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Synthesis and Photocatalytic Performance of ZnO-Impregnated Activated Carbon Derived from Oil Palm Fronds for Congo Red Degradation

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Abstract. A ZnO-impregnated activated carbon (AC–ZnO) composite derived from oil palm fronds was successfully synthesized and exhibited high photocatalytic activity toward Congo Red degradation. Congo Red is a persistent azo dye frequently detected in textile wastewater and poses serious environmental and health risks. This study aims to synthesize ZnO-impregnated activated carbon derived from oil palm fronds and to evaluate its photocatalytic performance for Congo Red degradation under UV irradiation. Activated carbon was prepared from oil palm fronds and impregnated with ZnO using a wet impregnation method with ZnO loadings of 5–25% and impregnation times of 6 and 12 h, followed by calcination at 400 °C. The composite materials were characterized by FTIR, XRD, and UV–DRS. Photocatalytic activity was assessed using a 10 ppm Congo Red solution and catalyst dosages of 25–75 mg under UV light. The highest degradation efficiency of 93.87% was achieved using 75 mg AC–ZnO with 15% ZnO loading and 6 h impregnation time. Enhanced performance was attributed to the synergistic effect between adsorption by activated carbon and photocatalytic oxidation by ZnO. The novelty of this study lies in the development of a ZnO-impregnated activated carbon composite derived from oil palm fronds and the systematic evaluation of ZnO loading and impregnation time on its photocatalytic performance toward Congo Red degradation. The biomass-derived AC–ZnO composite demonstrates strong potential as a sustainable and low-cost photocatalyst for the treatment of dye-contaminated wastewater.

Introduction

The textile and dyeing industries are significant contributors to environmental pollution, particularly through the discharge of dye-laden wastewater into aquatic ecosystems. Among various synthetic dyes, Congo Red (CR) has gained attention due to its chemical stability, toxicity, and potential carcinogenic properties, thus necessitating effective removal methods (Cheah & Sum, 2022; Fajriani et al., 2023). Recent advancements in photocatalytic degradation technologies utilizing semiconductor materials have emerged as promising solutions for degrading pollutants such as CR into benign byproducts like carbon dioxide (CO_2) and water (H_2O) (Alkahlawy et al., 2020; Peng et al., 2013).

Zinc oxide (ZnO) is noted as one of the most effective photocatalysts due to its superior oxidation ability, cost efficiency, and low toxicity (Katika et al., 2024; Vu et al., 2020). However, its practical applications are often hindered by low adsorption capacity and the rapid recombination of electron-hole pairs generated under light illumination (Aleena et al., 2025; Li et al., 2024). To address these challenges, integrating ZnO with porous support materials, particularly activated carbon (AC), has been shown to enhance its photocatalytic efficiency. The large surface area and developed pore structure of AC can provide increased interaction sites for dye molecules, whereas ZnO can facilitate efficient photocatalytic reactions (Chen, 2017; Yao et al., 2025).

The use of biomass-derived activated carbon, such as that produced from oil palm fronds, has recently gained traction as a sustainable alternative to conventional carbon

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sources (Dante et al., 2019; Lv et al., 2025). Oil palm fronds are abundant agricultural byproducts rich in lignocellulosic content, making them suitable precursors for activated carbon synthesis. Studies have indicated that its impregnation onto activated carbon derived from oil palm fronds can lead to optical modifications and narrowing of the band gap, further optimizing photocatalytic performance (Basavarajappa et al., 2018; Сун et al., 2019). However, the full potential of this composite material in degrading CR has yet to be comprehensively evaluated.

This research aims to investigate the photocatalytic activity of ZnO-impregnated activated carbon derived from oil palm fronds for the degradation of Congo Red under UV irradiation. The effects of ZnO loading and catalyst dosage were systematically evaluated. The novelty of this work lies in developing a sustainable AC–ZnO composite from oil palm fronds and elucidating the influence of ZnO loading and impregnation time on its photocatalytic degradation efficiency toward CR (Qiao et al., 2016; Thiripuranthagan et al., 2015).

Experimental

Material and Methods

Oil palm fronds were collected from local oil palm plantations in West Sumatra, Indonesia. Zinc nitrate hexahydrate ($Zn(NO_3)_2{\cdot}6H_2O$, ≥99%, Smart-Lab) was used as a ZnO precursor. Congo Red dye (analytical grade, Merck, Germany) was employed as the model pollutant. Distilled water was used in all preparation steps.

Procedures

Preparation of Activated Carbon from Oil Palm Fronds

Oil palm fronds were washed thoroughly with tap water followed by distilled water to remove adhering impurities, cut into small pieces, and oven-dried at 110 °C for 6 h. The dried samples were carbonized in a muffle furnace (heaters from LAC Asia ltd brand Ht40) at 250 °C for 90 min. The obtained char was ground and sieved to particle sizes below 100 mesh. Physical activation was carried out using a domestic microwave oven (2.45 GHz) operated at a power of 300 W for 5 min. The activation temperature was not monitored because the microwave system did not have temperature measurement or control capability. The activated carbon was washed repeatedly with distilled water until the pH of the filtrate reached approximately 7.0 and then dried at 110 °C for 1 h.

Synthesis of ZnO-Impregnated Activated Carbon (AC–ZnO)

ZnO-impregnated activated carbon was prepared by a wet impregnation method. Five grams of activated carbon were dispersed in 100 mL aqueous zinc nitrate hexahydrate solution ($Zn(NO_3)_2{\cdot}6H_2O$, analytical grade, ≥99% purity, Smart-Lab) with ZnO loadings of 5, 10, 15, 20, and 25% (w/v).

The suspensions were stirred at 250 rpm using a magnetic stirrer (IKA C-MAG HS7, Germany) for 6 and 12 h at room temperature. After impregnation, the samples were dried at 100 °C and subsequently calcined at 400 °C for 6 h in a muffle furnace to convert zinc nitrate into ZnO. The obtained composites were labeled as AC–ZnO according to ZnO loading and impregnation time.

Characterization

Characterization of ZnO, activated carbon, and ZnO-impregnated activated carbon (AC–ZnO) composites was carried out using several analytical techniques. Fourier Transform Infrared Spectroscopy (FTIR, Shimadzu IRTracer-100, Japan) was employed in the range of 4000–400 cm^{-1} to identify functional groups, including O–H, C–O, C=C, and Zn–O vibrations. Crystalline phases of ZnO, activated carbon, and AC–ZnO were analyzed by X-ray Diffraction (XRD, PANalytical X'Pert PRO) using Cu Kα radiation (λ = 1.5406 Å). Optical properties and light absorption behavior of the AC–ZnO composites were evaluated using UV–Diffuse Reflectance Spectroscopy (UV–DRS, Shimadzu UV-2600, Japan), and the band gap energy was estimated using the Tauc plot method.

Photocatalytic Activity Test

Photocatalytic experiments were conducted using 50 mL of CR solution (10 ppm) mixed with AC–ZnO photocatalyst at dosages of 25, 50, and 75 mg. Prior to UV irradiation, the suspension was magnetically stirred in the dark for 30 min to establish adsorption–desorption equilibrium. The mixture was then irradiated under a UV lamp (Philips, 15 W) for 120 min with continuous stirring.

After irradiation, the suspension was centrifuged at 4000 rpm for 10 min, and the supernatant was analyzed using a UV–Vis spectrophotometer (Shimadzu UV-1800, Japan) at 498 nm. The degradation efficiency (%) was calculated using:

$$\text{Degradation efficiency (\%)} = \frac{A_0 - A_t}{A_0} \times 100 \qquad (1)$$

where A_0 is the initial absorbance and A_t is the absorbance after irradiation time *t*.

All photocatalytic experiments were conducted as single measurements for preliminary screening. The results are reported as degradation efficiencies under different ZnO

loadings, impregnation times, and catalyst dosages.

Result and Discussion

Formation of ZnO-Impregnated Activated Carbon Composite

ZnO-impregnated activated carbon (AC–ZnO) was successfully synthesized via wet impregnation followed by calcination at 400 °C. The formation of the composite was confirmed by FTIR and XRD analyses, which revealed the presence of Zn–O vibrations and characteristic diffraction peaks of hexagonal wurtzite ZnO in the AC–ZnO sample. Furthermore, UV–DRS analysis showed a reduction in band gap energy from 3.20 eV for pure ZnO to 2.62 eV for AC–ZnO, indicating an interaction between ZnO and activated carbon. These characteristics were associated with the enhanced photocatalytic degradation of CR, with the highest degradation efficiency reaching 93.87% under optimum conditions.

Effect of ZnO Loading and Catalyst Dosage on Photocatalytic Degradation

Photocatalytic activity of AC–ZnO was evaluated using a 10 ppm CR solution under UV irradiation, with the maximum absorption wavelength observed at 498 nm. The degradation efficiency of AC–ZnO with different ZnO loadings and catalyst dosages at an impregnation time of 6 h is presented in Figure 1.

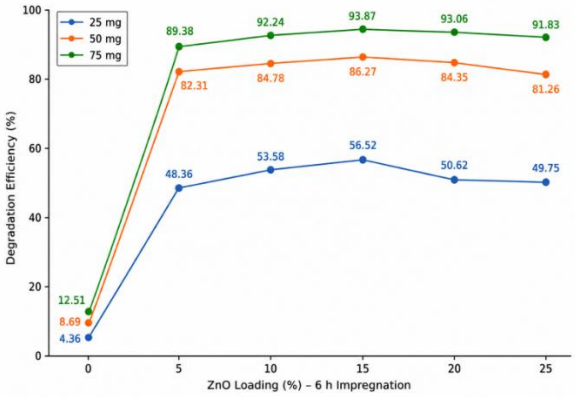

Figure 1. Photocatalytic degradation efficiency of Congo Red (10 ppm) using AC–ZnO with different ZnO loadings (5–25%) and catalyst dosages (25, 50, and 75 mg) at 6 h impregnation time under UV irradiation.

The results show that degradation efficiency increased with increasing ZnO loading up to 15%. The highest degradation efficiency of 93.87% was achieved using 75 mg AC–ZnO with 15% ZnO loading. This improvement can be attributed to the increased number of active sites and enhanced formation of reactive oxygen species such as •OH and $•O_2^-$ radicals, which play a crucial role in dye oxidation (Shinde et al., 2017). At lower ZnO loadings, the limited amount of photocatalytic sites leads to lower degradation efficiency.

However, it was observed that upon further increasing ZnO loadings to 20% and 25%, there was a notable decline in degradation efficiency. This phenomenon can be explained by the potential obstruction of the pore structure of activated carbon due to excessive ZnO coverage, leading to reduced surface area accessibility and impaired mass transfer of dye molecules (Amornpitoksuk & Suwanboon, 2015). Additionally, the accumulation of ZnO may escalate the recombination rate of photogenerated electron-hole pairs, which in turn diminishes the overall photocatalytic activity (Bagal et al., 2023).

These observations align with similar trends documented in previous studies involving ZnO-supported photocatalytic systems, which indicate that beyond a certain loading threshold, the photocatalytic performance tends to plateau or even decline due to these adverse interactions (Bagal et al., 2024), (Shinde et al., 2017). For instance, the composite materials in other studies have demonstrated optimal dye degradation efficiencies typically in the range of 80% to 95% when subjected to UV irradiation, echoing the performance metrics achieved in the current research (Cheah et al., 2025). The degradation efficiency of 93.87% highlighted in this study thus illustrates a competitive efficacy for waste management applications.

Effect of Impregnation Time

The degradation efficiency of AC–ZnO with different ZnO loadings and catalyst dosages at an impregnation time of 12 h is shown in Figure 2.

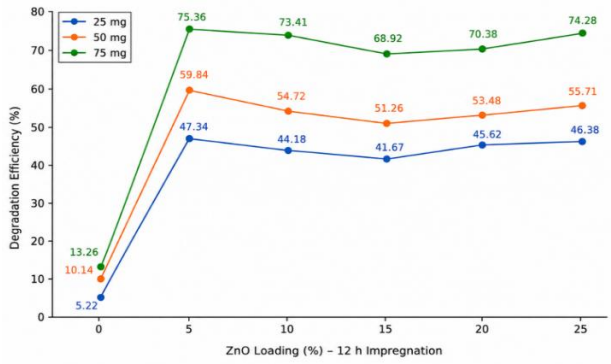

Figure 2. Photocatalytic degradation efficiency of Congo Red (10 ppm) using AC–ZnO with different ZnO loadings (5–25%) and catalyst dosages (25, 50, and 75 mg) at 12 h impregnation time under UV irradiation.

In general, the degradation efficiencies at 12 h impregnation were lower than those at 6 h. Prolonged impregnation may lead to excessive deposition of ZnO inside the pores of activated carbon, reducing adsorption capacity and limiting the accessibility of photocatalytic sites (Norozi et al., 2023). These results suggest that impregnation time is a critical parameter that must be optimized together with ZnO loading.

FTIR Analysis

FTIR analysis confirmed the successful formation of ZnO in the AC–ZnO composites.

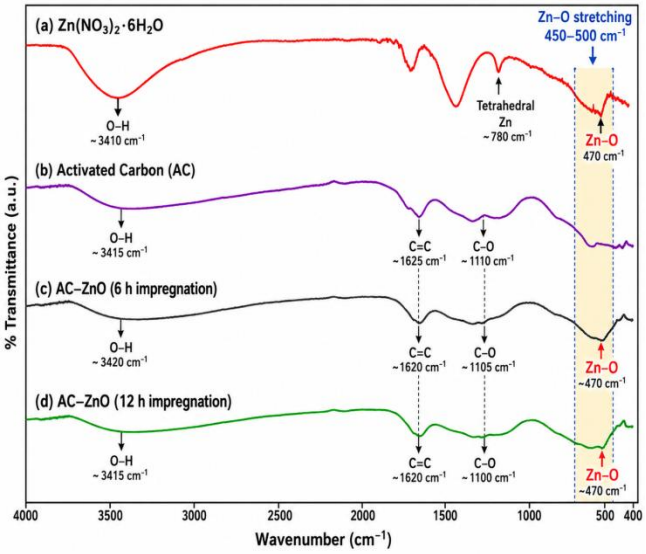

Figure 3. FTIR spectra of (a) $Zn(NO_3)_2{\cdot}6H_2O$, (b) activated carbon (AC), (c) AC–ZnO (6 h impregnation), and (d) AC–ZnO (12 h impregnation). Adapted from Syabila and Khair (2022).

As shown in Figure 3, an absorption band appeared in the region of 450–500 cm^{-1}, corresponding to Zn–O stretching vibrations. In addition, characteristic O–H, C=C, and C–O bands were retained after impregnation and calcination, indicating that the activated carbon framework remained structurally stable. A more detailed interpretation of the FTIR spectra has been reported in our previous study (Syabila & Khair, 2022), therefore, only the features relevant to ZnO formation are discussed herein.

Optical Properties (UV–DRS Analysis)

Previous work reported that ZnO exhibited a band gap of approximately 3.20 eV and that impregnation onto activated carbon reduced the band gap to about 2.62 eV (Syabila & Khair, 2022). In the present study, these optical properties are referenced only to support the observed photocatalytic behavior. This phenomenon has been reported previously and is attributed to electronic interactions between ZnO and the carbon matrix that facilitate charge transfer that improve photocatalytic behavior (Ali et al., 2016; Ibrahim, 2022; Nibret et al., 2015). In the present work, UV–DRS results are included to support the photocatalytic behavior, while detailed discussion of optical modification has been reported elsewhere (Syabila & Khair, 2022).

The UV–DRS transmittance spectra (Figure 4) show decreased transmittance intensity with increasing ZnO loading, indicating enhanced light absorption by the composite materials. In Figure 4, T5–T25 represent AC–ZnO samples with ZnO loadings of 5–25%, respectively.

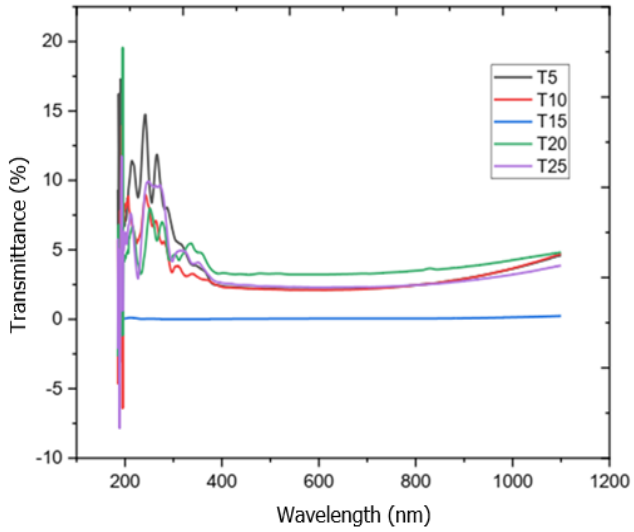

Figure 4. UV–DRS transmittance spectra of AC–ZnO with different ZnO loadings (T5 = 5%, T10 = 10%, T15 = 15%, T20 = 20%, and T25 = 25%)..

XRD Analysis

As presented in the XRD patterns (Fig.5), distinct diffraction peaks appear at approximately 2θ values of 31.7°, 34.4°, and 36.2°, which respectively correspond to the (100), (002), and (101) planes of hexagonal wurtzite ZnO (Babu & Narayanan, 2013; Lubis et al., 2025; Nasrollahzadeh et al., 2018; Wang et al., 2014). This alignment with the known characteristic peaks for bulk ZnO confirms successful impregnation of ZnO onto the activated carbon matrix. The presence of these peaks amidst the broad diffraction pattern of AC indicates that the crystalline ZnO effectively integrates into the predominantly amorphous structure of activated carbon, thereby enhancing its functionality in photocatalytic applications (Abro et al., 2020; Shrestha et al., 2020).

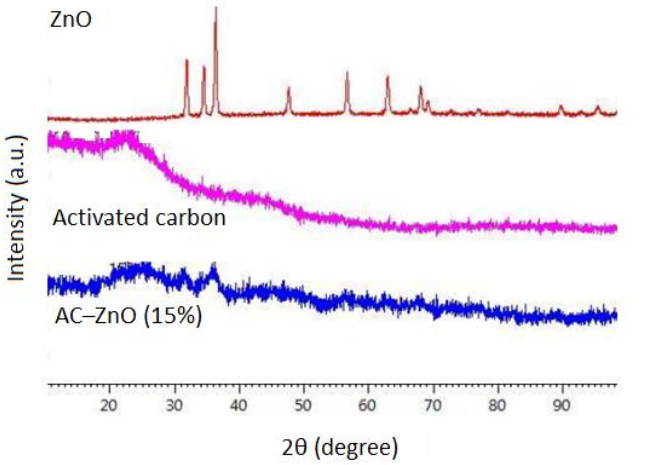

Figure 5. XRD patterns of (a) ZnO, (b) activated carbon, and (c) AC–ZnO with 15% ZnO loading. The AC–ZnO sample with 15% ZnO loading was selected because it exhibited the highest photocatalytic degradation efficiency.

Activated carbon exhibits a broad diffraction hump, characteristic of amorphous carbon. The coexistence of ZnO crystalline peaks with the amorphous carbon background indicates successful impregnation of ZnO without altering its crystal structure.

Proposed Photocatalytic Mechanism

The photocatalytic degradation of CR over AC–ZnO involves synergistic adsorption and photocatalysis. Activated carbon adsorbs CR molecules and brings them into close proximity with ZnO active sites (Movahedi et al., 2009). Under UV irradiation, ZnO generates electron–hole pairs. The photogenerated holes react with water or hydroxide ions to form •OH radicals, while electrons reduce dissolved oxygen to form $\bullet O_2^-$ radicals (Vu et al., 2020). These reactive species oxidize CR molecules into smaller intermediates and ultimately mineralize them into CO_2 and H_2O (Movahedi et al., 2009; Rokesh et al., 2016).

Practical Implications and Limitations

From a practical perspective, the use of oil palm frond–derived activated carbon as a support material offers advantages in terms of low cost, sustainability, and waste valorization. The high degradation efficiency obtained under relatively mild conditions suggests that AC–ZnO has potential for application in dye-contaminated wastewater treatment.

This study has several limitations. Photocatalytic experiments were conducted as single measurements without kinetic analysis or catalyst reusability tests. In addition, mineralization of CR was not evaluated using parameters such as COD or TOC. Beyond demonstrating effective CR degradation, this study highlights the potential of converting oil palm frond waste into a functional support material for ZnO photocatalysts. The findings provide new insights into how ZnO loading and impregnation duration influence the physicochemical properties and photocatalytic behavior of AC–ZnO composites, offering a basis for the development of sustainable biomass-derived photocatalysts.

Conclusion

The AC–ZnO composite synthesized from oil palm frond-derived activated carbon and ZnO exhibited excellent photocatalytic activity toward CR degradation under UV irradiation. The optimum condition was obtained at 15% ZnO loading and 6 h impregnation time with a catalyst dosage of 75 mg, resulting in the highest degradation efficiency of 93.87%. FTIR, XRD, and UV–DRS analyses confirmed the successful formation of the AC–ZnO composite and revealed a reduction in band gap energy to 2.62 eV, which contributed to the improved photocatalytic performance. The results demonstrate that oil palm frond-derived activated carbon can serve as an effective support for ZnO, producing a sustainable and low-cost photocatalyst for dye-contaminated wastewater treatment. These findings provide a basis for future studies focusing on catalyst stability, reusability, and reaction kinetics.

Conflict of Interest

The authors declare that there is no conflict of interest.

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