With continued interdisciplinary collaboration and innovation, BiVO_4 nanoparticles are well-positioned to become a key component of next-generation biomedical technologies. The coming years are likely to bring new breakthroughs in their design and application, pushing the field closer to clinical realization.

Authors' Contributions

1. Ihsan Ullah – Conceptualization, literature review, and initial drafting of the manuscript.
2. Mustafa Kamal – Conceptualization, literature review, and initial drafting of the manuscript.
3. Habib un Nabi – Conceptualization, literature review, and initial drafting of the manuscript.
4. Adnan Khan – Data analysis and organization related to biomedical applications.
5. Sayyad Fayaz Ahmad Shah – Data analysis and organization related to biomedical applications.
6. Subhan Ali – Critical revisions and refinement of scientific content.
7. Muhammad Ghayoor – Critical revisions and refinement of scientific content.
8. Misbah Gul – Formatting, reference management, and proofreading.

Hangqing Huang – Supervision, overall guidance, and final manuscript approval.

References

1. Shrivastava Siddhartha, Dash Debabrata (2009) Applying nanotechnology to human health: revolution in biomedical sciences. pp. 184702.
2. Fidelia Lalrindiki, N Premjit Singh, N Mohondas Singh (2024) A review of synthesis, photocatalytic, photoluminescence and antibacterial properties of bismuth vanadate-based nanomaterial. pp. 112846.
3. Mansoor Jamal, Gul Asimullah Khan Nabi, Hao Sun, Khair Ullah, Osama Ali Khattak, et al. (2024) Preparation of manganese-doped bismuth oxide for the photocatalytic degradation of methylene blue. p. 1-7.
4. Dabodabo DJG, CJH Solidor (2025) Metal Oxide Nanoparticles for Various Applications, in Carrageenan-Mediated Green Synthesis of Metal Oxide Nanoparticles for Various Applications. CRC Press, p. 71-88.
5. Ahmad A, M Imran, NJP Sharma (2022) Precision nanotoxicology in drug development: current trends and challenges in safety and toxicity implications of customized multifunctional nanocarriers for drug-delivery applications. 14(11):2463.
6. Mohammad-Ali Shahbazi, Leila Faghfour, Mónica PA Ferreira, Patrícia Figueiredo, Hajar Maleki, et al. (2020) The versatile biomedical applications of bismuth-based nanoparticles and composites: therapeutic, diagnostic, biosensing, and regenerative properties. 49(4): 1253-1321.
7. Magdalena Jurczyk, Katarzyna Jelonek, Monika Musiał-Kulik, Artur Beberok, Dorota Wrześniok, et al. (2021) Single-versus dual-targeted nanoparticles with folic acid and biotin for anticancer drug delivery 13(3): 326.
8. Thi Thuy Truong, Sudip Mondal, Vu Hoang Minh Doan, Soonhyuk Tak, Jaeyeop Choi, et al. (2024) Precision-engineered metal and metal-oxide nanoparticles for biomedical imaging and healthcare applications. 332: 103263.
9. Restuccia N (2018) Biocompatible Nanoparticles: Synthesis, Analysis and Applications in Biological and Medical fields.
10. Omar M Khubiev, Anton R Egorov, Anatoly A Kirichuk, Victor N Khrustalev, Alexander G Tskhovrebov, et al. (2023) Chitosan-based antibacterial films for biomedical and food applications 24(13): 10738.
11. Zheng Zesen, Huihui Zhang, Jiaxin Yang, Xiaoyang Liu, Lianglong Chen, et al. (2025) Recent advances in structural and functional design of electrospun nanofibers for wound healing.
12. Jun Dong, Zonghua Wang, Fangfang Yang, Huiqi Wang, Xuejun Cui, et al. (2022) Update of ultrasound-assembling fabrication and biomedical applications for heterogeneous polymer composites 305: 102683.
13. Ali MA, D Islam (2019) Surface Modification and Bioconjugation of Nanoparticles for MRI Technology. pp. 405-430.
14. Hajar Q Alijani, Siavash Iravani, Rajender S Varma (2022) Bismuth vanadate (BiVO_4) nanostructures: eco-friendly synthesis and their photocatalytic applications. 13(1):59.
15. Muhammad Khan, Xiaohui Sun, Muhammad Kashif, Amir Zada, Shohreh Azizi, et al. (2025) Exploration of bismuth-based nanomaterials: From fundamental concepts to innovative synthesis techniques and emerging applications. 538: 216687.
16. J P Deebasree, V Maheskumar, B Vidhya (2018) Investigation of the visible light photocatalytic activity of BiVO_4 prepared by sol gel method assisted by ultrasonication. 45:123-132.
17. Misbah Gul, Muhammad Kashif, Sheraz Muhammad, Shohreh Azizi, Hao Sun (2025) Various Methods of Synthesis and Applications of Gold-Based Nanomaterials: A Detailed Review. 25(7): 2227-2266.

18. Misbah Gul, Muhammad Kashif, Kashif Shahid, Natasha (2024) Eco-friendly approaches in the synthesis of ZnO nanoparticles using plant extract: A review. 3(2): 1-25.
19. Jalal Amir, Sheraz Muhammad, Muhammad Kashif, Azmat Ali Khan, Misbah Gul, et al. (2025) Synthesis, characterization and dielectric properties evaluation of NiO-CO₃O₄ nanocomposite. 22(1): 63-72.
20. Muffarih Shah, Abdul Hameed, Muhammad Kashif, Noor Majeed, Javariya Muhammad, et al. (2024) Advances in agar-based composites: a comprehensive review. 346: 122619.
21. Kevin W Powers, Maria Palazuelos, Brij M Moudgil, Stephen M Roberts (2007) Characterization of the size, shape, and state of dispersion of nanoparticles for toxicological studies. 1(1): 42-51.
22. JE Castle, PA Zhdan (1997) Characterization of surface topography by SEM and SFM: problems and solutions. 30(5): 722.
23. M Ganeshbabu, N Kannan, P Sundara Venkatesh, G Paulraj, K Jeganathan, et al. (2020) Synthesis and characterization of BiVO₄ nanoparticles for environmental applications. 10(31): 18315-18322.
24. Bin Zhang, Bing Yan (2010) Analytical strategies for characterizing the surface chemistry of nanoparticles. 396(3): 973-982.
25. B Reza Peymanfar, Mona Yektaei, Shahrzad Javanshir, Elnaz Selseleh-Zakerin (2020) Regulating the energy band-gap, UV-Vis light absorption, electrical conductivity, microwave absorption, and electromagnetic shielding effectiveness by modulating doping agent. 209:122981.
26. Jesus Rodriguez-Loya, Maricarmen Lerma, Jorge L Gardea-Torresdey (2023) Dynamic light scattering and its application to control nanoparticle aggregation in colloidal systems: A review 15(1): 24.
27. Schrader B (2008) Infrared and Raman spectroscopy: methods and applications. John Wiley & Sons.
28. Flip Kunc, Mary Gallerneault, Olton Kodra, Andreas Brinkmann, Gregory P Lopinski, et al. (2022) Surface chemistry of metal oxide nanoparticles: NMR and TGA quantification. 414(15):4409-4425.
29. Fijehangir Shah, Hao Sun, Zijun Qiao, Talha Sharif, Misbah Gul (2024) Enhanced degradation of methylene blue dye using hydrothermally synthesized Nickel-doped Strontium oxide catalysts. 3(12): 13-27.
30. Ajmal Shah, Adnan, Talha Sharif, Muhammad Majid Khan, Zain ul Abidin, et al. (2024) Photocatalytic Degradation of Methyl Violet and Auramine-O Dyes Using Ni/ZnO Nanocomposites for An Environmental Solution for Dye Wastewater. 3(1):1-11.
31. Drummen GPJM (2012) Fluorescent probes and fluorescence (microscopy) techniques-illuminating biological and biomedical research. 17(12):14067-14090.
32. Pavan Mohan Neelamraju, Karthikay Gundepudi, Pradyut Kumar Sanki, Kumar Babu Busi, Tapan Kumar Mistri, et al. (2024) Potential applications for photoacoustic imaging using functional nanoparticles: A comprehensive overview. 10(15): e34654.
33. Ze Wang, Guan Wang, Tingting Kang, Shuwei Liu, Lu Wang, et al. (2021) BiVO₄/Fe₃O₄@ polydopamine superparticles for tumor multimodal imaging and synergistic therapy. 19: 1-11.
34. Shan Jiang, Yihang Zhang, Jianyu Gong (2024) Applications of bismuth-based nanoparticles for the removal of pollutants in wastewater: a review.
35. Sandile Phinda Songca (2023) Combinations of photodynamic therapy with other minimally invasive therapeutic technologies against cancer and microbial infections. 24(13): 10875.
36. Patial B (2024) BiVO₄-based heterojunction nanophotocatalysts for water splitting and organic pollutant degradation: a comprehensive review of photocatalytic innovation 44(4): 495-519.
37. T Jiteshwaran, BJanani, Asad Syed, Abdallah M Elgorban, Islem Abid, et al. (2024) Interfacial engineering of BiVO₄/PANI pn heterojunction for enhanced photocatalytic degradation of p-nitrophenol: Pathway, toxicity evaluation and mechanistic insights. 49: 104361.
38. Zhuang Yang, Meng Yuan, Bin Liu, Wenying Zhang, Aziz Maleki, et al. (2022) Conferring BiVO₄ nanorods with oxygen vacancies to realize enhanced sonodynamic cancer therapy. 61(44): e202209484.
39. Duygu Takanoglu Bulut (2025) Exploring the dual role of BiVO₄ nanoparticles: unveiling enhanced antimicrobial efficacy and photocatalytic performance, p. 1-25.
40. Chhabilal Regmi, Dipesh Dhakal, Soo Wahn Lee (2018) Visible-light-induced Ag/BiVO₄ semiconductor with enhanced photocatalytic and antibacterial performance. 29(6):064001.
41. Farhad Moradi, Arshin Ghaedi, Zahra Fooladfar, Aida Bazrgar (2023) Recent advance on nanoparticles or nanomaterials with anti-multidrug resistant bacteria and anti-bacterial biofilm properties: A systematic review. 9(11).
42. Jiaqi Zhao, Tianjiao Li, Yajuan Yue, Xina Li, Zhongjian Xie, et al. (2024) Advancements in employing two-dimensional nanomaterials for enhancing skin wound healing: a review of current practice. 22(1): 520.
43. Haoran Yin, Menghan Huang, Lixia Wang, Sheraz Muhammad, Tayirjan Taylor Isimjan, et al. (2025) Lattice-mismatched MOF-on-MOF nanosheets with rich oxygen vacancies show fast oxygen evolution kinetics for large-current water splitting. pp. 125105.
44. Sheraz Muhammad, Lixia Wang, Zhiyang Huang, Aling Zhou, Hazrat Bilal, et al. (2025) Recent advances in lanthanide-based materials for oxygen evolution reaction: Challenges and future prospects. 534: 216573.
45. Shan Yang, Chen Chen, Yue Qiu, Cheng Xu, Jing Yao (2021) Paying attention to tumor blood vessels: cancer phototherapy assisted with nano delivery strategies 268: 120562.
46. Gul M (2024) Synthesis and Evaluation of Some Novel 1, 3-Dimethylbarbituric Acid Derivatives as Potent Anti-Urease Agents: Comprehension through *In Vitro*, Molecular Docking, and DFT Investigations 50(5): 1609-1626.
47. Jianing Yi, Luyao Liu, Wenjie Gao, Jie Zeng, Yongzhi Chen, et al. (2024) Advances and perspectives in phototherapy-based combination therapy for cancer treatment.
48. Ranil Vikraman Kumarasamy, Jeane Rebecca Roy, Prabhu Manickam Natarajan, Monica Mironescu, Chella Perumal Palanisamy, et al. (2024) Clinical applications and therapeutic potentials of advanced nanoparticles: A comprehensive review on completed human clinical trials. 6: 1479993.
49. C Mallikarjunaswamy, S Pramila, G Nagaraju, Ramith Ramu, V Lakshmi Ranganatha (2021) Green synthesis and evaluation of antiangiogenic, photocatalytic, and electrochemical activities of BiVO₄ nanoparticles. 32(10): 14028-14046.
50. Samireh Badrigilan, Fatemeh Heydarpanahi, Jalal Choupani, Mehdi Jaymand, Hadi Samadian, et al. (2020) A review on the biodistribution, pharmacokinetics and toxicity of bismuth-based nanomaterials. 15: 7079-7096.

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