Enhanced photocatalytic degradation of Cotton red dye using boron doped TiO_2

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Abstract

Photocatalytic degradation is an effective process for eliminating organic pollutants from wastewater, which is essential for maintaining ecological and environmental safety. Photocatalysis, an advanced oxidation technique, has gained significant attention for water treatment in recent years. Boron-doped titanium dioxide (B/TiO_2) nanoparticles were synthesized using a modified sol-gel method under ambient conditions. The nanoparticles were analyzed for crystal structure, thermal stability, bandgap, surface morphology, particle size, molar ratio, recombination behavior of photogenerated charge carriers, and charge transfer properties. This study reports the synthesis of B–TiO_2 nanoparticles and their efficient photocatalytic performance. The objective was to introduce boron as a dopant to enhance the photocatalytic activity of TiO_2, particularly in the visible light region.

Keywords: Semiconductor; Sol-gel; Degradation; Photocatalysis; Boron; TiO_2

1. Introduction

Environmental issues affecting the planet are a matter of global concern, and with rapid societal progress, their severity and complexity continue to increase (Samanta et al., 2002). Among these challenges, water pollution has emerged as a major issue, drawing widespread attention (Jiang et al., 2019; Wang & Yang, 2016). A significant volume of organic dyes is discharged annually into aquatic ecosystems due to their extensive production and usage, leading to serious environmental problems (Sohni et al., 2019). Titanium dioxide (TiO_2) has been widely studied for heterogeneous photocatalysis in water treatment because of its strong oxidizing capability. However, its photocatalytic activity is restricted to UV light owing to its wide bandgap of 3.2 eV (Gao et al., 2011). To overcome this limitation, non-metal doping strategies have been investigated to extend TiO_2 sensitivity into the visible region and enhance charge separation efficiency. Studies have shown that boron doping modifies the electronic band structure of TiO_2, thereby improving its photocatalytic response under visible light (Feng et al., 2011; Barkul et al., 2021).

In this work, boron-doped TiO_2 (B–TiO_2) was synthesized by incorporating boron into the TiO_2 lattice. The material exhibited strong photocatalytic activity for the degradation of Cotton Red dye under visible light. Optimal synthesis conditions were established, and detailed structural and performance analyses were carried out. The results indicate that B–TiO_2 is a promising photocatalyst for the remediation of dye-contaminated wastewater under solar irradiation.

2. Materials and Methods

Titanium tetraisopropoxide (TTIP, Sigma-Aldrich, 97%), ethanol (Aldrich, 99.9%), boric acid (Sigma-Aldrich), acetic acid, and Cotton Red dye (Sigma-Aldrich) were used as received without further purification. A stock solution of Cotton Red (CR) was prepared in double-distilled water, and the required dilutions were made accordingly.

2.1 PREPARATION OF BORON DOPED TIO_2

The typical procedure for producing B-doped TiO_2, as outlined in Krishan et al. (2014), involves making a few adjustments: TiO_2 photocatalysts were synthesized with titanium iso-propoxide ($Ti(OC_4H_9)_4$, ethanol (C_2H_5OH), and acetic acid (CH_3COOH) as precursor materials. Solution A was created by combining 180 mL of deionized water with 20 mL of $Ti(OC_4H_9)_4$, acetic acid, Boric acid, and B doped TiO_2. Solution B was prepared by combining 60 mL of with 200 mL of ethanol. After one hour of adding solution A drop by drop into solution B, there was an additional two hours of uninterrupted stirring. The produced gel was aged at room temperature for 24 hours. The gel was subsequently subjected to a six-hour heating process at a temperature of 110°C in order to remove moisture. The photo catalyst that was produced underwent grinding and calcination at a temperature of 600°C for a duration of 3 hours, with a heating rate of 5ºC per minute

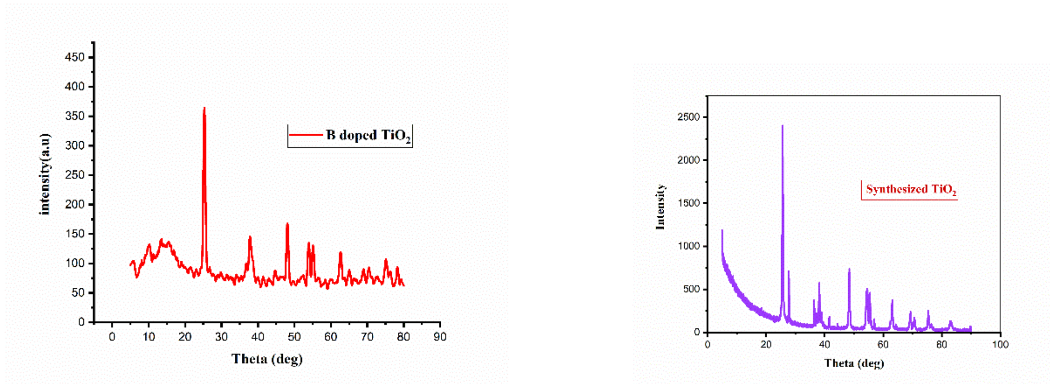
2.1.1 Characterization

The morphology of the synthesized material was examined using scanning electron microscopy (SEM). The crystal structure was analyzed with an X-ray powder diffractometer. The pH of the solutions was measured using a calibrated pH meter.

3. Results and Discussion

3.1 XRD ANALYSIS

The crystalline structures of bare TiO_2 and B–TiO_2 were analyzed using XRD, and the results are shown in **Figure 1**. Both samples exhibited characteristic diffraction peaks of TiO_2. In the B–TiO_2 spectrum, a distinct peak appeared at approximately 25.5°, corresponding to the anatase phase, which was absent in the spectrum of pure TiO_2. This suggests that the incorporation of boron influenced the crystalline phase composition, leading to a mixed anatase–rutile structure under the applied synthesis conditions (Feng et al., 2011). These results confirm the successful incorporation of boron into the TiO_2 lattice.

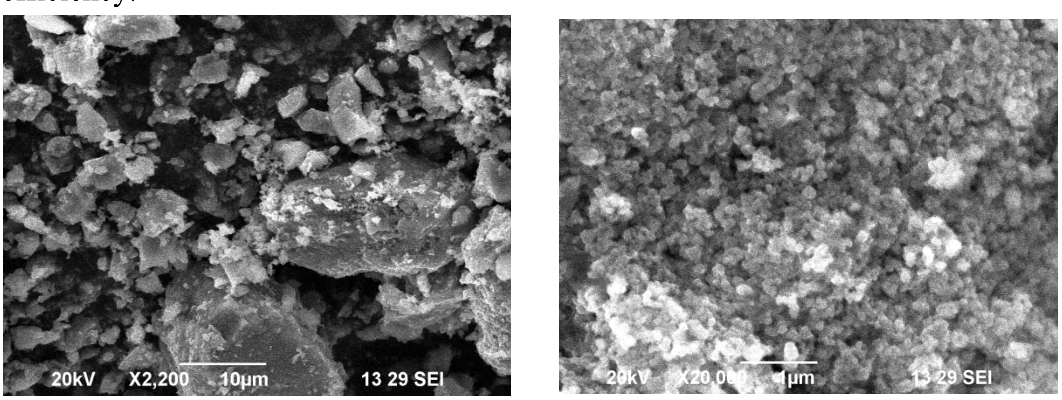


(a) (b)

Figure 1. XRD patterns of Boron doped (a) and undoped TiO_2 (b)

3.1.1 Scanning electron microscope

The morphology of B–TiO_2 was examined using SEM to understand the structural features contributing to its enhanced photocatalytic activity. Comparative analysis of bare TiO_2 and B–TiO_2 revealed notable differences in surface structure. As shown in Figures 2a and 2b, the B–TiO_2 nanoparticles exhibited a predominantly spherical shape with evidence of nanoscale clustering and agglomeration. Such morphology provides a porous framework with abundant active sites, which facilitates improved light absorption and charge carrier migration, thereby enhancing photocatalytic efficiency.



(a) (b)

Figure 2. SEM images of (a) boron doped and (b) as undoped TiO_2

3.1.2 FT-IR Spectrum

The FT–IR spectra of undoped and boron-doped TiO_2 nanoparticles, recorded in the range of 4000–400 cm^{-1}, are presented in **Figure 3**. A broad band around 3400 cm^{-1} corresponds to the O–H stretching vibration, while the peak near 1650 cm^{-1} is attributed to the bending vibration of H–O–H, both arising from surface-adsorbed water and hydroxyl groups. This indicates the presence of bonded hydrogen species on the nanoparticle surface. Notably, no distinct absorption band corresponding to pure boric acid (H_3BO_3) was observed, suggesting that boron was successfully incorporated into the TiO_2 lattice, most likely in the form of Ti–O–B linkages [Deng et al., 2010; Chen et al., 2007; Lei et al., 2015]. Peaks appearing near 1400 cm^{-1} further support the presence of Ti–O–B bonds, consistent with previous reports on B–TiO_2 and B_2O_3–SiO_2/TiO_2 systems prepared by sol–gel methods [Jung et al., 2004]. The characteristic Ti–O–Ti lattice vibrations appeared below 1000 cm^{-1}, confirming the preservation of the TiO_2 crystal framework in both undoped and doped samples [Deng et al., 2010; Chen et al., 2007; Lei et al., 2015]. These results validate the successful incorporation of boron into the TiO_2 lattice while maintaining the anatase crystal structure.

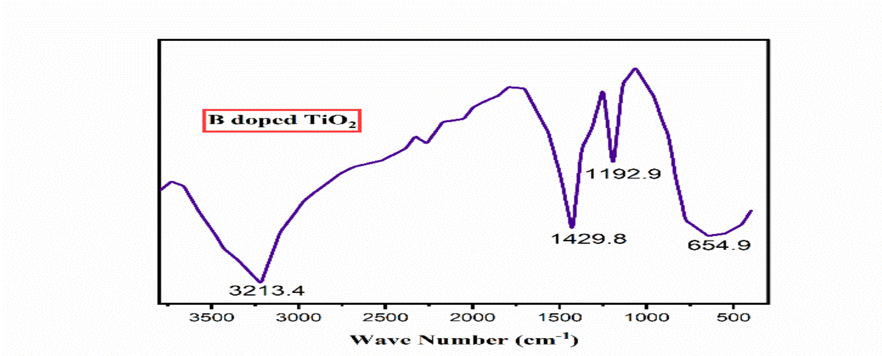
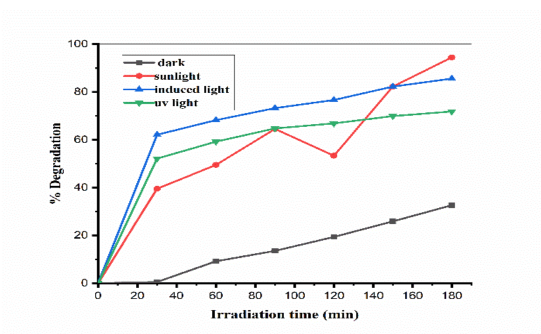
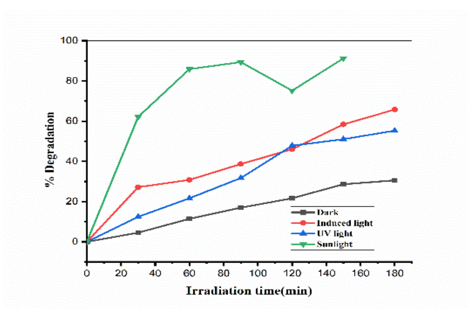


Figure 3 represents the FTIR spectra of boron doped TiO_2

3.2 Effect on light sources

The photocatalytic degradation of Cotton Red (CR) dye was studied using B–TiO_2 under different irradiation conditions, including visible light, natural sunlight, UV light, and in the absence of light (dark control). Among these, the B–TiO_2 sample exposed to sunlight exhibited the highest photocatalytic activity, achieving the most efficient degradation of CR dye. This confirms the significant role of solar-driven visible light activation in enhancing the photocatalytic performance of B–TiO_2.





(a) **(b)**

Figure 4. shows the light sources of B doped (a) and (b) shows undoped TiO_2.

3.2.1 Photocatalytic activity

The effect of boron concentration on the photocatalytic activity of TiO_2 was systematically investigated. Among the tested samples, the catalyst with **0.02% B–TiO_2** exhibited superior photocatalytic efficiency under both visible and UV irradiation. This enhancement can be attributed to the increased surface area and improved light-harvesting ability, which are the primary factors influencing photocatalytic activity.The degradation of Cotton Red dye was used to evaluate the photocatalytic performance of undoped and boron-doped TiO_2 nanoparticles. As shown in **Figure 5**, the boron-doped TiO_2 demonstrated significantly higher degradation efficiency compared to undoped TiO_2. In particular, the sample with **5% boron doping** achieved nearly complete degradation (~99%) by the end of the reaction, outperforming all other tested compositions.

However, further increasing the boron content (10% and 20%) resulted in a noticeable decline in photocatalytic activity despite their higher surface area. This reduction is likely due to excessive boron incorporation, which alters the optical properties of TiO_2, leading to reduced UV light absorption and charge carrier recombination. Consequently, an optimum dopant concentration is critical for maximizing photocatalytic efficiency.

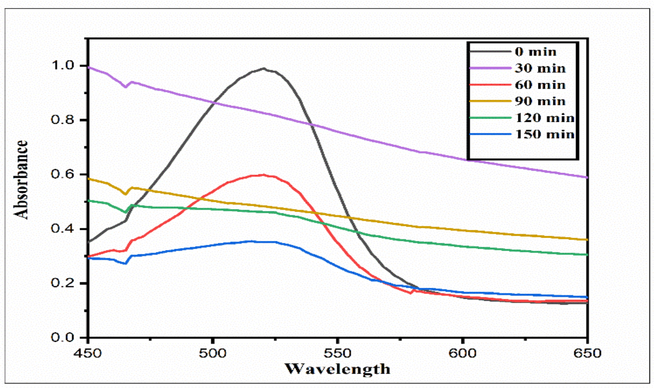


Figure5. Represents % degradation of Cotton Red dye using boron doped TiO_2

Table 1. Degradation percentage of B doped and undoped TiO_2

Degradation %	B-TiO_2	undoped TiO_2
degradation in presence of oxygen	99 %	91 %
degradation at optimum conditions	94 %	89 %

3.2.2 Recycling of the catalyst

The reusability of the photocatalyst was evaluated over four consecutive degradation cycles. After each cycle, the photocatalyst was recovered, washed, and reused under the same experimental conditions. As shown in **Figure 6**, the degradation efficiency gradually decreased with successive cycles, which can be attributed to factors such as catalyst loss during recovery, surface fouling, or partial deactivation of active sites. Nevertheless, the photocatalyst retained considerable activity even after four cycles, demonstrating good stability and recyclability.

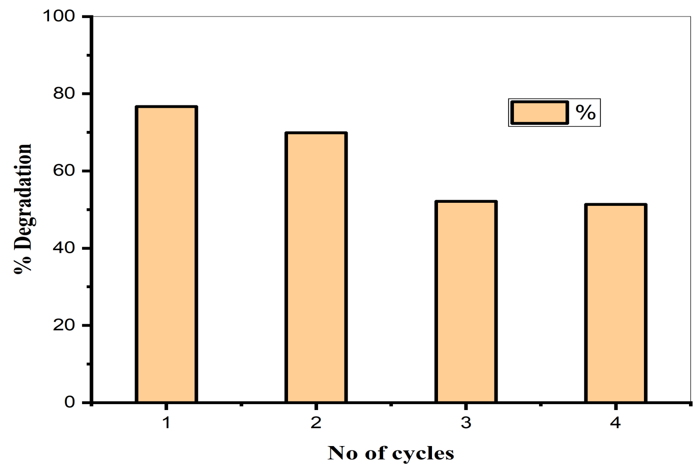


Figure 6. Recycling the photocatalyst.

4. Conclusions

The B–TiO_2 photocatalyst was synthesized using a simple sol–gel process, and its performance in the photocatalytic degradation of hazardous Cotton Red (CR) dye was investigated. The results confirmed that B–TiO_2 is a highly efficient photocatalyst for CR degradation. Under optimal conditions, nearly complete photodegradation of the dye occurred within 150 minutes of sunlight exposure. Compared to undoped TiO_2, the boron-doped samples exhibited a more homogeneous and compact structure.The effect of boron content on structure and photocatalytic activity was also examined. Boron incorporation up to 5% significantly enhanced catalytic performance, with 5% B–TiO_2 achieving ~99% degradation efficiency within 3 hours. FTIR spectra indicated the presence of free hydroxyl groups in all samples, and the main vibrational features of B–TiO_2 closely resembled those of undoped TiO_2. These findings demonstrate that boron doping effectively improves the photocatalytic efficiency of TiO_2, making it a promising material for dye degradation under solar irradiation.

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Authors' Contributions

Author conducted the research performed experiments, analyzed the data, and wrote the manuscript.

Supervisor provided guidance supervision, and cirtical revisions. Both approved the final manuscript.

Conflicts of Interest

The author declare no conflicts of interest related to this research.

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