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# A Review On Sol-Gel Production Of Unmodified And Lanthanum-Modified BiFeO3 Nanomaterials And Photoelectrochemical Studies Of Hydrogen Evolution

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$BiFeO_3$ (bismuth ferrite) is a promising visible-light-responsive photocatalyst used in photoelectrochemical (PEC) hydrogen production due to its narrow band gap, good chemical stability and multiferroic properties. The synthesis, structural, surface morphology, and photoelectrochemical performance of pure and lanthanum-doped $BiFeO_3$ nanomaterials prepared using the sol - gel method are discussed. The sol-gel method has a number of benefits, such as low processing temperature, good compositional control, high purity, and uniform distribution of particles, which makes it an appropriate method to produce doped perovskite nanomaterials. The formation of the $BiFeO_3$ phase with higher crystallinity following the incorporation of lanthanum and the significant decrease in the number of impurity phases in the doped samples were confirmed by X-ray diffraction studies. The observation under scanning electron microscopy showed that there were morphological changes that could be noticed as La-doped $BiFeO_3$ showed more uniform and less agglomerated particles than pure $BiFeO_3$. These structural and morphological changes helped to increase charge separation and decrease electron-hole recombination. Photoelectrochemical investigations revealed that lanthanum-doped $BiFeO_3$ exhibited better photocurrent density and increased hydrogen evolution during irradiation by visible light. This enhanced performance is largely due to an increase in crystallinity, increase in charge transport and reduction of impurity phases. This review has demonstrated the promise of La-modified $BiFeO_3$ nanomaterials as efficient photoanodes in the future of sustainable solar-driven hydrogen production as well as future applications of clean energy.

**Keywords:** Bismuth Ferrite ($BiFeO_3$), nanomaterials, Photocatalysis, X-ray diffraction (XRD), Scanning electron microscopy (SEM)

## 1.Introduction

One of the world's most plentiful and long-term energy sources is solar power. Renewable and clean energy technology development has risen to the forefront as a world priority in response to the ever-increasing environmental concerns and the relentless depletion of fossil fuels. Solar power stands out among renewable energy options due to its infinite supply, low environmental impact, and broad availability. Creating chemical energy from solar radiation and storing it as hydrogen fuel is an encouraging strategy for harnessing solar power. The high energy density and few byproducts of hydrogen's combustion make it a promising candidate for use as a clean energy carrier. Hence, there has been a lot of focus in recent years on finding effective ways to produce hydrogen using solar energy. One major method for directly converting solar energy into hydrogen is photoelectrochemical (PEC) water splitting, which uses semiconductor materials to break water molecules into hydrogen and oxygen.[1]

The water splitting process is driven by semiconductor photocatalysts, which absorb solar light and produce electron-hole pairs. This makes them an essential component of photoelectrochemical systems. On the other hand, the photoelectrode materials' optical and electrical characteristics heavily impact the PEC hydrogen generation efficiency. A photocatalyst that meets all of the criteria would be very stable in water, have an appropriate band gap for visible light absorption, efficiently separate charges, and have low rates of recombination of photogenerated charge carriers. For PEC water splitting, many semiconductor materials have been studied as potential photocatalysts. Because of its resistance to photocorrosion, cheap cost, and outstanding chemical stability, titanium dioxide ($TiO_2$) has been one of the most researched materials among these. Having a band gap of around 3.2 eV, $TiO_2$ is primarily able to absorb light in the ultraviolet part of the solar spectrum. The total efficiency of solar-to-hydrogen conversion in $TiO_2$-based devices is restricted because ultraviolet light is only a tiny portion of solar energy. To get over this constraint and make better use of visible light, scientists are looking at new semiconductor materials with lower band gaps. [2-3]

As a possible photocatalyst for photoelectrochemical uses, bismuth ferrite ($BiFeO_3$) has garnered a lot of interest as of late. At ambient temperature, the multiferroic perovskite oxide material $BiFeO_3$ displays ferroelectric and antiferromagnetic characteristics. Because of its small band gap of around 2.2-2.3 eV, $BiFeO_3$ is able to absorb a large amount of visible light, which is one of its main benefits. Being resistant to photocorrosion and having outstanding chemical stability, $BiFeO_3$ is an ideal material for photocatalytic and photoelectrochemical applications. The fast recombination of photogenerated electron-hole pairs, poor charge transport characteristics, and the existence of secondary impurity phases during synthesis are some of the issues that restrict the practical performance of pure $BiFeO_3$ as a photocatalyst, despite these promising attributes. the efficiency of hydrogen production in PEC systems is reduced due to these restrictions. [4]

A number of modification options have been investigated in an effort to improve $BiFeO_3$ photocatalytic performance and thereby overcome these obstacles. Doping $BiFeO_3$ with appropriate elements is one successful method. The electrical structure of the host material may be altered by doping in order to increase the mobility of charge carriers, decrease the recombination of electrons and holes, and vary the band gap in order to increase light absorption. In terms of the structural stability and electrical properties of $BiFeO_3$, lanthanum (La) has been the dopant of choice. By substituting $La^{3+}$ ions at the $Bi^{3+}$ site, one can change the crystal structure, enhance the material's morphology, and decrease the formation of impurity phases. The material's photocatalytic and photoelectrochemical performance may be greatly enhanced with these alterations, which in turn improves the efficiency of hydrogen evolution. The process used to create photocatalytic materials also has a significant impact on their characteristics. The photocatalytic activity is affected by changes in particle size, shape, crystallinity, and phase purity that might result from different synthesis methods. For nanostructured material fabrication, the sol-gel approach is a popular choice among synthesis techniques due to its many benefits, including low processing temperature, excellent compositional control, high purity, and uniform particle dispersion. Preparing doped photocatalytic materials is a breeze using the sol-gel approach because dopant ions may be easily incorporated into the host lattice. Using a straightforward sol-gel technique, this research generated nanomaterials composed of pure $BiFeO_3$ and $BiFeO_3$ doped with lanthanum. We used imaging electron microscopy (SEM) and X-ray diffraction (XRD) to study the produced materials' photoelectrochemical, morphological, and structural characteristics. In addition, photoelectrochemical experiments were conducted under light to assess the photocatalytic activity of the materials that were produced. The major goal of this study is to examine the impact of lanthanum doping on the structural and photocatalytic characteristics of $BiFeO_3$ for possible use in solar hydrogen generation by comparing the efficiency of hydrogen generation with pure and La-doped $BiFeO_3$.17-20]

## 2. SOL–GEL SYNTHESIS OF PURE AND La-DOPED $BiFeO_3$

Nanomaterials made of pure bismuth ferrite ($BiFeO_3$) and bismuth ferrite doped with lanthanum (La-$BiFeO_3$) were created utilizing an easy and inexpensive sol-gel process. Without further purification, all of the compounds used in the synthesis process were of analytical grade, having a purity level of 99.9%.

In order to make the solution stable, the necessary precursor ingredients were distilled water, bismuth nitrate pentahydrate, iron nitrate nonahydrate, lanthanum nitrate hexahydrate, and a little amount of concentrated nitric acid.[5]

In order to create pure $BiFeO_3$ (BFO), 50 mL of distilled water was mixed with a stoichiometric quantity of bismuth nitrate pentahydrate while swirling continuously. To make sure the precursor was completely dissolved, the solution was heated to about 80 °C. To account for the possibility of bismuth loss during annealing, an extra 5 wt% of bismuth nitrate was added, as bismuth tends to volatilize during the high-temperature synthesis process. The solution was progressively supplemented with the necessary stoichiometric amount of iron nitrate nonahydrate after stirring for about 10 minutes. With constant stirring, a few drops of strong nitric acid were added to stabilize the solution and stop precipitation. With continuous stirring, the resultant homogenous solution was heated to around 120 °C and allowed to gradually convert into a thick gel. When the gel forms, it means the sol-gel process has been successful and the metal ions have been dispersed evenly among the molecules. In order to get a dry precursor powder, the surplus solvent was removed from the produced gel by drying it in an air oven. A mortar and pestle were used to grind the dry powder until the particles were evenly distributed. The next step in preparing the powder for heat treatment was to press it into pellet shape.

The next step was to anneal the pellets in a furnace set at 500 °C for two hours so that the $BiFeO_3$ phase could be more effectively formed and crystallized. A comparable process was used to synthesize lanthanum-doped $BiFeO_3$ (BLFO). To produce a 10% lanthanum doping concentration at the bismuth site, a suitable stoichiometric quantity of lanthanum nitrate hexahydrate was added to the precursor solution in this example. To maintain uniform synthesis parameters, the following processes were performed under the same conditions: gel formation, drying, pelletization, and annealing. Both pure and La-doped $BiFeO_3$ nanomaterials, appropriate for future structural and photoelectrochemical studies, were successfully produced using this approach.[6]

The sol–gel synthesis of $BiFeO_3$ involves hydrolysis, condensation, gel formation, and thermal decomposition reactions of metal nitrate precursors. During the synthesis process, bismuth nitrate, iron nitrate, and lanthanum nitrate undergo chemical transformations leading to the formation of crystalline $BiFeO_3$ and La-doped $BiFeO_3$ nanomaterials.

**(i) Dissociation of Metal Nitrate Precursors**

Bismuth nitrate dissociates in aqueous medium as:

$$Bi(NO_3)_3 \cdot 5H_2O \rightarrow Bi^{3+} + 3NO_3^- + 5H_2O$$

Iron nitrate dissociation:

$$Fe(NO_3)_3 \cdot 9H_2O \rightarrow Fe^{3+} + 3NO_3^- + 9H_2O$$

Lanthanum nitrate dissociation:

$$La(NO_3)_3 \cdot 6H_2O \rightarrow La^{3+} + 3NO_3^- + 6H_2O$$

**(ii) Formation of $BiFeO_3$ During Heat Treatment**

After gel formation and annealing, $Bi^{3+}$ and $Fe^{3+}$ ions react to form $BiFeO_3$:

$$Bi_2O_3 + Fe_2O_3 \rightarrow 2BiFeO_3$$

**(iii) Formation of Lanthanum-Doped $BiFeO_3$**

Lanthanum ions substitute $Bi^{3+}$ ions in the crystal lattice:

$$Bi_{1-x}La_xFeO_3$$

For 10% lanthanum substitution:

$$Bi_{0.9}La_{0.1}FeO_3$$

The incorporation of $La^{3+}$ ions stabilizes the perovskite structure, reduces impurity phase formation, and improves crystallinity and charge transport properties.

### 2.1 $BiFeO_3$ as a Photocatalyst for Hydrogen Production

Belonging to the perovskite oxide family, $BiFeO_3$, also known as Bismuth Ferrite, is an intriguing semiconductor material. Because of its small band gap of around 2.2-2.3 eV and rhombohedral crystal structure with the R3c space group, it is able to absorb a large fraction of the solar spectrum's visible light. These features have made $BiFeO_3$ a promising photocatalyst for solar hydrogen generation and photoelectrochemical (PEC) water splitting.

As a photoanode material, $BiFeO_3$ is often used in PEC systems. Photons with enough energy transfer electrons from the valence band to the conduction band, creating electron-hole pairs, when the material is subjected to light irradiation. At the interface between the electrode and electrolyte, these charge carriers take part in reduction and oxidation processes, which cause water molecules to split into oxygen and hydrogen.

While holes take part in oxygen evolution processes, the produced electrons go toward the cathode to create hydrogen. Several variables frequently restrict the photocatalytic efficacy of pure $BiFeO_3$, notwithstanding these benefits. The production of secondary impurity phases like $Bi_{25}FeO_{40}$ and structural flaws are among them. Another issue is the quick recombination of photogenerated electron-hole pairs. Hence, to improve the overall photocatalytic performance of $BiFeO_3$ in applications involving hydrogen production, it is vital to enhance its structural stability and charge separation efficiency.[7]

### 2.2 Modification Strategies for $BiFeO_3$

Different modification strategies have been considered to enhance the photocatalytic and photoelectrochemical activities of $BiFeO_3$ , especially in applications of solar-driven water splitting and hydrogen generation. Despite the attractive properties of $BiFeO_3$ which include visible-light absorption, chemical stability and narrow band gap, its practical efficacy is usually limited by the rapidities of recombination of photo-generated electron-hole pairs, the lack of electrical conductivity and the formation of undesired impurity phases during its production. In order to eliminate these constraints, scientists have designed a number of methods such as metal ion doping, heterojunction formation, nanostructure engineering, and composite fabrication using conductive materials such as graphene.

#### 2.2.1 Metal Ion Doping

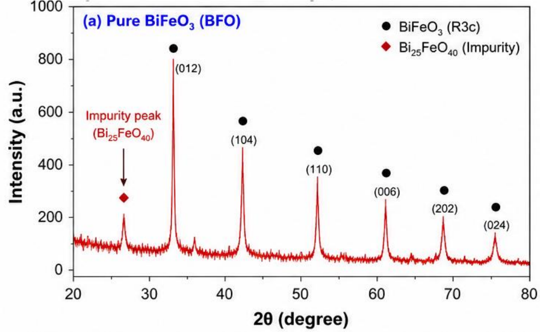
Metal ion doping is one of the most promising strategies to improve the structural, optical and electrical properties of $BiFeO_3$. In this method, appropriate dopant ions are incorporated into crystal-lattice of $BiFeO_3$ to alter its electronic structure and enhance the charge transport properties. The lanthanum (La), neodymium (Nd), samarium (Sm) and gadolinium ions (Gd), have been widely studied as dopants due to their favorable ionic radii and their ability to stabilize the perovskite structure. Special focus has been paid to lanthanum doping that can greatly determine the photocatalytic behavior of $BiFeO_3$. The replacement of lattice-distorting $La^{3+}$ ions at the $Bi^{3+}$ lattice site minimises lattice distortion and the formation of secondary impurity phases such as $Bi_{25}FeO_{40}$. Furthermore, La incorporation increases crystallinity and phase purity which result in an improved structural stability. The presence of lanthanum also promotes efficient separation and mobility of photogenerated electron–hole pairs, thereby minimizing charge recombination losses. As a result La-doped $BiFeO_3$ has better visible-light absorption, photocurrent density, and hydrogen evolution efficacy in comparison to pure $BiFeO_3$, and it is thus a promising photocatalyst in sustainable applications of solar energy conversion using photocatalysts.[8]

## 3. STRUCTURAL CHARACTERIZATION

### 3.1 X-Ray Diffraction (XRD)

The XRD patterns of pure $BiFeO_3$ (BFO) and $BiFeO_t$ doped with lanthanum (BLFO). A rhombohedral crystal structure belonging to the R3c space group was successfully formed, as confirmed by the diffraction peaks detected for the pure BFO sample. On the other hand, the oxygen-rich secondary phase $Bi_{25}FeO_{40}$ was associated with a minor impurity peak that was seen around 227° ≈˥. On the other hand, structural alterations are evident in the XRD pattern of the La-doped BFO sample. After adding 10% lanthanum, the two strong peaks linked to the Bi site combined into one. This proves that the substitution of La causes a structural change from rhombohedral symmetry to orthorhombic symmetry. Further evidence of enhanced crystallinity and phase purity was the absence of impurity peaks in the doped sample. nine to ten

The XRD patterns of pure $BiFeO_3$ (BFO) and $BiFeO_3$ doped with lanthanum (BLFO). The presence of the $BiFeO_3$ phase is confirmed by the XRD profile of pure BFO. A rhombohedral crystal structure belonging to the R3c space group may be inferred from the diffraction peaks [12]. But there were also a few of smaller impurity phases visible beside the main phase. The oxygen-rich impurity phase $Bi_{25}FeO_{40}$ is indicated by a tiny intensity peak that appears about $2O \approx 27°$. Figure 1(b) shows the XRD pattern of BFO doped with La. Two prominent peaks, each corresponding to the Bi site, combined into a single peak after 10% lanthanum doping. The structural change from rhombohedral to orthorhombic symmetry is caused by La doping, as shown by this merger [11]. Furthermore, the doped sample showed no signs of impurity phases, indicating an improvement in phase purity.



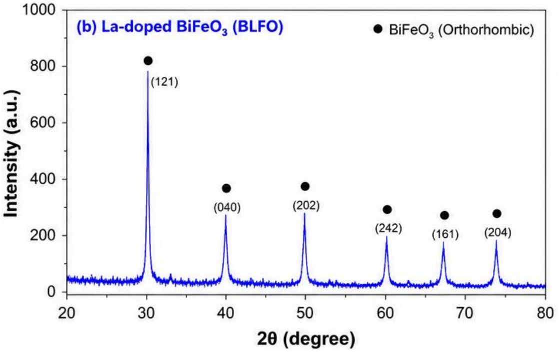


**Figure 3.1:** X-Ray Diffraction (XRD) Patterns of Pure $BiFeO_3$ and Lanthanum-Doped $BiFeO_3$ Nanomaterials

### 3.2 Effect of Lanthanum Doping on Crystal Structure

The crystal structure and overall characteristics of $BiFeO_3$ are significantly affected by lanthanum doping. Because of variations in ionic radii, the crystallographic arrangement of the material is affected by the minor lattice deformation caused by the replacement of $La^{3+}$ ions at the $Bi^{3+}$ site. XRD analyses show that La doping improves phase purity and reduces the production of secondary impurity phases like $Bi_{25}FeO_{40}$. The structural change from rhombohedral to orthorhombic symmetry that occurs after doping also helps with crystallinity and stability. Better charge transfer and reduced defect-induced recombination losses are two major benefits of these structural modifications that make them ideal for photocatalytic applications.

## 4. SURFACE MORPHOLOGY STUDIES

### 4.1 Scanning Electron Microscopy (SEM)Analysis

The surface morphology of both pure $BiFeO_3$(BFO) and BLFO doped with lanthanum was studied by scanning electron microscopy (SEM), and the resulting micrographs  Particles in pure BFO are very clumped together and have a very uneven size and shape, as seen in the scanning electron micrograph. Strong particle-particle interactions during synthesis might cause this agglomeration. The SEM picture of the La-doped BFO sample, on the other hand, reveals clear morphological alterations in the particles. When contrasted with the pure BFO sample, the particles here seem less aggregated, more uniform, and somewhat round. These findings point to the fact that lanthanum's inclusion affects the synthesis process, namely nucleation and crystal growth. The outcome is a significant change to the material's surface shape. These structural alterations may increase the doped material's photocatalytic performance generally, because surface morphology is a key factor in photocatalytic activity.[12] Scanning electron microscopy (SEM) was used to examine the surface morphology of the synthetic material, The scanning electron micrographs (SEMs) of pure $BiFeO_3$ (BFO) show that the particles are clumped together and vary in size. The nanoparticles may have significant interactions with each other during production, which might lead to this particle clustering. Notable morphological alterations occurred with lanthanum doping. Compared to the pure sample, the La-doped BFO particles seem more spherical and have a less agglomerated appearance. This suggests that the nucleation, growth, and crystallization processes are affected by the addition of lanthanum. The scanning electron microscopy (SEM) results show that even a little quantity of dopant introduced into the host lattice may drastically change the surface shape. Morphological alterations like this may improve a material's photocatalytic performance since surface structure is so important in photocatalytic processes.

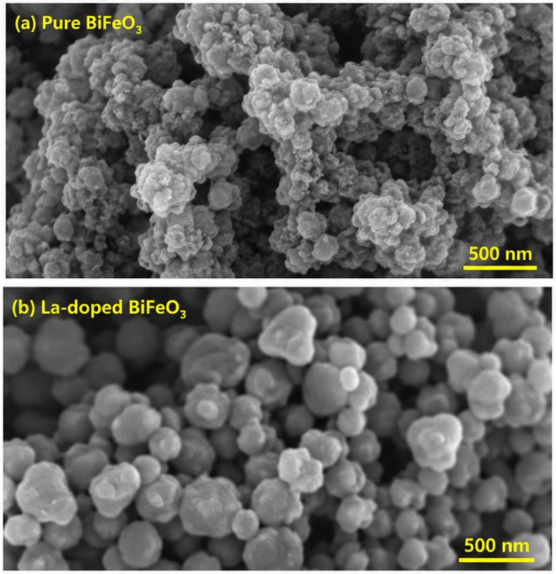


**Figure 4.1:** Scanning Electron Microscopy (SEM) Images of Pure $BiFeO_3$ and Lanthanum-Doped $BiFeO_3$ Nanomaterials

## 5. PHOTOELECTROCHEMICAL PERFORMANCE

$BiFeO_t$ doped with La (BLFO), and both types of BFO were tested for photoelectrochemical (PEC) performance using a conventional three-electrode setup. As photoanodes, the thin films were applied using Araldite adhesive on Perspex sheets with a 1 cm diameter circular hole. Before taking any measurements, we made sure the films were securely attached by letting the glue set fully. An ohmic contact was created by attaching a copper wire to the reverse side of the Ti foil that supported the thin layer using silver paint. This allowed for the establishment of an electrical connection. In order to conduct the photoelectrochemical studies, a three-electrode configuration was used. The working electrode consisted of the manufactured BFO-based photoanodes, the counter electrode was a 1 cm diameter of platinum foil, and the reference electrode was a saturated calomel electrode (SCE). The tests were conducted using an electrolyte that offers an appropriate alkaline environment for the electrochemical reactions: a water-based solution of sodium hydroxide with a concentration of 0.5 mol/L. A 150 W xenon (Xe) lamp was used as the light source for illumination throughout the tests in order to mimic the sun spectrum. Under both dark and light circumstances, the current-voltage characteristics of the photoanodes were recorded using a PG302B potentiostat/galvanostat for the photoelectrochemical measurements. The inverted burette technique was used to collect the gas generated at the cathode in order to estimate the rate of hydrogen evolution. A saturated calomel electrode (SCE) was used in conjunction with an applied voltage of 0 V for the experiments. [14]

The photoelectrochemical I–V properties of the BLFO photoanode. The low current density in the dark suggests that there is very little charge carrier activity when light is not present. The current density, however, increases dramatically when the photoanode is illuminated by sunlight. The fact that the photoanode is able to absorb light and produce charge carriers more efficiently is shown by its improved photocurrent responsiveness. The semiconductor material's high photoactivity is shown by its increased current density, which implies that it might be used for solar hydrogen generation. The development of hydrogen during photoelectrochemistry is proportional to the photocurrent density [12]. It is possible that the enhanced charge separation and reduced recombination losses caused by the La-doped BFO photoanode's better crystal structure and lack of impurity phases are responsible for its superior solar spectrum response.[16]

### 5.1 Hydrogen Evolution Mechanism

The mechanism of hydrogen evolution in La-doped $BiFeO_3$ involves several photoelectrochemical processes. When the semiconductor is illuminated with visible light, electrons are excited from the valence band to the conduction band, generating electron–hole pairs. The photogenerated electrons migrate toward the cathode through the external circuit and participate in the reduction reaction to produce hydrogen gas. Simultaneously, the holes oxidize water molecules at the photoanode surface to generate oxygen. Lanthanum doping enhances this process by improving charge separation efficiency and minimizing electron–hole recombination. As a result, a larger number of charge carriers participate in the water-splitting reaction, leading to enhanced hydrogen generation efficiency.

The photoelectrochemical hydrogen evolution mechanism in La-doped $BiFeO_3$ is based on visible-light-induced charge generation, separation, and redox reactions occurring at the semiconductor–electrolyte interface.

**(i) Photoexcitation Process**

When visible light irradiates the semiconductor surface, electrons are excited from the valence band (VB) to the conduction band (CB), producing electron–hole pairs:

$$BiFeO_3 + h\nu \rightarrow e_{CB}^- + h_{VB}^+$$

where:

- $h\nu$= incident photon energy
- $e_{CB}^-$= excited electron in conduction band
- $h_{VB}^+$= hole generated in valence band

**(ii) Hydrogen Evolution Reaction (Reduction)**

The photogenerated electrons migrate toward the cathode and reduce water molecules or hydrogen ions to produce hydrogen gas:

$$2H^+ + 2e^- \rightarrow H_2 \uparrow$$

### (iii) Oxygen Evolution Reaction (Oxidation)

Simultaneously, holes oxidize water molecules at the photoanode surface:

$$2H_2O + 4h^+ \rightarrow O_2 + 4H^+$$

### (iv) Overall Water Splitting Reaction

The complete photoelectrochemical water splitting reaction is:

$$2H_2O \rightarrow 2H_2 + O_2$$

### (v) Role of Lanthanum Doping

Lanthanum doping enhances PEC hydrogen evolution through:

1. Improved crystallinity and phase purity
2. Reduced electron–hole recombination
3. Enhanced charge carrier mobility
4. Better visible-light absorption
5. Increased photocurrent density

The substitution of $La^{3+}$ ions into the $BiFeO_3$ lattice creates structural modifications that facilitate efficient charge separation and electron transport, thereby improving hydrogen generation efficiency under visible-light irradiation.

## 6. MECHANISM OF ENHANCED HYDROGEN EVOLUTION

The I-V properties of the lanthanum-doped $BiFeO_3$ (BLFO) photoanode in photoelectrochemistry. In order to assess the synthesized material's photoresponse and hydrogen generating capacity, several experiments were conducted. The low current density in the dark suggests that relatively few charge carriers are produced when light is not present. The current density, however, increases dramatically when light is shone on the photoanode. This increase in photocurrent shows that the semiconductor material is very photoactive when exposed to light.

The BLFO photoanode can effectively absorb solar energy and produce electron-hole pairs, which are involved in the photoelectrochemical water splitting process, as seen by the rise in photocurrent. Hydrogen evolution at the cathode is improved by efficiently separating and transporting these charge carriers that are photogenerated. Thus, a larger current density is directly correlated with a higher capacity to produce hydrogen. in [13] Several variables contribute to the enhanced performance of the La-doped $BiFeO_3$ photoanode. Lanthanum doping improves charge carrier separation by decreasing recombination losses, increases crystallinity, and decreases the presence of impurity phases. Consequently, when contrasted with the pure $BiFeO_3$ sample, the doped material displays superior photoelectrochemical performance and solar spectrum response. Due of these qualities, La-doped $BiFeO_3$ is an attractive candidate for effective solar hydrogen generation. [11][15]

## 7. CHALLENGES AND FUTURE PERSPECTIVES

A number of obstacles prevent the widespread use of $BiFeO_3$ based photocatalysts for solar-driven hydrogen generation, despite their promising demonstration of promise. The total conversion of solar energy into hydrogen is reduced due, in part, to the poor quantum efficiency, which is one of the primary concerns. Furthermore, the material's performance might be negatively affected by instability under long-term light when it comes to protracted photoelectrochemical operation. Phase purity is another important parameter that may be hard to maintain during synthesis; if not, undesirable secondary phases might emerge, which reduces the photocatalytic activity. Another important aspect that decreases the effectiveness of the water-splitting process is the fast recombination of photogenerated electron-hole pairs. Research in the future should concentrate on finding better material design solutions to get around these restrictions. Improving charge separation and increasing light absorption are two outcomes of fabricating multi-component heterostructures. The electrical conductivity and electron transport of two-dimensional (2D) materials like graphene or transition metal dichalcogenides might be greatly enhanced by using $BiFeO_3$ Improving the shape of nanostructures also allows for the creation of greater surface area and active catalytic sites. To further improve photocurrent production, it is necessary to upgrade charge transfer systems. Sustainable energy technologies may benefit from $BiFeO_3$-based photocatalysts if their efficiency in converting solar energy into hydrogen is enhanced by the use of modern synthesis methods in conjunction with theoretical modeling and computational investigations.

### 7.1 Environmental and Energy Applications of $BiFeO_3$

$BiFeO_3$-based photocatalysts have attracted considerable interest for renewable energy and environmental remediation applications. Apart from hydrogen production through photoelectrochemical water splitting, $BiFeO_3$ nanomaterials have also been investigated for photocatalytic degradation of organic pollutants, wastewater treatment, solar fuel generation, and environmental purification. Their visible-light-responsive nature and chemical stability make them suitable for sustainable energy technologies. The incorporation of rare-earth dopants such as lanthanum further enhances their applicability by improving photocatalytic efficiency and long-term stability under illumination conditions.

## 8. CONCLUSION

The researchers in this work used a straightforward and inexpensive sol-gel process to effectively create nanomaterials of pure $BiFeO_3$ (BFO) and lanthanum-doped $BiFeO_3$ (BLFO). This method of synthesis was effective in creating materials with better structural characteristics and regulated composition. Several analytical methods were used to study the photoelectrochemical, structural, and morphological characteristics of the produced samples. With excellent crystallinity, the $BiFeO_3$ phase was proven to have formed by the X-ray diffraction investigation. A minor impurity phase was seen in the pure BFO sample, but there were no discernible impurity peaks in the La-doped sample, indicating better phase purity. Lanthanum doping is crucial for stabilizing the crystal structure and increasing the material's overall structural quality, as this illustrates. After lanthanum doping, the scanning electron microscope (SEM) pictures showed that the surface morphology changed significantly. It was observed that La-doped BFO particles were more uniform, less agglomerated, and somewhat spherical in shape compared to the highly agglomerated and irregularly shaped pure BFO particles. Surface area and active sites accessible for photocatalytic reactions may be enhanced by such morphological enhancements. Under light, the current density of the La-doped BFO photoanode is much greater than in darkness, according to the photoelectrochemical measurements. The doped material's better solar spectrum response and increased photoactivity are shown by its enhanced photocurrent response. Improved hydrogen evolution during photoelectrochemical water splitting is a direct result of the higher current density, which implies more efficient creation and separation of photogenerated charge carriers. The study's findings show that

$BiFeO_3$'s structural, morphological, and photoelectrochemical characteristics are greatly enhanced by lanthanum doping. With its improved material characteristics and increased photocurrent, La-doped $BiFeO_3$ shows great promise as a photoanode material for future renewable energy applications and efficient solar-driven hydrogen generation.

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