



FTIR Analysis of ZnO-Functionalized Activated Carbon Derived from Oil Palm Empty Fruit Bunches for Potential Photocatalytic Applications

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Abstract :

This study investigates the surface chemical characteristics of ZnO-functionalized activated carbon (AC) derived from oil palm empty fruit bunches (OPEFB) using Fourier Transform Infrared (FTIR) spectroscopy. Activated carbon was prepared through carbonization at 400 °C followed by chemical activation using KOH. ZnO functionalization was performed via the sol-gel method with a nominal ZnO loading of 10 wt% relative to AC. FTIR analysis revealed dominant absorption bands corresponding to O–H stretching ($\sim 3430\text{ cm}^{-1}$), C=O stretching ($\sim 1630\text{ cm}^{-1}$), and C–O vibrations ($\sim 1050\text{--}1100\text{ cm}^{-1}$), indicating the presence of oxygen-containing surface functional groups. The appearance of a characteristic Zn–O vibrational band in the $450\text{--}600\text{ cm}^{-1}$ region confirmed the incorporation of ZnO within the composite structure. Minor peak shifts and variations in band intensity observed after ZnO modification suggest changes in the local chemical environment and possible interactions between ZnO nanoparticles and oxygen-containing functional groups. However, FTIR analysis alone does not provide definitive confirmation of specific interfacial bonding configurations. The results indicate that KOH activation preserved reactive oxygenated functionalities that remained stable after ZnO incorporation. The coexistence of porous AC characteristics and ZnO-associated vibrational features suggests that the synthesized AC/ZnO composite possesses surface chemical properties relevant for adsorption-assisted photocatalytic applications. This work demonstrates the potential valorization of OPEFB biomass into functional carbon-based hybrid materials.

Keywords: FTIR, ZnO, activated carbon, biomass

1. Introduction

The rapid expansion of industrialization and urban activities has significantly intensified water pollution, particularly from organic contaminants such as synthetic dyes, pharmaceuticals, and agricultural chemicals (Lestari, et al. 2025; Zhao, Li, et al. 2020). Among these pollutants, methylene blue (MB) (Mishra et al. 2022) and other cationic dyes are widely recognized due to their persistence (Viswanathan 2017), chemical stability, and resistance to biodegradation (Xu et al. 2023). The continuous discharge of dye-containing wastewater poses serious environmental and health concerns, as these compounds reduce light penetration, inhibit photosynthetic activity in aquatic ecosystems, and may induce toxic, mutagenic, or carcinogenic effects. Consequently, the development of efficient, low-cost, and environmentally sustainable materials for pollutant removal remains a critical challenge in environmental remediation research (Viswanathan 2018).

Activated carbon (AC) has long been regarded as one of the most effective adsorbent materials owing to its high specific surface area, tunable pore structure, and abundance of surface functional groups (Faisal et al. 2021). These characteristics enable AC to adsorb a wide variety of pollutants through physical adsorption, electrostatic interactions, and surface complexation mechanisms (Azam et al. 2022). However, the relatively high production cost associated with conventional precursors, such as coal and synthetic polymers, limits its

broader application. Recently, increasing attention has been directed toward the utilization of biomass waste as a renewable and economical precursor for AC production (Mohd Azmi et al. 2022). Biomass-derived activated carbon not only reduces production costs but also supports waste valorization strategies aligned with circular economy and sustainable materials development (Robinson, Hensley, and Medlin 2016).

Oil palm empty fruit bunches (OPEFB), a major byproduct of the palm oil industry, represent an abundant lignocellulosic biomass resource, particularly in palm oil-producing countries such as Indonesia. Despite its large availability, OPEFB remains underutilized and is often disposed of through open burning or landfilling, contributing to secondary environmental issues. Converting OPEFB into activated carbon offers a promising pathway to transform agricultural waste into high-value functional materials. Moreover, the inherent carbon-rich composition and porous structure of OPEFB-derived biochar provide a suitable foundation for further physicochemical modification (Zakaria et al. 2023).

Chemical activation using potassium hydroxide (KOH) is widely recognized as an effective technique for enhancing the porosity and surface reactivity of biomass-derived carbon materials. During activation, KOH promotes pore formation through redox reactions and carbon etching processes, resulting in increased surface area and the generation of oxygen-containing functional groups, including hydroxyl ($-\text{OH}$), carbonyl ($\text{C}=\text{O}$), and $\text{C}-\text{O}$ species. These surface functionalities play a crucial role in determining adsorption behavior and serve as active sites for anchoring inorganic nanoparticles. Therefore, KOH-activated carbon derived from OPEFB provides not only an efficient adsorbent but also a versatile support material for composite synthesis (Huang et al. 2019).

Among various semiconductor materials, zinc oxide (ZnO) has attracted considerable interest due to its wide band gap (3.37 eV), strong oxidation capability, chemical stability, and relatively low toxicity. ZnO exhibits promising photocatalytic properties for degrading organic pollutants (Bhaskar and Bhame 2024). Nevertheless, pure ZnO often suffers from rapid electron-hole recombination and limited adsorption capacity, which may reduce its overall photocatalytic efficiency. To address these limitations, coupling ZnO with activated carbon has emerged as a promising strategy (An et al. 2018). Activated carbon can enhance pollutant adsorption, improve ZnO dispersion, and potentially facilitate charge separation by acting as an electron acceptor. Such synergistic interactions may contribute to improved photocatalytic performance (Lestari, et al. 2025).

A fundamental understanding of surface chemistry and functional group interactions is essential for evaluating and optimizing composite materials. Fourier Transform Infrared (FTIR) spectroscopy serves as a powerful analytical technique for identifying chemical bonds, surface functional groups, and structural modifications resulting from activation and nanoparticle incorporation. FTIR analysis enables the detection of characteristic vibrational bands associated with oxygen-containing groups and Zn-O bonds, providing insights into chemical interactions at the ZnO-carbon interface. Variations in peak position, intensity, and broadening can indicate changes in surface functionalities and possible interfacial interactions (Alprol et al. 2025).

Despite numerous studies on activated carbon and ZnO-based composites, spectroscopic investigations focusing on the surface chemical modifications of KOH-activated OPEFB-derived carbon following ZnO functionalization remain relatively limited. Many studies emphasize adsorption or photocatalytic performance, while detailed interpretation of functional group evolution and interfacial interactions is less frequently addressed. A systematic FTIR analysis is therefore necessary to elucidate the chemical characteristics governing composite behavior.

This study aims to investigate the surface chemistry of ZnO-functionalized activated carbon derived from OPEFB using FTIR spectroscopy. Specifically, the objectives are: (i) to identify the dominant functional groups present on KOH-activated carbon; (ii) to examine spectral changes after ZnO incorporation; and (iii) to interpret potential interactions between ZnO nanoparticles and surface oxygen-containing functionalities. The findings are expected to provide fundamental insights into the structural and chemical features of the AC/ZnO composite and to support future investigations on adsorption-assisted photocatalytic applications.

2. Research Methods

Materials

Oil palm empty fruit bunches (OPEFB) were collected from a local palm oil mill in North Sumatra, Indonesia. The chemicals used in this study included potassium hydroxide (KOH), sodium hydroxide (NaOH), zinc acetate dihydrate ($\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$), zinc oxide (ZnO), methylene blue (MB), and ethanol, all of

analytical grade and purchased from Merck. Deionized (DI) water was used throughout all experimental procedures. The equipment employed included standard laboratory glassware, an analytical balance, a hotplate with magnetic stirrer, an oven, a muffle furnace, a reflux system equipped with a condenser, thermometers, and filtration apparatus.

Preparation of Activated Carbon

The collected OPEFB was thoroughly washed with deionized water to remove adhering impurities, dust, and residual oil. The cleaned biomass was dried in an oven at 105 °C for 24 h to eliminate moisture content. The dried OPEFB was then cut into smaller pieces and subjected to carbonization at 400 °C for 1 h in a muffle furnace under limited air conditions to obtain biochar. The resulting biochar was chemically activated using potassium hydroxide (KOH). The activation process involved impregnating the biochar in a KOH solution under continuous stirring and mild heating for 5 h. After activation, the solid product was filtered and repeatedly washed with deionized water until the filtrate reached a near-neutral pH (pH 6–7). The activated carbon (AC) was subsequently dried in an oven at 110 °C for 12 h and stored in an airtight container for further use.

Synthesis of ZnO-Functionalized Activated Carbon

ZnO-functionalized activated carbon (AC/ZnO composite) was synthesized using the sol–gel method. The composite composition was designed at a nominal ZnO loading of 10 wt% relative to activated carbon (AC). The mass of zinc acetate precursor was selected to obtain approximately this ZnO content after conversion. A mixture containing 1.16 g of KOH-activated carbon (AC) and 22.5 g of zinc acetate dihydrate ($\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$) was dispersed in 40 mL of ethanol under magnetic stirring. The suspension was transferred into a two-neck round-bottom flask equipped with a reflux condenser and heated at 80 °C for 2 h under continuous stirring to promote sol–gel formation and deposition of zinc species onto the AC surface. After reflux, the mixture was allowed to cool to room temperature, followed by filtration and washing with deionized water and ethanol to remove residual impurities and unreacted precursors. The obtained solid was dried at 105 °C for 12 h and stored in a desiccator. The final product was labeled as AC/ZnO composite.

FTIR Characterization

FTIR analysis was performed to identify the surface functional groups and chemical structure of the synthesized materials. The spectra were recorded in the wavenumber range of 4000–500 cm^{-1} using an FTIR spectrometer. The analysis focused on detecting oxygen-containing functional groups and Zn–O vibrational bands associated with ZnO incorporation.

3. Results and Discussion

FTIR characterization was conducted to analyze the surface functional groups and chemical structure of the ZnO-functionalized activated carbon (AC/ZnO composite). This technique provides important information regarding the chemical modifications induced by KOH activation and subsequent ZnO incorporation. The composite was prepared using a 90:10 weight ratio (w/w), corresponding to a 10 wt% ZnO loading relative to activated carbon (AC). This composition was selected to obtain a hybrid material that integrates the high surface area and porous characteristics of AC with the semiconducting properties of ZnO. The FTIR spectrum of the synthesized AC/ZnO composite is presented in Figure 1.

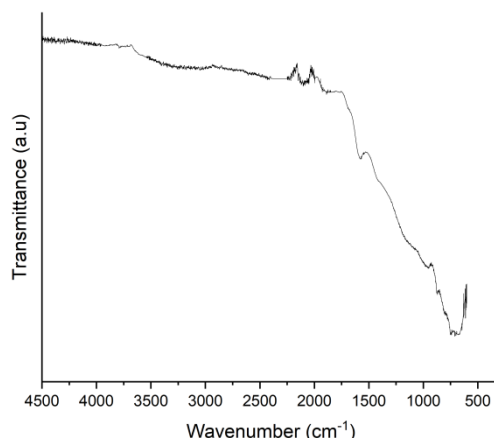


Figure 1. FTIR spectrum of ZnO-functionalized activated carbon derived from oil palm empty fruit bunches (OPEFB).

The FTIR spectrum exhibits several absorption bands within the wavenumber range of 4000–500 cm^{-1} , indicating the presence of oxygen-containing functional groups characteristic of activated carbon as well as Zn–O vibrational features (Albiss and Abu-Dalo 2021). A broad absorption band centered around 3430 cm^{-1} is attributed to O–H stretching vibrations, which may originate from hydroxyl groups, adsorbed moisture, or surface oxygenated functionalities. The persistence of this band after ZnO modification suggests that hydroxyl groups remain present on the carbon surface, potentially contributing to surface reactivity and hydrophilicity (Khalid et al. 2016). A peak observed near 1630 cm^{-1} corresponds to C=O stretching vibrations, typically associated with carbonyl or carboxyl groups. These oxygen-containing functional groups are commonly formed during chemical activation using KOH, where redox reactions and surface oxidation occur. The retention of this band following ZnO incorporation indicates that ZnO deposition did not eliminate the surface oxygenated functionalities, implying that these groups may still play a role in interfacial interactions and adsorption processes (Al-Asadi et al. 2025).

The absorption band detected in the region of 1050–1100 cm^{-1} is assigned to C–O stretching vibrations, characteristic of alcohol, phenolic, or ether groups. Such functionalities are known to enhance surface polarity and provide potential coordination sites for metal oxide species. The presence of these bands in the AC/ZnO composite indicates that oxygenated surface groups were largely preserved after ZnO functionalization. A distinct absorption band observed in the low wavenumber region around 570 cm^{-1} is attributed to the Zn–O stretching vibration, confirming the successful incorporation of ZnO into the activated carbon matrix. This spectral feature serves as direct evidence of ZnO presence within the composite structure. Minor variations in peak position, intensity, and band broadening were observed after ZnO modification. These spectral changes may indicate alterations in the local chemical environment and possible interactions between ZnO nanoparticles and oxygen-containing surface functional groups. However, it should be emphasized that FTIR analysis alone does not provide definitive confirmation of specific interfacial bonding configurations, such as Zn–O–C linkages (Sayed et al. 2024).

The observed functional groups are consistent with those reported for biomass-derived activated carbon and ZnO-based composites. Previous studies have identified similar absorption bands corresponding to O–H, C=O, C–O, and Zn–O vibrations, supporting the validity of the present spectral interpretation. The coexistence of oxygen-containing functional groups and Zn–O bands suggests that the composite retains key chemical features associated with adsorption and photocatalytic materials. From a structural standpoint, the FTIR results suggest that ZnO nanoparticles were successfully associated with the activated carbon surface. The preservation of oxygenated functional groups indicates that the chemical activation process effectively generated reactive sites that remained stable after ZnO incorporation. These functionalities are known to influence adsorption behavior and may facilitate interfacial interactions between ZnO and the carbon matrix (Cruz et al. 2017).

In terms of potential application, the hybrid structure of the AC/ZnO composite is expected to be advantageous for combined adsorption and photocatalytic processes. The porous activated carbon matrix may

enhance pollutant adsorption, while ZnO may contribute photocatalytic activity under light irradiation. Although photocatalytic performance was not experimentally evaluated in this study, the identified surface functional groups and Zn–O spectral features indicate structural characteristics relevant for adsorption-assisted photocatalytic investigations. The relatively broad nature of certain absorption bands, particularly in the 1000–1700 cm^{-1} region, may be attributed to overlapping vibrations of multiple oxygen-containing functional groups and the amorphous character of the activated carbon structure. The carbonization and activation processes can induce partial aromatization and dehydrogenation, which may reduce the intensity of aliphatic C–H vibrations. Such spectral behavior is consistent with previous reports on chemically activated biomass-derived carbons (Cruz et al. 2018; Yang and Lua 2003).

Overall, the FTIR characterization confirms the presence of ZnO and the retention of oxygen-containing functional groups within the AC/ZnO composite. The results provide valuable information regarding surface chemistry and structural features of the synthesized material. Nevertheless, further analyses, including XRD, SEM, and photocatalytic performance testing, are recommended to obtain a more comprehensive understanding of structure–property relationships.

4. Conclusion

This study investigated the surface chemical characteristics of ZnO-functionalized activated carbon derived from oil palm empty fruit bunches (OPEFB) using FTIR spectroscopy. The analysis successfully identified the dominant oxygen-containing functional groups on the KOH-activated carbon, including O–H, C=O, and C–O vibrations. Following ZnO incorporation, the appearance of the characteristic Zn–O absorption band confirmed the presence of ZnO within the composite structure. Comparative evaluation of the FTIR spectra before and after ZnO modification revealed minor peak shifts and variations in band intensity, suggesting changes in the local chemical environment. These spectral features may indicate possible interactions between ZnO nanoparticles and oxygen-containing surface functionalities. However, FTIR analysis alone does not provide definitive confirmation of specific interfacial bonding configurations such as Zn–O–C linkages. Overall, the results demonstrate that KOH activation preserved reactive oxygenated functional groups that remained stable after ZnO functionalization. The coexistence of porous activated carbon and ZnO-associated vibrational features indicates that the synthesized AC/ZnO composite possesses surface characteristics relevant for adsorption-assisted photocatalytic applications. Further investigations involving structural, morphological, and performance analyses (e.g., XRD, SEM, photocatalytic testing) are recommended to validate the functional implications of the observed surface chemistry.

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