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Advanced Engineering of TiO_2/Biochar Semiconductor–Biochar Photocatalysts for Efficient Tartrazine Dye Degradation: Mechanistic Insights and UV–Vis Spectrophotometric Evaluation

Rekayasa Lanjut Fotokatalis TiO_2/Biochar Berbasis Semikonduktor–Biochar untuk Degradasi Efisien Zat Warna Tartrazin: Wawasan Mekanisme dan Evaluasi Spektrofotometri UV–Vis

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ABSTRACT

This study aimed to evaluate the photocatalytic performance of TiO_2/Biochar composites for tartrazine degradation using UV–Vis spectrophotometric analysis. The experiments were conducted using various catalyst dosages and treatment conditions, including UV–Vis irradiation, UV–A irradiation, and dark adsorption. The results showed that the optimum catalyst dosage was 0.5 g/L with a degradation efficiency of 74%, while UV–Vis irradiation produced the highest degradation activity compared to other treatments. The degradation process was characterized by the gradual decrease in C/C_0 values with increasing irradiation time, indicating a progressive reduction in tartrazine concentration and demonstrating effective photocatalytic activity of the TiO_2/Biochar composite. These findings demonstrate that TiO_2/Biochar has strong potential as an effective photocatalyst for tartrazine degradation in practical wastewater treatment applications.

Keywords: TiO_2/Biochar, photodegradation, tartrazine, UV–Vis.

ABSTRAK

Penelitian ini bertujuan untuk mengevaluasi efektivitas fotokatalis TiO_2/Biochar dalam degradasi zat warna tartrazin menggunakan metode spektrofotometri UV–Vis. Pengujian dilakukan dengan variasi dosis katalis dan perlakuan berupa penyinaran UV–Vis, UV–A, serta adsorpsi gelap. Hasil penelitian menunjukkan bahwa dosis katalis optimum sebesar 0,5 g/L menghasilkan efisiensi degradasi sebesar 74%, sedangkan penyinaran UV–Vis menghasilkan aktivitas degradasi tertinggi dibandingkan perlakuan lainnya. Proses degradasi ditandai dengan penurunan nilai C/C_0 secara bertahap seiring dengan meningkatnya waktu penyinaran, yang menunjukkan terjadinya penurunan konsentrasi tartrazin secara progresif serta aktivitas fotokatalitik komposit TiO_2/Biochar yang efektif. Hasil penelitian ini menunjukkan bahwa TiO_2/Biochar memiliki potensi yang besar sebagai fotokatalis yang efektif untuk degradasi tartrazin dalam pengolahan limbah cair.

Kata kunci: TiO_2/Biochar, fotodegradasi, tartrazin, UV–Vis.

INTRODUCTION

The discharge of synthetic dyes, particularly tartrazine, into aquatic environments has become a serious environmental issue due to their toxicity, high stability, non-biodegradable nature, and resistance to conventional wastewater treatment methods. Tartrazine is extensively used in food, pharmaceutical, cosmetic, and textile industries because of its bright yellow color and high solubility, resulting in its widespread presence in industrial effluents. The accumulation of tartrazine in aquatic environments may reduce light penetration, disrupt aquatic ecosystems, and potentially cause adverse health effects in humans and aquatic organisms. Conventional treatment techniques, such as coagulation, adsorption, and biological degradation, often exhibit limited efficiency in completely removing azo dyes from wastewater. Consequently, semiconductor-based photocatalysis has emerged as a promising and environmentally friendly technology for degrading hazardous organic pollutants through advanced oxidation processes under light irradiation.

Recent studies have demonstrated that semiconductor nanomaterials such as ZnO-based nanocomposites exhibited enhanced photocatalytic performance due to improved charge separation, increased light absorption, and reactive oxygen species generation (Hassaan et al., 2024; Khan et al., 2024). Among various semiconductor photocatalysts, TiO_2 is widely used because of its high chemical stability, non-toxicity, and strong oxidation capability. TiO_2 possesses a band-gap energy of approximately 3.0–3.2 eV, enabling photoactivation under UV irradiation and the generation of reactive oxygen species responsible for pollutant degradation. Moreover, biochar has received considerable attention as a photocatalyst support material because of its porous structure, large surface area, abundant surface functional groups, and excellent adsorption capability (Chandra et al., 2021). The integration of biochar with semiconductor materials can enhance pollutant adsorption, facilitate electron transfer, and suppress electron–hole recombination, thereby enhancing photocatalytic degradation efficiency (Zahid et al., 2025). Previous studies have also highlighted that synergistic adsorption–photocatalysis mechanisms contribute significantly to the removal of persistent contaminants from aqueous systems. However, most previous studies mainly focused primarily on antibiotic degradation and general semiconductor modification, while investigations specifically addressing TiO_2/biochar photocatalysts for tartrazine degradation and mechanistic evaluation remain scarce (Liu et al., 2024). In addition, detailed studies concerning the synergistic interaction between TiO_2 and biochar using UV–Vis spectrophotometric monitoring during the degradation process have not been comprehensively explored. Accordingly, this study was conducted to synthesize and characterize a TiO_2/biochar photocatalyst and evaluate its photocatalytic performance for tartrazine degradation under UV irradiation. Furthermore, this study aimed to investigate the effect of biochar incorporation on the photocatalytic activity and to elucidate the synergistic adsorption–photocatalysis mechanism involved in the degradation process using UV–Vis spectrophotometric analysis.

RESEARCH METHOD

Materials:

This study employed an experimental laboratory method to evaluate the performance of TiO_2/Biochar photocatalysts in the degradation of tartrazine dye. The materials used in this study included TiO_2, biochar, and tartrazine as the model dye pollutant, ethanol (96%), and distilled water. TiO_2 was used as the photocatalytic material, while corncob biochar served as a supporting matrix to enhance adsorption capacity and photocatalytic performance. Tartrazine was used as a model dye pollutant in the degradation experiments. Ethanol (96%) and distilled water were utilized throughout the photocatalyst preparation and experimental procedures. All chemicals were of analytical grade and were used without further purification.

Instrument:

The instruments used in this study included the following: a UV–Vis spectrophotometer, a UV–A lamp (Lucky Herp Reptile Basking Spot Lamp, 50 W), a high-pressure mercury lamp (Philips HPL-N 250W/542, 250 W) as the UV–Vis irradiation source, a Fourier-transform infrared (FTIR) spectrometer, an X-ray diffractometer (XRD), a scanning electron microscope (SEM), a magnetic stirrer, an analytical balance, a pH meter, volumetric flasks, graduated cylinders, beakers, volumetric pipettes, dropper pipettes, syringe filters, cuvettes, and sample bottles.

Preparation of TiO_2/Biochar Photocatalyst

Corncob biochar was produced by carbonizing dried corncobs in a furnace at 500°C for 2 h. The resulting biochar was ground and sieved through a 200-mesh sieve to obtain a uniform particle size distribution.

The TiO_2/Biochar photocatalyst was synthesized using an ultrasonication-assisted method. TiO_2 (24 g) was dispersed in 800 mL of 96% ethanol and ultrasonicated for 60 min to obtain a homogeneous suspension. Subsequently, 56 g of corncob biochar was added, and the suspension was magnetically stirred for 7 h, followed by ultrasonication for an additional 15 min. The mixture was concentrated using a rotary evaporator under reduced pressure at 60°C, dried at 105°C for 3 h, and calcined at 400°C for 2 h to obtain the TiO_2/Biochar composite photocatalyst. The photocatalyst was stored in a desiccator until further use.

Characterization of TiO_2/Biochar Photocatalyst

FTIR analysis was performed to identify the functional groups of the prepared materials

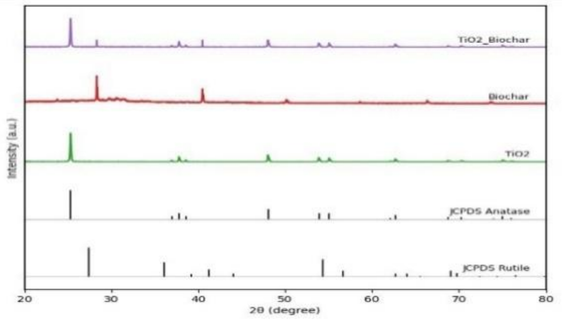


Figure 1. FTIR spectra of pristine TiO_2, biochar, and the TiO_2/Biochar composite showing the formation of interfacial interactions between TiO_2 and biochar through Ti–O–C bonding.

Figure 1 presents the FTIR spectra of pristine TiO_2, biochar, and TiO_2/Biochar composite. Pristine TiO_2 exhibited characteristic absorption bands at 879,65 cm^{-1} corresponding to Ti–O–Ti stretching vibrations. Biochar showed absorption bands at 1647,48 cm^{-1}, 1379,11 cm^{-1}, and 984,01 cm^{-1}, which were attributed to aromatic C=C vibrations, C–H bending, and C–O stretching groups, respectively. Following composite formation, additional absorption bands were observed at 916,92 cm^{-1}, which can be assigned to Ti–O–C bonding. The appearance of this band indicates the formation of interfacial interactions between TiO_2 particles and oxygen-containing functional groups on the biochar surface. The preservation of both Ti–O and carbon-related functional groups suggests that the chemical structures of TiO_2 and biochar remained intact after synthesis while forming a stable composite structure.

XRD analysis was performed to determine the crystalline structure of the photocatalysts

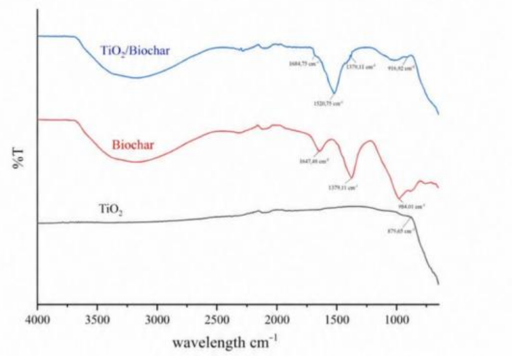
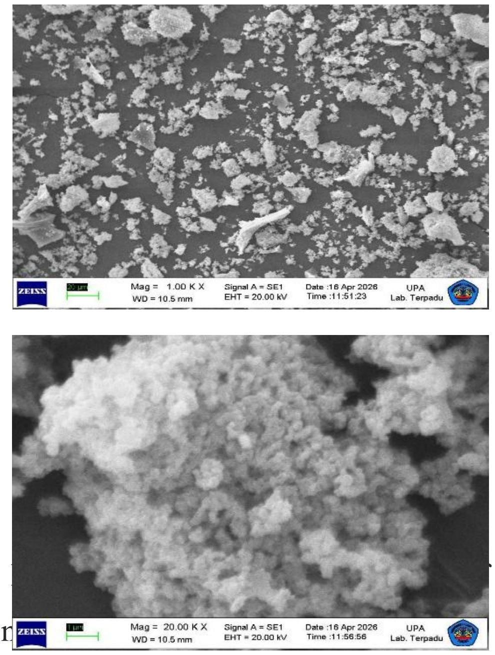


Figure 2. XRD patterns of pristine TiO_2, biochar, and the TiO_2/Biochar composite compared with standard JCPDS anatase and rutile phases.

Figure 2 presents the XRD patterns of pristine TiO_2, biochar, and TiO_2/Biochar composite. The XRD pattern of TiO_2/Biochar exhibited diffraction peaks at approximately 25.3°, 37.8°, 48.0°, 54.0°, 55.1°, and 62.7°, corresponding to the (101), (004), (200), (105), (211), and (204) crystal planes of the anatase phase of TiO_2. These peaks were consistent with the standard JCPDS data of anatase TiO_2, confirming that the crystal structure of TiO_2 was preserved after composite formation. No additional diffraction peaks attributable to impurity phases were observed, indicating that the synthesis process did not alter the crystal phase of TiO_2. A slight decrease in diffraction intensity was detected in the composite compared with pristine TiO_2, which can be attributed to the presence of amorphous biochar partially covering the TiO_2 surface. These results demonstrate that biochar acts as a supporting matrix while maintaining the highly active anatase phase required for photocatalytic applications.

SEM analysis was performed to examine the surface morphology of the samples



pristin TiO_2/Biochar composite at (a) 1,000× and (b) 20,000× magnifications showing the distribution of TiO_2 particles on the porous biochar matrix.

Figure 3 presents SEM micrographs of pristine TiO_2, biochar, and the TiO_2/Biochar composite at different magnifications. The SEM images revealed that the TiO_2/Biochar composite possessed a rough and heterogeneous surface morphology. At low magnification (1,000×), irregularly distributed particles were observed on the biochar matrix, indicating successful immobilization of TiO_2 on the support biochar surface. At higher magnification (20,000×), TiO_2 particles appeared as aggregated nanostructures attached to the biochar surface. Although partial agglomeration was observed, the particles remained relatively well dispersed throughout the biochar matrix. The rough and porous structure of biochar provided abundant anchoring sites for TiO_2 particles, thereby increasing the available active surface area and improving contact between the photocatalyst and pollutant molecules. Furthermore, the ultrasonic-assisted synthesis method likely promoted homogeneous particle distribution through cavitation effects, resulting in improved interfacial contact between TiO_2 and biochar. Overall, the TiO_2/Biochar photocatalyst was characterized by (i) the preservation of the anatase TiO_2 crystalline phase, (ii) the formation of Ti–O–C interfacial bonds between TiO_2 and biochar, and (iii) the homogeneous distribution of TiO_2 particles on a rough and porous biochar matrix. These characteristics indicate strong interfacial interaction between TiO_2 and biochar, which may enhance pollutant adsorption, facilitate charge transfer, suppress electron–hole recombination, and ultimately improve photocatalytic degradation efficiency toward tartrazine under UV irradiation.

Effectiveness of TiO_2/Biochar for Tartrazine Degradation

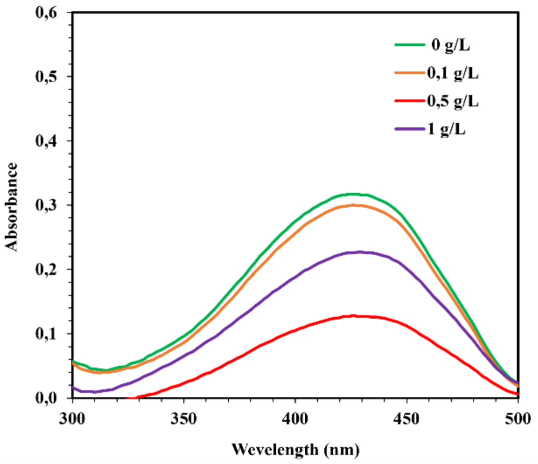


Figure 4. Absorbance spectra of tartrazine at various TiO_2/Biochar catalyst dosages.

Figure 4 shows the absorbance spectra of tartrazine at various TiO_2/Biochar catalyst dosages. The absorbance values decreased with increasing catalyst dosage, indicating enhanced degradation activity. The most significant decrease in absorbance was observed at the 0.5 g/L catalyst dosage, showing the optimum photodegradation performance among all variations.

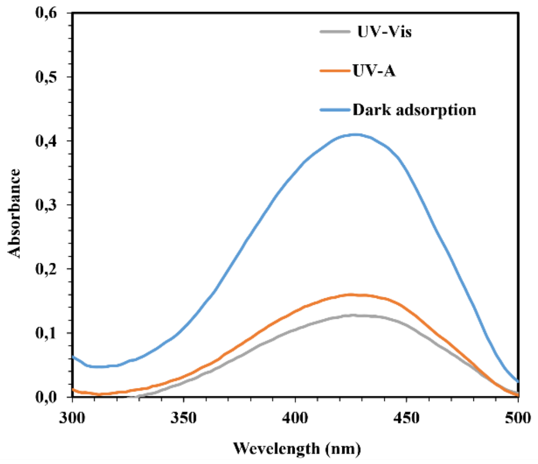


Figure 5. Effect of different treatment variations on the absorbance of tartrazine using TiO_2/Biochar photocatalyst.

Figure 5 shows the effect of different treatments on tartrazine degradation using 0.5 g/L of TiO_2/Biochar catalyst. UV–Vis irradiation produced the lowest absorbance value, indicating the highest degradation efficiency, while dark adsorption showed the highest absorbance due to the absence of photocatalytic activity. These results demonstrate that the type of light source significantly influences the degradation performance of TiO_2/Biochar photocatalysts.

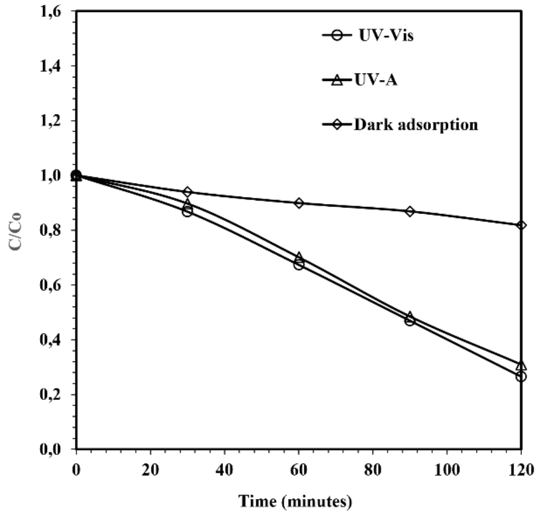


Figure 6. Effect of UV–Vis irradiation, UV–A irradiation, and dark adsorption on the degradation of tartrazine using TiO_2/Biochar photocatalyst.

Figure 6 shows the effect of different treatment conditions on tartrazine degradation using the TiO_2/Biochar photocatalyst. The C/C_0 values decreased with increasing reaction time, indicating a gradual reduction in tartrazine concentration during the degradation process. UV–Vis irradiation exhibited the greatest decrease in C/C_0, followed by UV–A irradiation, while dark adsorption showed the lowest reduction. These results demonstrate that light irradiation plays an important role in enhancing the photocatalytic activity of the TiO_2/Biochar composite. The superior degradation performance under UV–Vis irradiation can be attributed to the more effective photoactivation of TiO_2. Anatase TiO_2 possesses a band gap energy of approximately 3.2 eV, corresponding to light wavelengths below 387 nm. Under irradiation, photons with sufficient energy excite electrons from the valence band to the conduction band, generating reactive oxygen species such as hydroxyl radicals (•OH) and superoxide radicals ($O_2^{\bullet -}$), which contribute to tartrazine degradation (Schneider et al., 2014). In contrast, dark adsorption mainly involved adsorption by the biochar surface without photocatalytic activation. Furthermore, the preservation of the anatase TiO_2 phase, the formation of Ti–O–C bonds, and the homogeneous distribution of TiO_2 particles on the biochar surface contributed to improved photocatalytic performance by enhancing charge separation, suppressing electron–hole recombination, and improving pollutant adsorption.

DISCUSSION

Figure 1 presents the FTIR spectra of pristine TiO_2, biochar, and TiO_2/Biochar composite. The appearance of the Ti–O–C absorption band in the composite confirms the successful interaction between TiO_2 and biochar. This interfacial bonding indicates that biochar was not merely physically mixed with TiO_2 but was chemically integrated into the composite structure. Such interactions are beneficial for photocatalytic applications because they facilitate electron transfer between TiO_2 and biochar, thereby suppressing electron–hole recombination and improving the generation of reactive oxygen species during the degradation process. Furthermore, the preservation of characteristic functional groups suggests that the synthesis method successfully produced a stable composite without damaging the original structures of TiO_2 and biochar.

Figure 2 shows the XRD patterns of pristine TiO_2, biochar, and TiO_2/Biochar composite. The diffraction peaks observed in the composite corresponded to the anatase phase of TiO_2, indicating that the crystalline structure remained stable after composite formation. The preservation of the anatase phase is particularly important because anatase TiO_2 is widely recognized as the most photoactive crystalline form of TiO_2. The slight decrease in peak intensity observed in the composite can be attributed to the presence of amorphous biochar on the catalyst surface. These findings suggest that biochar functions as a supporting matrix without altering the crystal structure of TiO_2, thereby maintaining the photocatalytic properties required for efficient tartrazine degradation.

Figure 3 presents SEM micrographs of the TiO_2/Biochar composite. The images revealed a rough and porous surface morphology with TiO_2 particles distributed across the biochar matrix. Although some particle agglomeration was observed, the overall distribution of TiO_2 indicated successful immobilization on the biochar surface. The porous structure of biochar provides abundant adsorption sites for pollutant molecules, while the deposited TiO_2 particles serve as active photocatalytic centers. This morphology is advantageous because it promotes closer contact between tartrazine molecules and the photocatalyst surface, enhancing both adsorption and photocatalytic degradation processes. Overall, the TiO_2/Biochar photocatalyst was characterized by the formation of Ti–O–C interfacial bonds, preservation of the anatase TiO_2 crystalline phase, and successful distribution of TiO_2 particles on a porous biochar matrix. These characteristics indicate strong interfacial interactions between TiO_2 and biochar, which can enhance pollutant adsorption, facilitate charge transfer, suppress electron–hole recombination, and ultimately improve photocatalytic degradation efficiency toward tartrazine under UV irradiation.

Figure 4 shows the absorbance spectra of tartrazine at various TiO_2/Biochar catalyst dosages of 0 g/L, 0.1 g/L, 0.5 g/L, and 1 g/L. All samples exhibited a maximum absorbance peak around 420–430 nm, which is characteristic of tartrazine absorption. The absorbance values decreased with increasing catalyst dosage. The treatment without catalyst (0 g/L) resulted in a final concentration of 6.5 ppm with a degradation percentage of 35%, while the 0.1 g/L dosage produced a final concentration of 6.1 ppm with 39% degradation. The optimum result was obtained at a catalyst dosage of 0.5 g/L, producing a final concentration of 2.6 ppm with a degradation efficiency of 74%. However, at a dosage of 1 g/L, the degradation efficiency decreased to 53% with a final concentration of 4.4 ppm. This reduction was likely caused by catalyst particle agglomeration and reduced light penetration, which decreased the effective active sites available for photocatalytic reactions. These results indicate that catalyst dosage significantly affects the photocatalytic activity of TiO_2/Biochar in tartrazine degradation. Similar findings have been reported by Khan et al. (2024) and Bekhit et al. (2024), who stated that excessive catalyst loading may reduce degradation efficiency due to light scattering and particle aggregation effects.

Figure 5 shows the effect of different treatment variations on tartrazine degradation using 0.5 g/L of TiO_2/Biochar catalyst. The treatments included UV–Vis irradiation, UV–A irradiation, and dark adsorption. The UV–Vis treatment produced the lowest final concentration of 2.6 ppm with the highest degradation efficiency of 74%. The UV–A treatment resulted in a final concentration of 3 ppm with a degradation percentage of 67%, while dark adsorption produced a final concentration of 8.1 ppm with only 18% degradation. The degradation efficiency increased significantly under light irradiation compared to dark adsorption conditions, indicating the important role of light energy in the photocatalytic process. UV–Vis irradiation exhibited the highest degradation efficiency, followed by UV–A irradiation, while dark adsorption exhibited the lowest removal efficiency. This occurred because light irradiation activated TiO_2, generating electron–hole pairs that formed reactive hydroxyl radicals capable of degrading tartrazine molecules (Schneider et al., 2014). In the dark adsorption treatment, the process mainly involved adsorption by the biochar surface without photocatalytic activation. Anatase TiO_2 possesses a band gap energy of approximately 3.2 eV, corresponding to light wavelengths below 387 nm. Under UV irradiation, photons with sufficient energy excite electrons from the valence band to the conduction band, generating reactive oxygen species such as hydroxyl radicals (•OH) and superoxide radicals ($O_2^{\bullet-}$), which contribute to tartrazine degradation (Schneider et al., 2014). Therefore, the higher degradation efficiency observed under UV–Vis irradiation may be attributed to more effective photoactivation of TiO_2 compared with UV–A irradiation alone. These findings are consistent with previous studies reported by Mahmoudi et al. (2024) and Huang et al. (2022), which demonstrated that light irradiation plays a crucial role in enhancing photocatalytic degradation efficiency.

Figure 6 shows the effect of UV–Vis irradiation, UV–A irradiation, and dark adsorption on tartrazine degradation using the TiO_2/Biochar photocatalyst. The C/C_0 values gradually decreased with increasing irradiation time, indicating that the degradation process occurred progressively during the experiment. UV–Vis irradiation produced the greatest decrease in C/C_0 at 120 min, followed by UV–A irradiation, whereas dark adsorption showed the lowest reduction. These results indicate that light irradiation significantly enhanced tartrazine degradation throughout the reaction period. Similar degradation behavior has been reported by Hassaan et al. (2024) and Sen et al. (2023), who observed that photocatalytic degradation using semiconductor-based materials is enhanced under light irradiation due to the generation of reactive radical species.

The photocatalytic performance obtained in this study was further compared with previous reports using biochar-based photocatalysts. Setiawan (2026) reported that a ZnO/Biochar photocatalyst achieved 84% tetracycline degradation under optimum conditions. Although the degradation efficiency obtained in the present study (74%) was lower, the difference may be attributed to variations in pollutant characteristics, photocatalyst composition, and experimental conditions. Nevertheless, the TiO_2/Biochar composite demonstrated effective photocatalytic activity toward tartrazine degradation and confirmed the potential of biochar-supported semiconductor materials for wastewater treatment applications.

CONCLUSION

The TiO_2/Biochar composite was successfully synthesized and exhibited characteristics favorable for photocatalytic applications, including the formation of Ti–O–C bonds, preservation of the anatase TiO_2 phase, and successful distribution of TiO_2 particles on the porous biochar surface. The optimum photocatalytic performance was achieved at a catalyst dosage of 0.5 g/L, resulting in 74% tartrazine degradation after 120 min. Among the investigated conditions, UV–Vis irradiation showed the highest degradation efficiency compared with UV–A irradiation and dark adsorption. These findings demonstrate that the synergistic effect between biochar adsorption and TiO_2 photocatalysis makes the TiO_2/Biochar composite a promising and environmentally friendly material for dye-contaminated wastewater treatment.

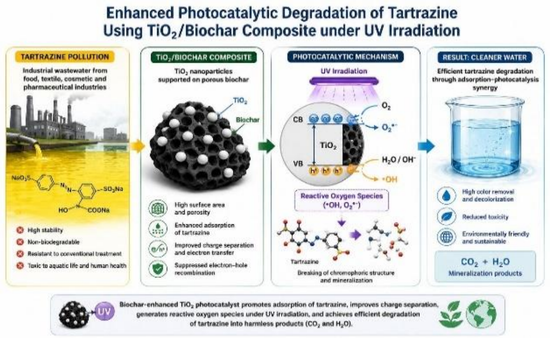


Figure 7. Degradation of tartrazine using a TiO_2/Biochar photocatalyst under UV irradiation.

Figure 7 illustrates the proposed photocatalytic degradation mechanism of tartrazine using a TiO_2/Biochar photocatalyst under UV irradiation. Tartrazine originating from industrial wastewater is initially adsorbed onto the porous biochar surface. Biochar not only enhances adsorption capacity but also promotes charge separation and suppresses electron–hole recombination in TiO_2. Upon UV irradiation, TiO_2 generates reactive oxygen species, including hydroxyl radicals (•OH) and superoxide radicals ($O_2^{\bullet-}$), which oxidize and degrade tartrazine molecules. Through the synergistic effects of adsorption and photocatalysis, tartrazine is progressively broken down into simpler compounds and ultimately mineralized into CO_2 and H_2O, resulting in cleaner and more environmentally friendly water.

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