Exploring the photo-catalytic degradation of methyl orange dye using Strontium doped Bismuth oxide nanoparticles

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Abstract

Low dimensional metal oxide Nps have garnered significant attention due to their distinctive characteristics and diverse application domains. This investigation can provide further elucidation regarding the synthesis of Strontium doped-Bi_2O_3 efficacious photocatalysts operating under visible light, thereby potentially addressing environmental quandaries. The photoactivity of Strontium doped-Bi_2O_3 Nps exhibits a significantly greater magnitude when compared to that of Bi_2O_3 nanoparticles lacking Strontium doping. The hydrothermal method shall be employed for the synthesis of Strontium-doped Bismuth oxide in the course of preparation. A solution of NH_4OH will be introduced to Bismuth nitrate and Strontium chloride. The resulting mixtures shall be subjected to vigorous stirring for a duration of 1 hour, after which they will be transferred into 100 mL autoclaves made of stainless steel and equipped with Teflon liners. These autoclaves shall then be heated to a temperature of 180 °C for a period of 6 h. The prepared samples shall subsequently undergo collection and undergo multiple washes utilising de-ionized water. In order to synthesise Strontium doped-Bi_2O_3 is imperative to subject the resulting compound to a subsequent calcination process at a temperature of 450° C. Infra-Red spectroscopy (FT-IR), UV-Visible, scanning electron microscopy (SEM), X-ray diffraction (XRD), techniques shall be employed for the investigation of the crystalline structures and morphologies of the powder. The resultant specimen shall subsequently serve as a catalyst for the photolytic degradation of organic dye methyl orange under diverse illumination circumstances. UV-Visible spectroscopy shall subsequently be employed to monitor the extent of photocatalytic efficacy.

Keywords: photocatalysis, dye degradation, Bismuth oxide, doping, characterization, methyl orange.

Explorando a degradação fotocatalítica do corante laranja de metila usando nanopartículas de óxido de Bismuto dopadas com Estrôncio

Resumo

Os Nps de óxido metálico de baixa dimensão têm atraído atenção significativa devido às suas características distintas e diversos domínios de aplicação. Esta investigação pode fornecer mais esclarecimentos sobre a síntese de fotocatalisadores eficazes dopados com estrôncio-Bi_2O_3 operando sob luz visível, abordando assim potencialmente dilemas ambientais. A fotoatividade do Bi_2O_3 Nps dopado com estrôncio exibe uma magnitude significativamente maior quando comparada à das nanopartículas de Bi2O3 sem dopagem com estrôncio. O método hidrotérmico será utilizado para a síntese de óxido de bismuto dopado com estrôncio durante a preparação. Uma solução de NH_4OH será introduzida ao nitrato de bismuto e cloreto de estrôncio. As misturas resultantes serão submetidas a agitação vigorosa por 1 h, após o que serão transferidas para autoclaves de 100 mL fabricadas em aço inoxidável e equipadas com liners de Teflon. Estas autoclaves serão então aquecidas a uma temperatura de 180 °C por um período de 6 horas. As amostras preparadas serão posteriormente coletadas e submetidas a múltiplas lavagens utilizando água deionizada. Para sintetizar Bi_2O_3 dopado com estrôncio é imperativo submeter o composto resultante a um processo de calcinação subsequente a uma temperatura de 450° C. Espectroscopia no infravermelho (FT-IR), UV-Visível, microscopia eletrônica de varredura (SEM), X - difração de raios (DRX), técnicas serão empregadas para a investigação das estruturas cristalinas e morfologias do pó. A amostra resultante servirá posteriormente como um catalisador para a degradação fotolítica do corante orgânico laranja de metila sob diversas circunstâncias de iluminação. A espectroscopia UV-Visível será posteriormente empregada para monitorar a extensão da eficácia fotocatalítica.

Palavras-chave: fotocatálise, degradação de corante, óxido de Bismuto, dopagem, caracterização, laranja de metila.

1. Introduction

In addition to studying how to manipulate matter at the atomic and molecular levels, nanotechnology is the branch of science that deals with matter at a scale of 1 billionth of a metre (109 m = 1 nm). The most basic building block of a nanostructure is a nanoparticle, which is much smaller than the everyday objects that are described by Newton's laws of motion but larger than an atom or a simple molecule that is subject to quantum mechanics. Nanoparticles are produced through a process called nanofabrication (Horikoshi et al., 2013).

Due to its exceptional qualities, including high refractive index, dielectric permittivity, thermal stability, and numerous applications in a variety of industries, including photocatalysis, gas sensing, capacitors, optical coatings, and photovoltaic cells, the substance Bi_2O_3 has attracted a lot of interest from the academic community (Ai et al., 2011; Lu et al., 2012). The use of efficient pollutants removal techniques is required because industrial effluents expose people to organic contaminants at excessive levels (Zaman et al., 2024). Water contamination poses a substantial worldwide environmental threat, with profound global repercussions. (Hamza et al., 2022; Ali, 2023; Kashif et al.).

Predominantly, it is driven by the presence of organic pollutants, dyes, and inorganic heavy metals as principal contributors to water pollution. (Muhammad et al., 2023; Ghani et al.). Previous studies have shown that Bi2O3, which has a band gap between 2.58 and 2.85 eV, is an efficient photocatalyst for the breakdown of contaminants and the splitting of water when exposed to visible light. Bi2O3's photocatalytic efficiency has been significantly decreased as a result of the quick recombination of charge carriers produced by photosynthesis (Liu et al., 2011; Qiu et al., 2011). It is possible to improve the properties of Bismuth oxide by adding extrinsic elements, especially the effectiveness of its photocatalytic properties.

This is because the doping process produces novel energy levels within the forbidden band that could act as storage spaces for electron-hole pairs produced by light, slowing down the rate at which they recombine (Ghule et al., 2022). Due to their crucial role in changing the electronic structure and increasing the host material's electron transition probabilities, doped materials exhibit notable optical and luminescent properties (Boulkroune et al., 2019). Numerous investigations have documented the doping of Bismuth Oxide with other substances, such as Zinc, Copper and Graphene oxide, among others (Baia et al., 2002; Kim et al., 1989).

Compared to their undoped counterparts, strontium-doped nanoparticles can display improved photocatalytic activity. The altered electronic properties that result in better charge separation and greater effectiveness in producing reactive species for dye degradation are the cause of this increased activity. Under the influence of light, Strontium-doped nanoparticles can produce reactive oxygen species (ROS) like hydroxyl radicals (˙OH). Strong oxidizers, these ROS can break down dye molecules into simpler, less dangerous products.

The effective applications of Strontium-doped Bismuth Oxide nanoparticles, including photocatalysis for dye degradation, have attracted interest recently. The photocatalytic capabilities of Bismuth oxide can be improved by the addition of Strontium which can also improve the efficiency of the breakdown of Organic Dyes. The band gap of Bismuth oxide can be altered by Strontium doping, changing the absorption spectra. Strontium can help produce intermediate energy levels within the band gap, enabling the material to absorb a wider variety of wavelengths, including visible light.

Because of their wider absorption spectrum, nanoparticles can now use more of the sun spectrum for photocatalytic activities. Doping with Strontium can facilitate effective charge separation inside nanoparticles structures. Effective photocatalysis requires photoexcited electrons and holes that are less prone to recombine as a result of light absorption. The total photocatalytic activity is enhanced by the presence of Strontium, which contributes to the creation of defect sites or energy levels that promote charge separation.

2. Materials and Methods

2.1 Chemicals and equipment's

The nitrates of Strontium ($Sr(NO_3)_2$) and Bismuth ($Bi(NO_3)_3$) were purchased in Daejung, South Korea. We purchased dye and Sodium hydroxide (NaOH) from Sigma-Aldrich in Schnelldrof, Germany. A stainless steel, 100 mL Teflon-lined autoclave with a maximum working temperature of 300 °C (Model: Tob new energy, Item Number: Tob reacter, China) was used. A micro-wave oven (Dawlance Microwave Oven- MD4 N, Output Power: 1000W) and a furnace (Temperature capability: up to 1300 °C, made by Across International) were used to heat, dry, and calcinate the samples.

2.2 Synthesis of Sr co-doped Bismuth oxide NPs

In the pursuit of the synthesis of Bismuth oxide nanoparticles, a meticulous hydrothermal methodology was adopted. The procedure involved the dissolution of Bismuth nitrate (quantified at 3 grams) in deionized water (measuring 75 milliliters). In tandem, Strontium nitrate (amounting to 1 milligram) was prepared and subsequently introduced into three discrete solutions of Bismuth salt. During this amalgamation, a ceaseless agitation was maintained to ensure the attainment of a homogeneous solution at ambient temperature. Throughout the formulation of the solutions, pH stabilization was judiciously executed through incremental additions of a 10% sodium hydroxide (NaOH) solution, administered drop by drop.

Emanation of a white precipitate was anticipated at this juncture. Post precipitation, a consistent solution of remarkable uniformity emerged. This homogeneous solution underwent a thermal transformation within a stainless steel and Teflon autoclave, enduring a ten-hour residence at 170 degrees Celsius under heightened pressure and temperature conditions. Upon the attenuation of the autoclave's thermal state, the precipitate underwent purification through both cleansing and centrifugation processes, thereby effecting the removal of residual, unreacted reactants. Subsequently, the resultant precipitate was subjected to a two-step procedure for the synthesis of both undoped and doped Bismuth oxide nanoparticles. Initial desiccation at 120°C was followed by a calcination step at 460°C, executed over the course of 60 minutes.

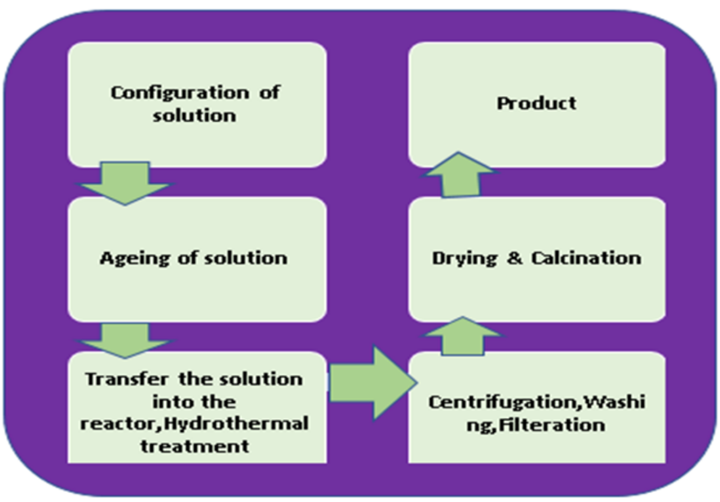

Figure 1. This is the general procedures for hydrothermal synthesis. Source: Authors, 2023.

2.3 Dye degradation

The photocatalytic activity of synthesized nano-powder samples was assessed through the degradation of MO (methyl orange) dye under light exposure. An incandescent light bulb, operating at 100 volts, served as the radiation source during the photocatalytic process. In a solution containing 5 ppm of methyl orange and 120 mL of solvent, 0.2 grams of the photocatalyst material were uniformly dispersed. Achieving an adsorption/desorption equilibrium, the suspension was agitated in darkness at room temperature for 25 minutes.

Subsequently, ionizing radiation was administered while the mixture underwent continuous agitation. Periodically, approximately 4-5 mL of the solution were withdrawn and subjected to centrifugation to eliminate solid catalyst particles. The catalyst's efficacy in adsorbing and degrading the dye was quantified using an ultraviolet-visible spectrometer. The dye removal percentage was determined by the following formula:

$$\text{Degradation efficiency (\%)} = Co - C/Co \times 100$$

2.4 Characterizations

Various characterization techniques were employed to comprehensively investigate sample properties. A double-beam spectrophotometer (model SP-300) facilitated the examination of maximum absorption across a wavelength range of 190 to 780 nm, enabling precise absorbance measurements. The FT-IR (Fourier-transform infrared) spectrometer (V. 640, USA) was utilized to assess functional groups, constructing spectra from 0.09 g samples within the chemical laboratory at Bacha Khan University, Charsadda, Khyber Pakhtunkhwa, Pakistan, over the range of 400 to 4000 cm^-1.

Photoluminescence (PL) analysis, conducted at Abdul Wali Khan University Mardan, played a pivotal role in assessing material purity, employing a spectral range of 230 to 1000 nm and employing a non-destructive approach. X-ray diffraction diffractometry (D-2 Phaser, Bruker, Denver, CO, USA) was employed, utilizing a 2 theta degree per minute scan rate and a Cu Kα radiation source, providing insights into the crystalline structure of the specimens. Surface morphology analysis of the samples was carried out using a scanning electron microscope (model JSM5910, JEOL, Kyoto, Japan) operated at an acceleration voltage of 30 kV. These methods collectively contributed to a comprehensive understanding of the sample characteristics.

3. Results and Discussion

3.1 UV-Vis spectroscopy

An Ultraviolet-Visible (UV-Vis) spectroscope was employed to assess the purity, crystallinity, and optical properties of nano-scale Bi2O3 powder, both in its undoped and doped forms. Figure 2 illustrates the UV-Vis spectrum, covering the wavelength range of 230 to 600 nanometers. The presence of a broad and extensive absorption band at 319 nm in the as-synthesized Bi2O3 underscores the significance of surface morphology in determining purity and particle size. Notably, the observation of monodispersed colloidal particles indicates the manifestation of quantum size effects, as previously reported by Athar in 2013.

The synthesized Bi2O3 nanomaterial exhibits an estimated band gap of approximately 3.88 electron volts (eV). This comprehensive analysis of the UV-Vis spectrum provides valuable insights into the characteristics of the Bi2O3 powder, shedding light on its purity, crystallinity, and optical behavior.

The incorporation of Sr into the mixture leads to a reduction in band gaps, as evidenced by the observed shift of absorption edges towards regions characterized by longer wavelengths. The experimental analysis of Bi2O3 nanocrystals doped with Sr at concentrations of 2%, 3%, and 4% has yielded intriguing findings regarding their absorption characteristics. Specifically, the absorption edges observed at approximately 297 nm, 288 nm, and 301 nm have sparked excitement within the scientific community. The utilization of absorption spectra has facilitated the determination of band gap energies for pristine Bi2O3 nanocrystals, as well as those doped with varying concentrations of Strontium (2%, 3%, and 4%). The resulting values obtained for these band gaps span a range from 4.170 to 4.30 to 4.110 electron volts (eV). The observations derived from our investigation demonstrate a persistent reduction in the band gap energies of Bismuth oxide nanoparticles as the concentration of Strontium increases.

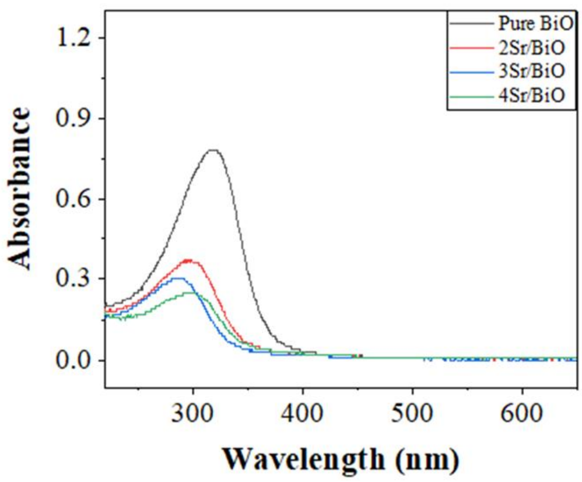

Figure 2. UV-Visible spectra of both doped and undoped Bismuth oxide nanoparticles. Source: Authors, 2023.

3.2 FTIR

The Fourier-transform infrared (FTIR) spectra of the synthesized nanomaterials were acquired in the wavenumber range of 400 cm^{-1} to 4000 cm^{-1}, as depicted in (Figure 3). The presence of prominent bands at 400 cm^{-1} and 800 cm^{-1} within the FTIR spectra of Bismuth oxide nanoparticles is attributed to the un-doped Bi-O stretching phenomenon, as illustrated in (Figure 3). Notably, the bending motion of the H-O-H moiety manifests a distinct peak at 1484 cm^{-1}. In the spectral region spanning from 3000 cm^{-1} to 3400 cm^{-1}, characteristic features suggest the potential presence of hydroxyl groups (OH-) and interstitial water molecules.

Of considerable significance is the observation that the stretching vibrations of Sr-O reach their maximum intensity at approximately 474 cm^{-1}, while the bending vibrations of Sr-O-Bi peak at around 632 cm^{-1}. These findings provide valuable insights into the structural and compositional aspects of the synthesized nanomaterials, enhancing our understanding of their chemical properties and potential applications.

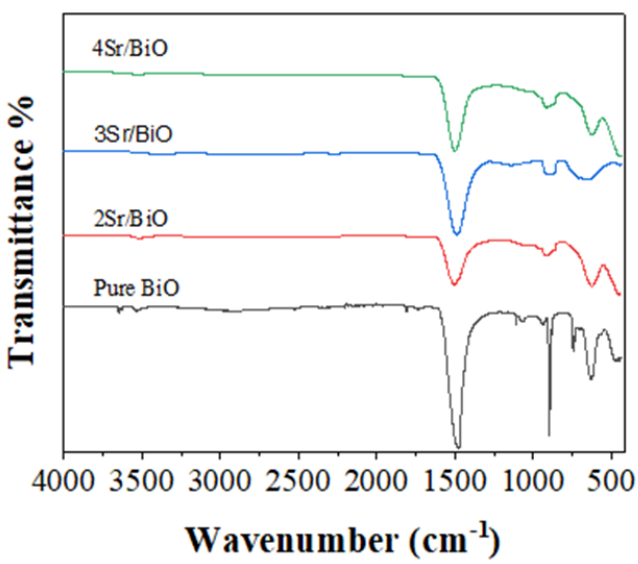

Figure 3. FTIR spectra of doped and undoped Bismuth-oxide nano-particles. Source: Authors, 2023.

3.3 XRD analysis

XRD analysis is a gernal method for characterizing the nanoparticles crystalline structure in below (Figure 4) At the specified 2-theta angles of 16, 20, 22, 24, 26, 28, 31, 33, 36, and 40°, one can readily observe the distinct crystalline surfaces denoted as (112), (200), (202), (213), (222), (312), (111), (332), (431), and (161) in the un-doped BiO material.

The observations derived from the X-ray powder diffraction analysis indicate that the examined specimens exhibit characteristics of superior crystalline substances, as evidenced by the narrow and well-defined nature of the observed peaks. The addition of Sr as dopants has remarkably stimulated the development of crystal planes (213), (312), and (431), evoking a sense of excitement. Furthermore, the intensity of the X-ray diffraction (XRD) peaks at 24, 28, and 36° has been significantly enhanced.

(Scherrer's equation) which was first discovered in 1950s, served as a valuable tool for determining the size of the nano-crystal catalyst. In this investigation, we have successfully determined the average crystallite diameters of various nanoparticles. Specifically, we have examined the un-doped and doped BiO 4Sr/BiO, 2Sr/BiO, and 3Sr/BiO nanoparticles. The results indicate that the average crystallite diameter for the 2Sr/BiO nanoparticles is 34 nm, while the un-doped BiO nanoparticles have an average crystallite diameter of 32 nm.

Furthermore, the doped BiO 4Sr/BiO nanoparticles exhibit an average crystallite diameter of 28 nm, and the 3Sr/BiO nanoparticles possess an average crystallite diameter of 25 nm. All of the samples exhibit minimal variation in their dimensions, and the X-ray diffraction (XRD) spectra do not exhibit any discernible indications of peak displacement. Furthermore, as depicted in figure 4.3, it is evident that the intensity of the X-ray diffraction (XRD) peak exhibits an upward trend as the concentration of Strontium (Sr) dopant is augmented.

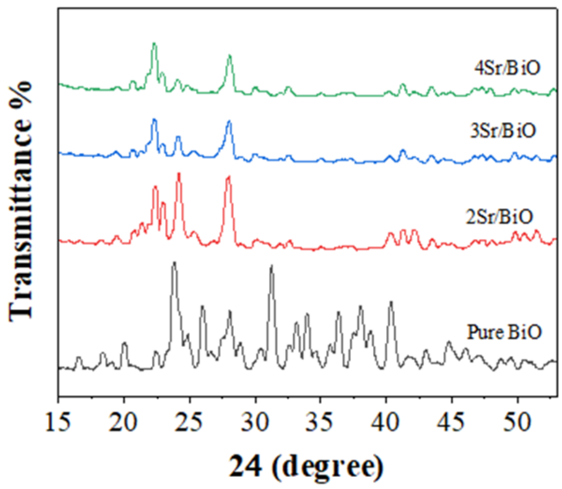

Figure 4. XRD analysis peaks of doped and un-doped Bismuth oxide Nanoparticles. Source: Authors, 2023.

3.4 Photoluminescence

The photoluminescence spectra of Bismuth oxide samples, which have been doped with Strontium, were meticulously analyzed at ambient temperature. This analysis was conducted by employing an excitation wavelength of 320 nm. The photoluminescence spectra of BiO nanoparticles, both undoped and doped with Sr, are depicted in (Figure 5). Analysis of the photoluminescence spectra reveals distinctive peaks at 427, 446, 468, 483, 493, 515, 573, and 596 nm in pristine Strontium oxide, exhibiting notably higher intensities compared to the corresponding peaks in the Bismuth oxide co-doped sample.

Particularly, the pure BiO sample exhibits an elevated peak intensity, indicative of an enhanced rate of electron-hole recombination, as photoluminescence (PL) intensity directly correlates with electron-hole pair recombination. These findings shed light on the distinct photoluminescent behaviors of the examined samples, emphasizing variations in their recombination dynamics.

The photocatalytic activity of Pure BiO was found to be relatively lower, as the concentration of photo-generated charge carriers plays a pivotal role in determining the photocatalytic activity of semiconductors. In sharp contrast to pristine BiO, a noticeable reduction in photoluminescence (PL) intensity was observed in all BiO samples subjected to co-doping with Sr. Notably, the sample containing a ratio of 4 Strontium (Sr) atoms per Bismuth oxide (BiO) molecule exhibited the lowest photoluminescence (PL) intensity. This diminished PL intensity suggests an increased presence of excited electrons within the system, which are efficiently transported across the interface in a uniform and continuous manner. These findings highlight the impact of Sr co-doping on the photoluminescent behavior of the BiO samples, emphasizing altered electron dynamics in the presence of Strontium.In the context of this experiment, the doped nanomaterial exhibits photo-catalytic properties, leading to the generation of reactive oxygen species during the degradation process of organic contaminants. The obtained photoluminescence (PL) data effectively validates the efficacy of this nanomaterial for the intended application.

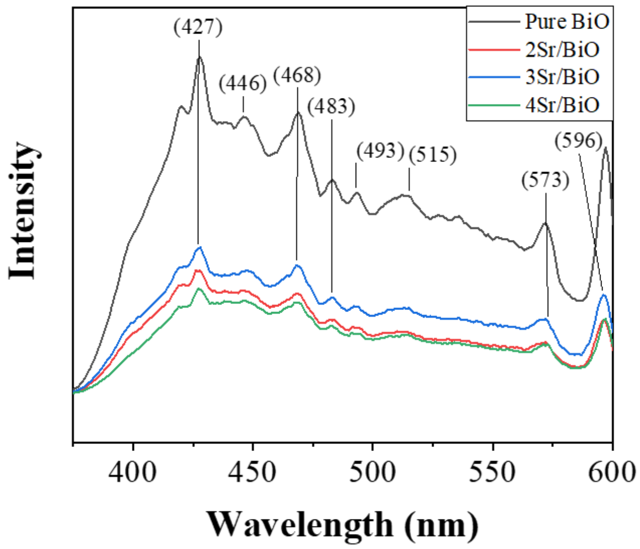

Figure 5. PL specta of doped and un-doped Sr/Bi2O3 Nps. Source: Authors, 2023.

3.5 Photocatalytic activity

Photocatalytic degradation Figure 6 (A, B, C, and D) is an intricate chemical process wherein the utilization of nanoscale Bismuth oxide (Bi_2O_3) particles, suitably infused with Strontium (Sr), is employed to facilitate the breakdown of organic pollutants under the influence of light. The incorporation of Sr dopants into the Bi_2O_3 nanoparticles serves to augment their photocatalytic prowess through the facilitation of charge carrier separation, thereby resulting in heightened photoactivity.

The aforementioned process exhibits great potential as a cutting-edge technological advancement in the realm of remediation for both water and air pollution. When a semiconductor absorbs electromagnetic radiation with energy equal to or exceeding its band gap, it triggers the initiation of photocatalytic reactivity within the material. This process leads to the generation of excited electrons and holes. Subsequently, as the electron-hole pairs migrate towards the surface, oxidation and reduction processes are effectively mediated through the interaction with adsorbates. The evaluation of photocatalytic activity in both Bi_2O_3 and Sr-doped Bi_2O_3 nanoparticles was accomplished by decomposing MO (methyl orange) in the presence of visible-light irradiation, while maintaining a consistent temperature.

This approach enabled the assessment of their photocatalytic capabilities under specific environmental conditions. To establish adsorption-desorption equilibrium between dye molecules and the photo-catalyst surface, a magnetic stirrer was employed to agitate the mixture for a 30-minute duration. The mixture was then exposed to visible light emitted by a Tungsten filament lamp positioned precisely three inches away. At 30-minutes intervals, a 10-milliliter volumetric sample was extracted from the reaction mixture and subjected to continuous agitation. This methodology ensured a systematic and controlled approach to monitor the photocatalytic process under visible-light irradiation conditions.

For illustrative purposes, Figure 6 exhibits the outcomes obtained from subjecting the mixture to centrifugation for a duration of 5 min, employing a rotational speed of 3000 revolutions per minute. Due to the substantial magnitude of its band gap and the rapid recombination of charges, it is observed that both pristine Bismuth oxide (Bi_2O_3) and Bismuth oxide doped with Strontium exhibit comparably subpar levels of photocatalytic activity. Indeed, it is evident that the photocatalytic activities experience a discernible augmentation upon the incorporation of Strontium as a dopant. The observed phenomenon demonstrates a positive correlation between the Sr dopant concentration and the extent of photocatalytic degradation, with the $3Sr/Bi_2O_3$ sample exhibiting the highest efficacy in this regard.

However, it is important to note that the photocatalytic activity (Figure 7) exhibits a noticeable decline when the concentration of strontium reaches a value of $4Sr/Bi_2O_3$ due to the inherent nature of Strontium as the primary causative agent behind the phenomenon known as the shadow effect of Strontium, this occurrence can be attributed to Sr itself. The investigation into the photocatalytic degradation of methyl orange reveals that the presence of Strontium is of utmost importance in optimizing the absorption of light and minimizing charge recombination in Bismuth oxide (Bi_2O_3) nanoparticles. The degradation efficiency, denoted as a percentage (%), can be calculated using the formula:

$$Co\text{-}C/Co \times 100\%$$

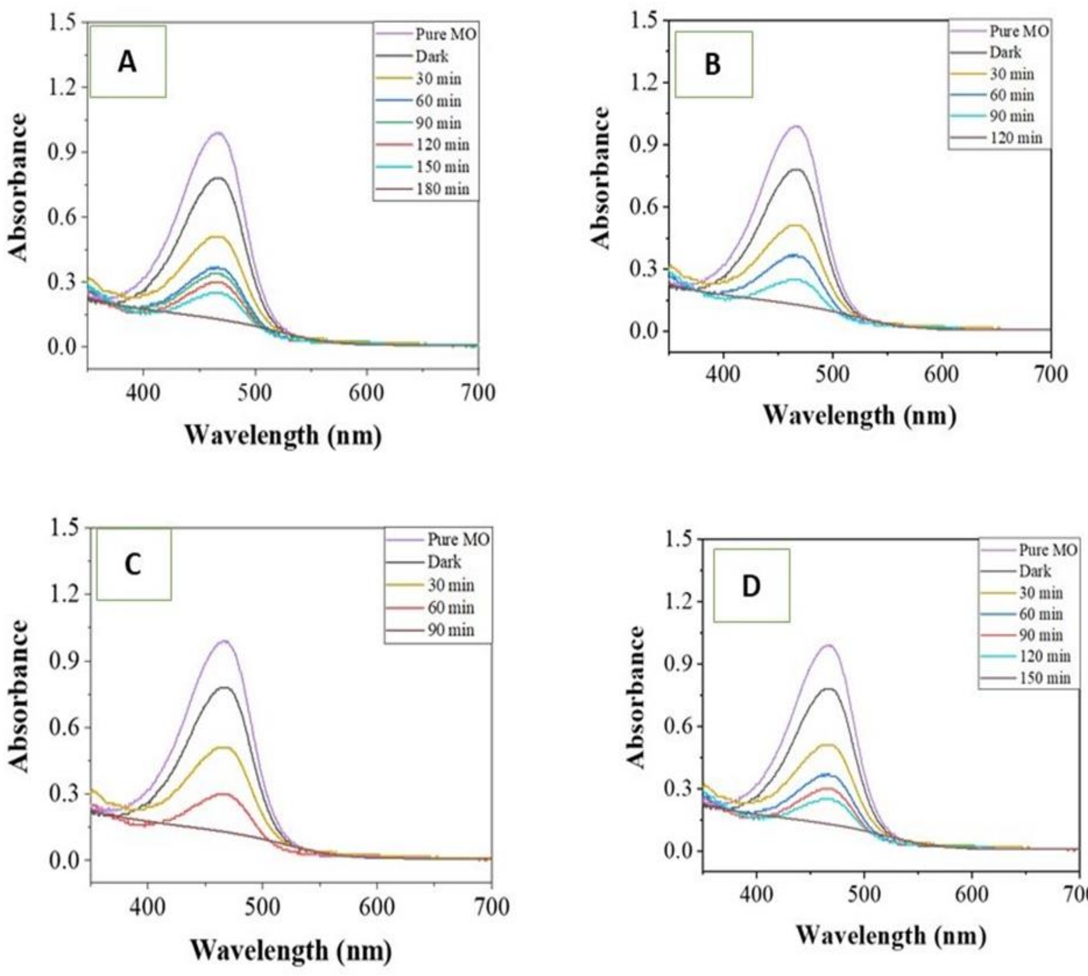

Figure 6. (A) BiO nano-particles utilized in MO photo-catalytic degradation. (B) $2Sr/Bi_2O_3$ nano-particles utilized in MO photo-catalytic degradation. (C) $3Sr/Bi_2O_3$ nano-particles utilized in MO photo-catalytic degradation and (D) $4Sr/Bi_2O_3$ nano-particles utilized in MO photo-catalytic degradation. Source: Authors, 2023.

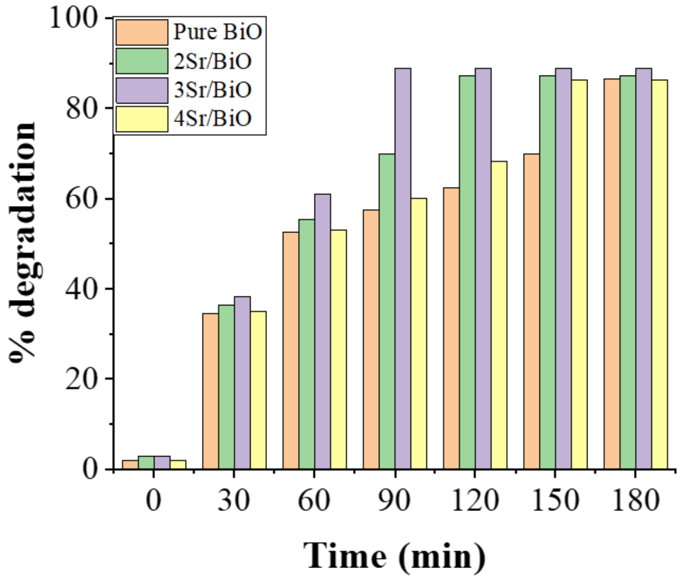

Figure 7. Comparison of the photo-catalytic activity of pristine Bi_2O_3 and 2, 3, 4Sr co-doped Bi_2O_3. Authors, 2023.

4. Conclusions

The exploration of nanoparticles composed of Bismuth oxide (Bi_2O_3) doped with Strontium has attracted considerable interest among the scientific community due to their noteworthy optical and electrical properties. These compounds demonstrate significant potential across a range of domains, encompassing, but not restricted to, solar cell technology, gas detection, and catalytic reactions. The potential augmentation of stability, thermal resistance, and conductivity properties of the material can be achieved through the integration of Strontium into Bismuth oxide (Bi_2O_3).

The properties of Strontium-doped Bismuth oxide nanoparticles are profoundly affected by the chosen synthesis technique and the concentration of the dopant. Further scientific inquiry is essential to fully grasp and enhance the properties of these substances for practical applications. The hydrothermal method was utilized to successfully synthesize nanoparticles of Strontium oxide and Strontium-doped Bismuth oxide. This synthesis involved the use of Strontium nitrate, Bismuth nitrate, and sodium hydroxide as the precursor materials. As a result of the calcination process, the expulsion of impurities takes place at the interface of the nanostructured material. As a consequence, this phenomenon facilitates the independent organization of the substance, leading to a notable augmentation in the dimensions of the crystallite. Strontium oxide, an example of metallic nanoparticles, demonstrates a diminutive size below 100 nm.

The substance under consideration demonstrates remarkable thermal stability, thereby exhibiting a resistance to oxidation even when subjected to elevated temperatures. Furthermore, it exhibits a formidable magnetic field of significant magnitude. The synthesized samples were subjected to thorough analyses in order to ascertain their phase purity, optical characteristics, and morphology. The aforementioned examinations encompassed the application of diverse analytical methodologies, including UV-Visible spectroscopy, FTIR spectroscopy, XRD analysis, scanning electron microscopy and polarized light microscopy.

The application of X-ray diffraction (XRD) was utilized to verify the composition of the meticulously engineered systems, thereby confirming their crystalline characteristics. The identification of vibrational modes in the structures of Sr-doped Bismuth oxide nanoparticles was successfully achieved by employing Fourier Transform Infrared (FTIR) spectral analysis. The study involved a thorough analysis of the optical properties displayed by nanoparticles composed of Strontium oxide, along with Bismuth oxide that has been doped with Strontium. This analysis was primarily focused on the ultraviolet-visible range of the electromagnetic spectrum. The experimental inquiry entailed a meticulous scrutiny of nanoparticle photo-catalysts consisting of Bismuth oxide and Bismuth oxide with the incorporation of Strontium.

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6. Authors' Contributions

Taimoor Ahmad: Contributed to experimental design and data collection. *Osama Ali Khattak*: Contributed to the literature review and background research. *Shah Nawaz*: Conducted experiments related to the photo-catalytic degradation of methyl orange dye. *Saif Ullah*: Participated in the design and execution of photo-catalytic experiments. *Jalal Amir*: Contributed to the theoretical framework and experimental design. *Muhammad Atif*: Played a role in data analysis and statistical evaluation. *Bahar Ali*: Assisted in the preparation of figures and graphs for the manuscript. *Ihsan Ghani*: Assisted in the synthesis and characterization of nanoparticles. *Mansoor Jamal*: Played a role in data collection and analysis. *Shafaq Murad*: Helped in manuscript preparation and revisions. *Abdur Raziq*: Participated in manuscript revisions. *Naqash Khan*: Played a role in data collection and analysis. *Muhammad Younas Khan*: Provided guidance throughout the study.

7. Conflicts of Interest

No conflicts of interest.

8. Ethics Approval

Not applicable.

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