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Recent advances in the synthesis of $BiFeO_3$ composites as photocatalysis: challenges and opportunities

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A B S T R A C T

Bismuth ferrite ($BiFeO_3$) is a widely studied multiferroic material with strong ferroelectric and magnetic properties, making it highly suitable for applications in sensors, actuators, and energy storage. The development of $BiFeO_3$ composites has gained significant attention due to their enhanced functional properties compared to pure $BiFeO_3$. Various synthesis techniques, including sol-gel processing, hydrothermal synthesis, and solid-state reactions, have been explored to optimize structural, electrical, and magnetic characteristics. The review also explores the applications of $BiFeO_3$ composites as photocatalysis, highlighting recent breakthroughs and potential future directions. This overview provides insights into the current state of $BiFeO_3$ composite synthesis and its implications for advancing multiferroic materials in modern technology.

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1. Introduction

Bismuth ferrite ($BiFeO_3$) is a prominent multiferroic material known for its unique combination of ferroelectric and magnetic properties, making it suitable for various applications, including sensors, actuators, and energy storage devices [1, 2]. The synthesis of $BiFeO_3$ composites has garnered significant attention due to their enhanced functional properties compared to pure $BiFeO_3$ [3, 4]. Recent studies highlight the potential of composite structures to improve the material's performance by optimizing the interface between different phases, leading to better magnetoelectric coupling and overall functionality [5-7] .

The importance of $BiFeO_3$ composites lies in their ability to exhibit superior properties through the integration of various materials. For instance, composites formed with materials like $Bi_4Ti_3O_{12}$ have shown promising results in achieving enhanced multiferroic responses due to the compatibility of their crystal structures, which allows for effective coupling at the interface [2]. Furthermore, advancements in synthesis techniques such as sol-gel methods and hydrothermal synthesis has facilitated the production of high-quality $BiFeO_3$ composites with tailored [8].

The synthesis process plays a critical role in determining the physical and chemical properties of $BiFeO_3$ composites [9]. Variations in synthesis methods can lead to differences in microstructure, phase purity, and crystallinity, all of which significantly influence the material's performance. For example, thin film processing techniques have been shown to enhance the remanent polarization and magnetization of $BiFeO_3$ due to strain effects introduced by substrate interactions during growth [10, 11]. Moreover, doping strategies during synthesis can further modify the electrical and magnetic characteristics of $BiFeO_3$ composites. The incorporation of dopants such as samarium has been reported to enhance the multiferroic response by improving the alignment of magnetic moments [12, 13] .Consequently, understanding and optimizing the synthesis conditions is essential for developing $BiFeO_3$ composites with desired properties for specific applications [14, 15]. The ongoing research into $BiFeO_3$ composites emphasizes the significance of synthesis techniques in tailoring material properties, which is crucial for advancing their practical applications in modern technology [16]. This review aims to synthesize recent

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findings regarding the synthesis methods, application, challenges, and opportunities associated with $BiFeO_3$ composites.

2. Synthesis Methods of $BiFeO_3$ Composites

$BiFeO_3$ composites are of significant interest due to their unique multiferroic properties, which combine ferroelectricity and magnetism [9, 17]. The synthesis of these composites can be achieved through various methods, each offering distinct advantages and challenges. This review discusses the prominent synthesis methods for $BiFeO_3$ composites, reported recent advancements, and the implications of these techniques. Fig.1 illustrates a type of methods for the synthesis of $BiFeO_3$.

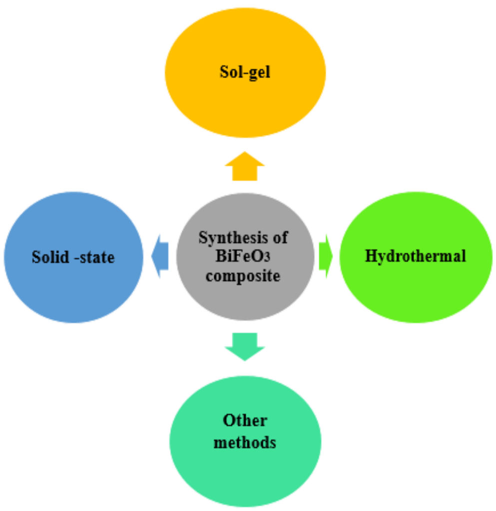

Fig. 1. Methods of synthesis of $BiFeO_3$ composite.

2.1. Sol-Gel Method

The sol-gel method has emerged as a prominent technique for synthesizing bismuth ferrite composites, particularly due to its ability to produce materials with high purity and uniformity at relatively low temperatures [18, 19]. The sol-gel process involves the transition of a solution (sol) into a solid (gel) phase, which is then subjected to heat treatment to achieve crystallization.

Fig. 2 displays the FESEM micrographs of the $BiFeO_3$ - $GdFeO_3$ nanocomposites. The white granular particles, visible among the $BiFeO_3$, represent $GdFeO_3$, while the quasi-spherical shapes indicate the presence of $BiFeO_3$ in the nanohybrid structure. The coexistence of these hybrid phases within the same field of view confirms the successful synthesis of $BiFeO_3$ - $GdFeO_3$ nanohybrids via the sol-gel method [20]. The primary advantage of this method lies in its ability to control the stoichiometry and morphology of the resulting materials. As shown in Fig. 3, pure $BiFeO_3$ (BFO) and $BiFe_{1-x}Co_xO_3$ (BFC_xO, where x = 0.01, 0.03, 0.05, 0.07, and 0.10) composite thin films were fabricated on Si substrates using the sol-gel technique. High-purity bismuth nitrate, ferric nitrate, and cobalt (II) nitrate hexahydrate were used as starting materials, mixed with ethylene glycol to create a homogeneous precursor solution of 0.2 mol/L after aging for 24 hours. This solution was applied to an impurity-free silicon substrate via spin-casting, which involved two steps: spinning at 500 rpm for 3 seconds and then at 4000 rpm for 20 seconds.

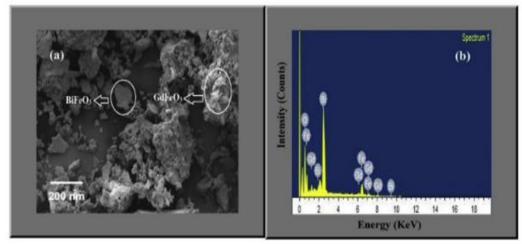

Fig. 2. FESEM micrographs of the $BiFeO_3$ - $GdFeO_3$ nanocomposites via the sol-gel method [20].

The wet films were pre-annealed at 350 °C for 6 minutes, and this process was repeated to achieve a semi-finished film of moderate thickness. Finally, the samples were crystallized in air at 500 °C for 1 hour and cooled to room temperature to obtain high-quality thin films [21]. Moreover, William et al. [22] emphasized that the sol-gel method allows for a uniform distribution of nanosized particles, which is critical for achieving the desired multiferroic properties of $BiFeO_3$. Moreover, the synthesis temperature can be significantly lower than that required for conventional solid-state methods, typically ranging from 300°C to 500°C [23]. This reduction in temperature not only saves energy but also minimizes the risk of secondary phase formation, which can compromise the material's properties [15]. In the sol-gel synthesis of $BiFeO_3$, various precursors such as bismuth nitrate and iron nitrate are commonly used. The choice of solvent and the presence of complexing agents can significantly influence the final product's characteristics. For example, Liu et al. [24] demonstrated that using polyvinyl alcohol (PVA) as a stabilizing agent during the sol-gel process resulted in improved crystallinity and reduced impurity levels in the synthesized $BiFeO_3$. Similarly, the incorporation of chelating agents like glycine has been shown to enhance the purity and phase homogeneity of $BiFeO_3$, as reported by Wahba et al. [25]. The properties of $BiFeO_3$ synthesized via the sol-gel method are often superior to those produced by other techniques. For instance, Yi et al. [26] highlighted that sol-gel-derived $BiFeO_3$ films exhibit outstanding ferroelectric properties, with large polarization values that are crucial for applications in memory devices and sensors. Additionally, the ability to tailor the microstructure through sol-gel processing allows for the optimization of electrical and magnetic properties, making it a versatile approach for developing advanced materials. However, challenges remain in achieving phase-pure $BiFeO_3$, as secondary phases such as bismuth oxide can form during the synthesis and subsequent calcination processes [27]. Zhang et al. [28] noted that careful control of the synthesis parameters, including temperature and precursor concentrations, is essential to mitigate these issues and enhance the purity of the final product.

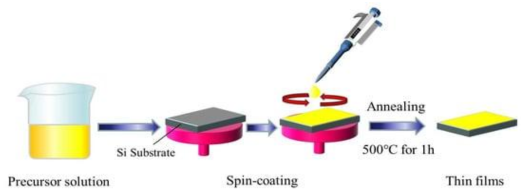

Fig. 3. A thin film preparation process for pure $BiFeO_3$ (BFO) and $BiFe_{1-x}Co_xO_3$ composites [21].

2.2. Hydrothermal Synthesis

Hydrothermal synthesis is a versatile method that allows for the controlled fabrication of $BiFeO_3$ with desired morphologies and sizes. The process typically involves the reaction of bismuth and iron precursors in an aqueous solution at elevated temperatures and pressures [11, 29] . For instance, Chen et al. [30] demonstrated that the use of a soul-gel-hydrothermal method could yield bismuth ferrite microcrystals at low temperatures, emphasizing the importance of optimizing precursor concentrations to achieve pure-phase $BiFeO_3$. Similarly, Li et al. [31] highlighted the role of polyethylene glycol (PEG) in controlling the morphology of $BiFeO_3$ microcrystals, resulting in uniform structures beneficial for various applications. The ability to manipulate the synthesis parameters, such as temperature and precursor concentration, is crucial for tailoring the properties of $BiFeO_3$ composites.

The structural integrity and phase purity of $BiFeO_3$ synthesized via hydrothermal methods have been extensively characterized. For example, Sun et al. [32] reported that $BiFeO_3$ nanoflakes produced through hydrothermal synthesis exhibited sharp X-ray diffraction (XRD) peaks corresponding to the pure phase of $BiFeO_3$, confirming the effectiveness of the hydrothermal method in achieving high crystallinity. Furthermore, the introduction of external factors, such as magnetic fields during synthesis, has been shown to influence the morphology and magnetic properties of $BiFeO_3$, leading to enhanced performance in applications such as magnetic sensors [33]. This highlights the potential of hydrothermal synthesis not only for producing high-quality materials but also for engineering their properties through external conditions. The photocatalytic properties of $BiFeO_3$ composites have also been a focal point of research. The incorporation of materials such as graphene or gold nanoparticles into $BiFeO_3$ has been explored to enhance its photocatalytic efficiency. For instance, Dai et al. [34] successfully synthesized $BiFeO_3$-graphene composites using hydrothermal methods, demonstrating improved photocatalytic activities due to the synergistic effects of the two materials. Additionally, the decoration of $BiFeO_3$ with Ag nanoparticles has been shown to retain its intrinsic magnetic properties while enhancing photocatalytic performance, making it a promising candidate for environmental remediation applications [35]. Abdalla S. Abdelhamid et al. [36] investigated the synthesis of a BiOF/$BiFeO_3$ hybrid heterojunction for photocatalytic applications. As shown in Fig.4 composite was synthesized hydrothermally and showed effective photocatalytic activity for the aerobic oxidation of benzylamine under simulated light. The results indicated a high conversion yield of approximately 80%, demonstrating the enhanced performance of the composite in this reaction.

2.3. Solid-State Reaction

The solid-state reaction method is one of the oldest techniques for synthesizing $BiFeO_3$ but often suffers from issues related to phase purity and particle size control [37, 38]. Recent studies have focused on optimizing various parameters to enhance the quality of $BiFeO_3$ synthesized via solid-state reactions [39, 40].

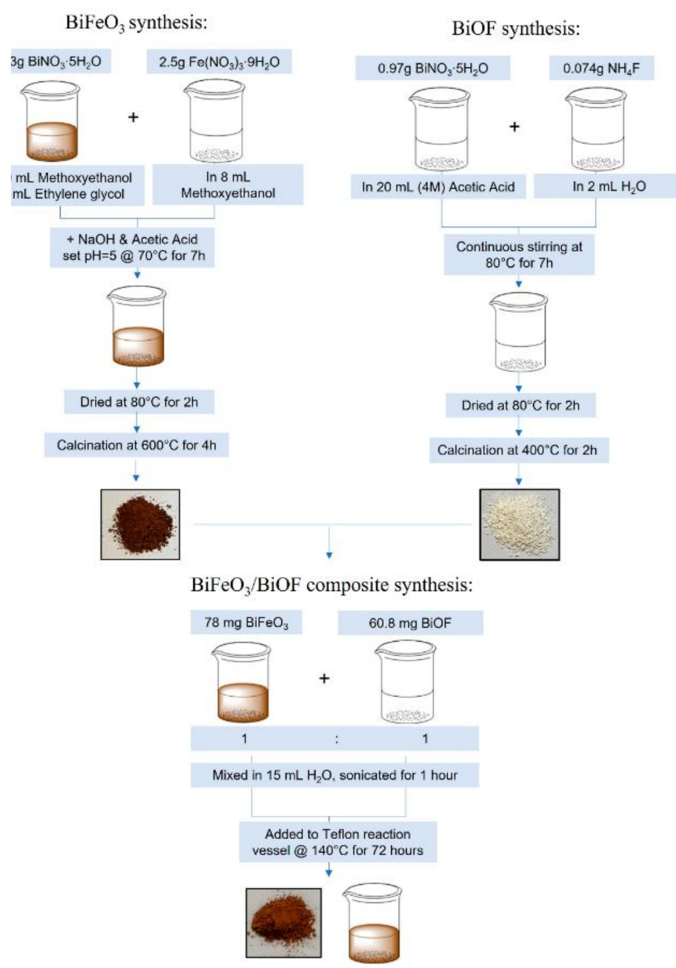

Fig. 4. Synthesizing $BiFeO_3$, BiOF, and BiOF/$BiFeO_3$ composite materials using hydrothermal methods [36].

The research by Tuluk et al. [37] indicates that adjusting calcination and sintering temperatures can significantly impact phase purity. For example, a study found that a calcination temperature of 750 °C followed by sintering at

775 °C produced high-density ceramics with minimal secondary phases. Incorporating mechanical activation before sintering has been shown to lower the formation temperature of the perovskite phase by approximately 100 °C. This approach enhances diffusion rates and promotes more uniform particle sizes, leading to improved magnetic and ferroelectric properties [41]. A novel technique called reaction flash-sintering has emerged as a promising alternative, allowing for rapid densification at lower temperatures. This method involves applying an electric field during sintering, which can lead to dense nanostructured polycrystals of $BiFeO_3$ in a matter of seconds [42].

2.4. Other Techniques for Synthesizing $BiFeO_3$ Composites

In addition to the more traditional methods such as solid-state reaction, sol-gel, and hydrothermal synthesis, several other innovative techniques have emerged for synthesizing $BiFeO_3$ composites. These methods often provide unique advantages in terms of control over morphology, particle size, and phase purity. Sonochemical synthesis is a technique that utilizes ultrasonic waves to promote chemical reactions in a solution [29]. This method has gained popularity for synthesizing $BiFeO_3$ composites due to its ability to enhance reaction kinetics and produce fine nanoparticles with controlled properties. In sonochemical synthesis, metal precursors (e.g., bismuth nitrate and iron nitrate) are dissolved in a solvent, typically water [43]. The solution is then subjected to ultrasonic irradiation, which generates cavitation bubbles that collapse violently, producing localized high temperatures and pressures. This environment facilitates the rapid formation of nanoparticles through nucleation and growth processes [44]. S. Das et al. [45] have reported for the first time that phase-pure $BiFeO_3$, synthesized via a sonochemical method, exhibits remarkable sensitivity in detecting low concentrations of SO_2, along with impressive response and recovery times. In contrast, $BiFeO_3$ produced through traditional precipitation methods, which do not involve sonication, contains impurity phases and fails to demonstrate similar SO_2 sensing capabilities.

3. Applications of $BiFeO_3$ Composites

$BiFeO_3$ composites are renowned for their unique combination of ferroelectric, magnetic, and optical properties. These characteristics make them suitable for a wide range of applications across various fields. The ability to tailor their properties through doping and composite formation enhances their functionality, leading to innovative uses in technology and industry [46, 47]. As one of the most promising technologies for environmental purification and solar energy conversion, semiconductor photocatalysis has gained considerable interest in recent years. Exploration of visible-light-driven photocatalysts is a hotspot of activity in the photocatalysis field [48]. Jiquan Li et al. [49] synthesized bismuth ferrite ($BiFeO_3$, BFO) submicron cubes and 3D BFO/graphene composites via a hydrothermal method. The 3D composites exhibited significantly enhanced photocatalytic activity, achieving a 92% degradation rate of methylene blue (MB) at a graphene oxide concentration of 3 mg/mL in 140 minutes. This improvement is due to their large specific surface area and 3D architecture, which enhance charge separation. The photocatalytic mechanism of the 3D BFO/graphene composite is illustrated in Fig. 5. Banoth et al. [50] explored the photocatalytic potential of $BiFeO_3$ (BFO)–Fe_2O_3 composites for the degradation of methylene blue (MB) dye under sunlight. Using a microwave-assisted co-precipitation method, they synthesized composites with different ratios of Fe_2O_3 (10%, 20%, and 30%) into $BiFeO_3$, named BFOF10, BFOF20, and BFOF30, respectively. This study revealed that the composites exhibited enhanced photocatalytic activity compared to pure $BiFeO_3$ due to improved visible light absorption and reduced electron-hole recombination. Notably, BFOF30 achieved a remarkable 94% degradation efficiency of MB under sunlight. This enhancement was attributed to the narrowed band gaps and improved microstructural characteristics, which facilitated efficient charge separation at the BFO–Fe_2O_3 interface. Additionally, the magnetic properties of the composites allowed for their easy recovery and reuse without structural degradation, as confirmed by XRD analysis post-photocatalysis [50]. Khikhlovskyi [51] highlighted that $BiFeO_3$ is one of the most promising multiferroic materials due to its coupled ferroelectric and antiferromagnetic properties at room temperature. They emphasized that while bulk $BiFeO_3$ exhibits weak magnetoelectric coupling, significant advancements have been made in thin-film heterostructures. These findings underscore the potential of nanoscale engineering in improving the functional properties of $BiFeO_3$ for advanced applications [52]. Heng Wu et al. [53] reviewed the fabrication and characterization of low-dimensional $BiFeO_3$ nanostructures, focusing on their unique properties and applications. They noted that nanostructured $BiFeO_3$ exhibits enhanced ferroelectricity, magnetism, and photocatalytic activity compared to its bulk counterpart. The review emphasized that controlling particle size and morphology through advanced synthesis techniques such as hydrothermal synthesis and sol-gel methods can significantly influence the material's performance in applications like energy harvesting, sensors, and environmental remediation. Similarly, Nan Wang et al. [54] discussed the structural performance and application potential of $BiFeO_3$ nanomaterials in their study. They highlighted that doping strategies and composite formation are effective approaches to enhance the photocatalytic efficiency and magnetic properties of $BiFeO_3$. The integration of $BiFeO_3$ with other materials in heterostructures has shown promise in improving charge separation and reducing recombination rates, making it suitable for applications in photocatalysis and spintronics. These studies collectively demonstrate that recent advances in synthesis methods, such as microwave-assisted co-precipitation and heterostructure engineering, have significantly enhanced the functional properties of $BiFeO_3$ composites.

These improvements open new avenues for other applications in energy harvesting, environmental remediation, and multifunctional devices. Recent literature highlights the versatility of $BiFeO_3$ due to its unique properties, which include a narrow band gap and strong photocatalytic activity under visible light irradiation. The efficiency of dye degradation is influenced by several factors, including the synthesis method, which can affect the structural and electronic properties of the photocatalyst [2, 14, 55, 56]. In this context, various synthesis techniques such as sol-gel [57], hydrothermal [11], and co-precipitation [58] methods have photocatalytic properties, making them more effective for environmental remediation applications. This review underscores the importance of optimizing synthesis methods to enhance the performance of $BiFeO_3$ composites in dye degradation, thereby contributing to advancements in photocatalytic technology for wastewater treatment.

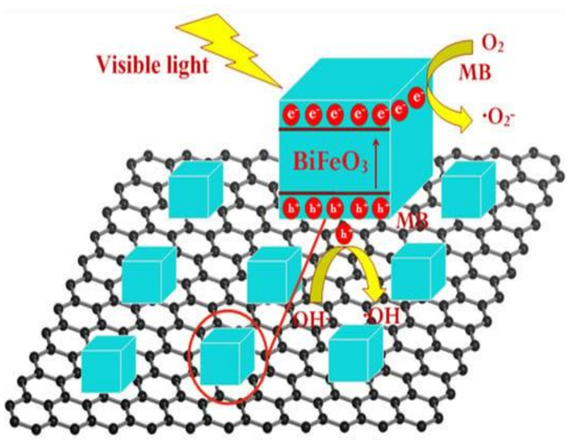

Fig. 5. A diagram of photocatalysis mechanism 3D BFO/graphene composite [49].

been employed to produce $BiFeO_3$ composites with enhanced photocatalytic performance. The comparative analysis presented in this study, as shown in Table 1, illustrates the differences in dye degradation rates among these composites. The results indicate that certain synthesis methods yield $BiFeO_3$ composites with superior

4. Future Directions for $BiFeO_3$ Composites

Recent progress in $BiFeO_3$ composites offers many opportunities for future research and development. Its unique multiferroic properties make $BiFeO_3$ a promising candidate for various technological applications. Research by Wang et al. emphasizes the significance of $BiFeO_3$-based heterostructures in advancing the material's properties and applications. Future studies should focus on optimizing the interfaces within these heterostructures to maximize performance in applications like data storage and energy conversion [11, 58].

The exploration of flexible substrates for $BiFeO_3$ thin films represents a promising direction for future research. Further research should investigate the mechanical properties and long-term stability of these flexible devices to ensure their viability in real-world applications such as wearable electronics and flexible sensors. Doping $BiFeO_3$ with various ions has shown the potential in improving its functional properties [59]. Wu et al.[53] highlighted that low-dimensional $BiFeO_3$ nanostructures exhibit size-dependent properties that can be further enhanced through strategic doping. Future work should explore a broader range of dopants and their effects on the electrical, magnetic, and optical properties of $BiFeO_3$ composites, aiming to tailor materials for specific applications.

Table 1

Comparative study of the dye degradation efficiencies of various $BiFeO_3$ composite photocatalyst with different synthesis.

Composite	Synthesis	Degradation Efficiency	Reaction condition	Dye used	Ref.
$BiFeO_3$/MOF	One-pot hydrothermal	48%	Visible light irradiation using a 300 W Xe lamp in a catalytic reactor at 20 °C	Methylene Blue (MB)	[60]
$BiFeO_3$/$GdFeO_3$	Sol-gel	56%	Natural sunlight and at atmospheric temperature/	Methylene Blue (MB)	[61]
$BiFeO_3$/ZnO	Hydrothermal method	-	Ultrasonic: 158 W, 40 kHz UV–vis light: 200–800 nm	RhB (11.2) MB (30.4) MO (19.3)	[62]
Bi_2S_3/$BiFeO_3$	Hydrothermal route	96%	under visible-light irradiation	Rhodamine B (RhB)	[63]

$BiFeO_3/ZnFe_2O_4$	Hydrothermal method.	-	under visible light irradiation	Tetracycline (1.63) and methylene blue (1.38)	[64]
$BiFeO_3$/CdS (9)/rGO	Hydrothermal method	96%,92%	visible light irradiation	Methylene Blue (MB) Methyl orange (MO)	[65]
$Ag/AgCl/Bi_2O_3/BiFeO_3$	Simple co-precipitation and sono-chemical	-	-	-	[66]
$BiFeO_3$/rGO	Sol-gel	98%	visible-light	Methylene Blue (MB)	[67]
$SnO_2/BiFeO_3$	Sol-gel synthesis	87.2% of RhB and 65.1% of 2,4-DCP	under the visible light irradiation,	2,4-DCP and RhB	[57]
$BiFeO_3 – TiO_2$	Hydrothermal	70%	under visible-light irradiation	-	[68]
$Bi_2O_3/BiFeO_3$ p-n	In-situ growth	Photodegradation rate was 8.7 and 5.4	under visible light irradiation	Tetracycline hydrochloride (TC)	[69]
$Ag_2S/BiFeO_3$	Precipitation method	~70% and ~84%	under Visible-Light Irradiation	Methyl orange (MO)	[70]
$BiFeO_3$-g-C_3N_4-WO_3 Z-scheme	wet chemical method	63%	visible light	2,4-DCP degradation	[55]
$Bi_2MoO_6/BiFeO_3$	Solvothermal process	82%, 98% and 93%	visible-light	Rhodamine B (RhB) and tetracycline hydrochloride (TC)	[56]
Z-scheme $Ag/FeTiO_3/Ag/BiFeO_3$	Sol-gel method	96.5%	under visible light irradiation	hydroxyl radicals (radical. OH), holes (h+) and superoxide radicals (radical .O2⁻)	[71]
$BiFeO_3$ /$CuBi_2O_4$ /BaTiO	The isoelectric point-assisted calcination method	93.5 %	V-vis and near-infrared (NIR) light,	Norfloxacin (NFX)	[72]

5. Conclusion

Recent advances in synthesizing $BiFeO_3$ composites highlight challenges and opportunities in this field. While issues related to phase purity, microstructural control, and scalability persist, innovative approaches such as doping strategies, heterostructure, and advanced characterization techniques offer pathways toward enhancing material performance. Continued research will be essential for unlocking the full potential of $BiFeO_3$ composites in various technological applications.

Author's contribution

Marzieh fattahi: Writing – original draft, Validation, Writing– review & editing, Methodology, Investigation.

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Declaration of competing interest

The author has no conflicts of interest to disclose.

Data availability

No data was used for the research described in the article.

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