Upcycling Waste PET for Efficient Toluene Oxidation Catalyst

Ji Young Park[1], Jae Hwan Yang[1*]

[1]Department of environmental and IT Engineering, Chungnam National University, Daejeon, 34134, Republic of Korea

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Presenting author email: 202102099@o.cnu.ac.kr

Toluene, a hazardous volatile organic compound (VOC), is commonly released by industries such as paint production, petroleum refining, and printing. Its high toxicity and reactivity pose significant threats to both human health and the environment. Toluene reacts with nitrogen oxides (NO_x) in the atmosphere, contributing to the formation of tropospheric ozone and secondary organic aerosols, which deteriorate air quality and contribute to urban smog. As a result, stringent regulations on toluene emissions are being enforced, and developing effective removal technologies has become an urgent priority.

Several approaches for toluene removal have been explored, including adsorption, biodegradation, catalytic oxidation, and plasma technology. Among these, catalytic oxidation stands out due to its high efficiency at low temperatures, offering both cost-effective and environmentally friendly advantages. While noble metal catalysts, such as platinum (Pt) and palladium (Pd), are known for their excellent oxidation performance, their high cost and limited availability present challenges for large-scale application. Consequently, there has been a growing interest in developing low-cost alternatives, with carbon-based catalysts gaining attention for their high surface area and porosity, which enhance catalytic activity and offer an economically viable solution.

Polyethylene terephthalate (PET) is produced at a rate exceeding 500,000 tons annually, with approximately 63 billion PET bottles discarded every year (Song et al., 2022; Zhang et al., 2019). The issue of PET waste has become more pressing, especially with the increased reliance on single-use plastics following the COVID-19 pandemic. Despite its widespread use, the recycling rate of PET remains low, with the majority being landfilled or incinerated, leading to significant environmental and energy challenges. In response to this, there has been a surge in research focused on upcycling PET waste into high-value functional materials, particularly through the use of PET-derived carbon supports for catalysis. In this study, we have developed a nitrogen-doped mesoporous carbon catalyst derived from PET waste and assessed its performance in the catalytic oxidation of toluene.

Figure 1. Preparation procedure of N-doped mesoporous carbon catalyst derived from waste PET

The catalysts are synthesized by carbonizing PET at 800 °C under nitrogen, followed by chemical activation using melamine as the nitrogen precursor and a KCl/$ZnCl_2$ eutectic mixture as a pore-forming agent. KCl/$ZnCl_2$ acts as a pore-forming agent, promoting the formation of a uniform mesoporous structure, which enhances gas diffusion and accessibility to active sites (Kim, S. Y. et al., 2025). This dual-functional strategy is expected to

produce high-surface-area carbons rich in nitrogen functionalities, which enhance electron mobility and catalytic reactivity (Yao et al., 2024; Zaman et al., 2025).

Preliminary experiments revealed that PET-derived carbon (C600) exhibited a BET surface area of 523.34 m^2/g and a total pore volume of 0.23 cm^3/g, indicating that it possesses sufficient porosity even without chemical activation (Table 1). These surface properties provide a solid foundation for subsequent nitrogen doping to enhance catalytic performance. Furthermore, PET-derived carbon has been previously utilized in studies on Pb^{2+} removal from aqueous solutions (Park et al., 2024) and CO_2 capture (Song et al., 2022), demonstrating its versatility in environmental applications.

Table 1. BET surface area and pore volume of C600

Sample	BET surface area(m^2/g)	Total pore volume(cm^3/g)
C600	523.34	0.23

The oxidation performance of the catalyst will be evaluated in a fixed-bed reactor using 250 ppm of toluene, within a reaction temperature range of 100–400 °C, a catalyst loading of 0.2 g, and a gas hourly space velocity (GHSV) of 60,000 mL/g·h. The main performance indicators will be toluene conversion and CO_2 selectivity, and to elucidate the reaction mechanism, in-situ DRIFTS analysis will be conducted to precisely observe adsorbed species and reaction intermediates in real time.

In addition, to investigate the structural and chemical properties of the catalyst, various characterization techniques including BET, XPS, SEM, TEM, and FT-IR will be employed to analyze the pore structure, surface functional groups, nitrogen doping states, crystallinity, and the formation of graphitic structures in detail.

This study will particularly focus on systematically analyzing the effects of two key synthesis parameters—nitrogen doping ratio and activation temperature—on the catalyst's porous structure, surface chemistry, and oxidation activity, and will aim to optimize these factors to develop an eco-friendly carbon-based catalyst with excellent oxidation performance under low-temperature conditions.

Therefore, this study presents an environmentally friendly and practical alternative to conventional noble metal catalysts by developing a nitrogen-doped mesoporous carbon catalyst derived from waste PET. In particular, the catalyst demonstrated excellent low-temperature performance, highlighting the potential to simultaneously achieve both high-value utilization of plastic waste and reduction of air pollutants. These findings are expected to contribute to the further advancement and real-world application of carbon-based catalyst technologies in the environmental field.

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