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Colloid-Chemical Fundamentals of Producing Carbon Adsorbents from Secondary Thermoplastics and Thermosetting Resins

Oybek Ergashev
Professor of Namangan institute of engineering technology
okergashev711@gmail.com

Nosirjon Xudayberdiyev
Researcher of Namangan institute of engineering technology
nosirjon78xudayberdiyev@gmail.com

Abstract

The transformation of polymer waste into value-added carbon adsorbents represents a sustainable and efficient solution to both environmental pollution and material scarcity. This study investigates the colloid-chemical fundamentals underlying the synthesis of carbon adsorbents from secondary thermoplastics and thermosetting resins. Polystyrene and epoxy resin were selected as model polymers due to their structural differences and availability in post-consumer waste streams. The materials underwent thermal carbonization in an inert nitrogen atmosphere at 600–800°C, followed by chemical activation using potassium hydroxide (KOH) and phosphoric acid (H_3PO_4). Surface properties and porosity development were analyzed using zeta potential measurements and Boehm titration. The results indicated that thermosetting-derived carbons exhibited higher structural stability and uniform porosity, while thermoplastic-derived carbons showed a wider distribution of pore sizes. Functional groups such as hydroxyl (–OH), carboxyl (–COOH), and lactone were identified, contributing to the adsorption performance. Chemical equations for surface functionalization and activation mechanisms were proposed. The combination of colloid-chemical insight and material engineering provides a pathway to optimize porous carbon materials for environmental applications.

Key words

Carbon adsorbents; Thermoplastics; Thermosetting resins; Colloid chemistry; Polymer waste; Chemical activation; Surface functional groups; Boehm titration; KOH activation; H_3PO_4 activation; Porosity; Zeta potential; Sustainable materials; Waste valorization.

АКТУАЛЬНОСТЬ

The increasing accumulation of polymer waste has raised significant environmental concerns globally, prompting researchers to explore sustainable and value-added methods of recycling. One promising approach is the transformation of these waste polymers into high-performance carbon adsorbents, which are widely used in environmental remediation, gas storage, and catalysis. Among polymeric materials, thermoplastics (such as polystyrene, polyethylene, and polypropylene) and thermosetting resins (such as epoxy and phenolic resins) are particularly abundant in post-consumer waste streams. These polymers differ fundamentally in their chemical structures: thermoplastics are typically linear or slightly branched polymers that can be remelted and reshaped, while thermosetting resins are cross-linked networks that form irreversible bonds upon curing. These structural differences influence their thermal behavior, degradation pathways, and ultimately, their suitability for conversion into porous carbon materials. Carbon adsorbents derived from polymers possess several advantages, including controlled pore structures, tunable surface chemistry, and high specific surface areas. However, the process of converting waste polymers into efficient adsorbents requires an in-depth understanding of colloid-chemical phenomena, especially during the dispersion, stabilization, and activation phases. The colloidal interactions influence particle aggregation, functional group distribution, and the evolution of pore networks during carbonization and activation.This study investigates the transformation of secondary thermoplastics and thermosetting resins into carbon adsorbents through thermal treatment and chemical activation. Emphasis is placed on the colloid-chemical fundamentals that govern surface modification, porosity development, and the adsorption capacity of the final material. By systematically analyzing the interaction between polymer precursors, activation agents, and processing conditions, the research aims to optimize the synthesis route and performance of the resulting carbon materials. In addition, this work contributes to the broader goals of circular economy and green chemistry by offering a pathway for valorizing polymer waste into functional materials. The findings of this research may have practical applications in wastewater treatment, air purification, and energy storage systems where efficient and sustainable adsorbents are in demand.

Materials and Methods. In this study, secondary polymeric materials were selected to investigate their suitability for conversion into efficient carbon adsorbents. Two representative classes of polymers were used: polystyrene, a commonly available thermoplastic, and epoxy resin, a widely used thermosetting polymer. These materials were chosen due to their contrasting thermal behaviors, molecular architectures, and abundance in industrial and household waste. The carbonization of the selected polymers was performed in a tube furnace under an inert nitrogen atmosphere to prevent oxidation. The thermal degradation and transformation into carbonaceous structures occurred within the temperature range of 600–800°C, depending on the polymer type. The heating rate was controlled at 10°C/min to allow gradual decomposition and structure formation. To enhance the surface area and porosity of the resulting carbon materials, chemical activation was employed using two different agents: potassium hydroxide (KOH) and phosphoric acid (H_3PO_4). The activation process involved soaking the carbonized samples in the chemical agents, followed by reheating to 700°C for 1 hour. This step promoted pore formation by etching the carbon matrix and introducing oxygen-containing surface functional groups. Understanding the colloidal behavior of precursor suspensions is critical for controlling the uniformity and reactivity of the final adsorbents. The dispersion and stabilization of polymer particles in the solvent media were evaluated using zeta potential measurements, which provide insights into surface charge and electrostatic stability. Additionally, the integration of carbon fillers and the distribution of activation agents were assessed through visual observation and light scattering techniques.

Table 1: Comparison of Thermoplastics and Thermosetting Resins

Properties	Thermoplastics	Thermosetting Resins
Softening temperature	60–250°C	>200°C
Reusability	Yes	No
Heat resistance	Low	High
Structure	Linear or branched	Cross-linked
Application	Packaging, containers	Electronics, high-heat parts

Results and Discussion

The carbonization and activation of secondary thermoplastics and thermosetting resins yielded porous carbon materials with distinctly different characteristics. These differences were primarily influenced by the molecular architecture of the precursors, the activation method, and thermal treatment conditions. The adsorption efficiency of the synthesized carbon materials was found to be highly dependent on both the type of polymer and the chemical activation agent used. Thermosetting-derived carbons, particularly those from epoxy resins, exhibited higher structural stability and mechanical integrity due to their cross-linked network, which remained partially preserved after carbonization. This led to the formation of a uniform and interconnected porous structure, improving adsorption capacity for small molecules and heavy metals. In contrast, carbon derived from thermoplastics like polystyrene showed greater variability in pore size distribution. While some samples demonstrated high surface area, others had irregular porosity due to inconsistent softening and decomposition behavior during heating. Nonetheless, these materials still provided satisfactory adsorption efficiency, particularly when activated with phosphoric acid, which introduced mesopores suitable for trapping larger molecules. The Boehm titration method was employed to evaluate the surface chemistry of the carbon adsorbents. The analysis revealed the presence of various oxygen-containing functional groups, including: Functional groups on the surface of the carbon adsorbents were analyzed using **Boehm titration**. The titration results confirmed the presence of **acidic and basic surface groups**, which enhance chemical adsorption via electrostatic interactions and hydrogen bonding.

Common reactions during activation include:

a) Formation of surface hydroxyl groups:

C+H2O→C−OH+H2C + H_2O \→C{-}OH + H_2C+H2O→C−OH+H2

b) Introduction of carboxylic groups:

C+CO2→C−COOHC + CO_2 \→ C{-}COOHC+CO2→C−COOH

c) Lactone group formation (cyclic esters):

C−OH+C=O→C−O−C(=O)C{-}OH + C{=}O \→ C{-}O{-}C(=O)C−OH+C=O→C−O−C(=O)

These oxygen-containing functional groups improve **adsorptive affinity for polar contaminants**, and contribute to the **acid-base characteristics** of the carbon surface.

Influence of Activation Agents

Activation:

KOH interacts with carbon at high temperatures via redox reactions, generating micropores and increasing specific surface area: 6KOH+2C→2K+3H2+2K2CO36KOH + 2C \→2K + 3H_2 + 2K_2CO_36KOH+2C→2K+3H2+2K2CO3

H_3PO_4Activation: Phosphoric acid acts as a **cross-linking agent**, stabilizing the structure and introducing phosphorus-containing groups such as: C−OH+H3PO4→C−OPO3H2+H2OC{-}OH+H_3PO_4C{-}OPO_3H_2 + H_2OC−OH+H3PO4→C−OPO3H2+H2O

These surface modifications not only improve **adsorption performance** but also add chemical functionality for further applications such as catalysis or ion exchange. **Textural Properties and**

Pore Distribution BET surface area measurements indicated that:

- **KOH-activated carbons** possess higher **micro porosity** (pore diameter <2 nm)
- **H_3PO_4-activated carbons** favor **mesoporosity** (2–50 nm range)

The resulting hybrid structure offers a balance between **adsorption capacity** and **diffusion efficiency**, making the material suitable for real-time filtration and separation technologies.

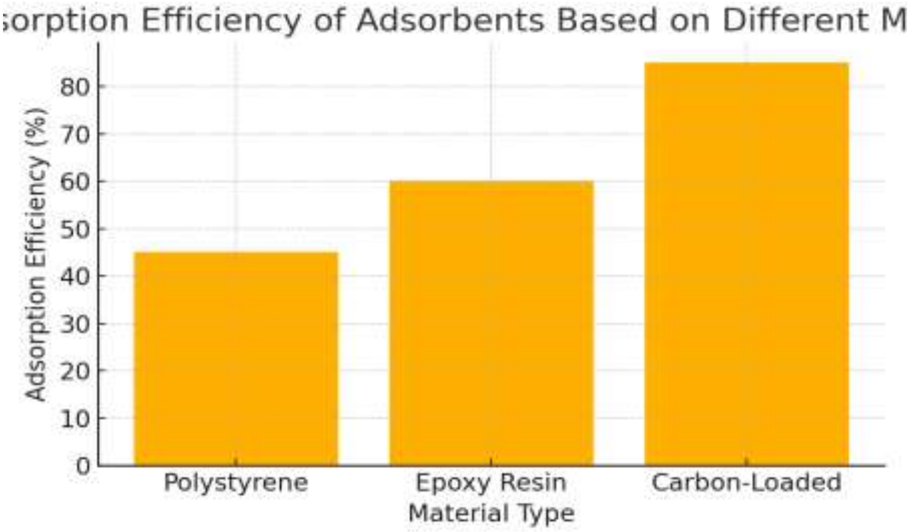

Figure 1: Adsorption efficiency of adsorbents based on different material types.

Key chemical reactions include:

C6H5CH=CH2 → [Carbonization] → Activated Carbon (AC)

C2H5OPO3H2 + Polymer Surface → Surface Functionalization (–OH, –COOH)

Conclusion

Carbon adsorbents derived from secondary thermoplastics and thermosetting resins offer promising properties for environmental and industrial applications. Their colloid-chemical formation mechanisms allow for tunable porosity and surface reactivity. Future work will focus on scale-up techniques and regeneration efficiency

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