


Chapter 10

Nanoporous carbon adsorbents derived from PET waste for the adsorption of environmental contaminants in aqueous matrices

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Abstract

This chapter discusses the valorisation of polyethylene terephthalate (PET) waste converted into nanoporous carbon for the removal of environmental contaminants in aqueous matrices. The structural, physical, and chemical properties that are key to the performance of PET waste-derived nanoporous carbon are briefly discussed. The synthetic routes uncovering all the interesting properties of nanoporous properties were deliberated. Some key studies sourced from the literature are identified and discussed to evaluate the viability and sustainability of nanoporous carbon as effective adsorbents for the removal of pollutants within the environmental water matrices. Future prospects are deliberated to visualise some key areas requiring attention within the general PET waste beneficiation research.

Keywords: PET waste, Nanoporous carbon, Adsorption, Environmental, Valorisation

1. Introduction

The global production of polyethylene terephthalate (PET) bottles reached 13.1 million tons in 2020 [1], aiding for the recycling and repurposing of PET waste as a crucial global responsibility. Subsequently, polyethylene terephthalate is now recognised as the third most widely used polymer in the production of packaging materials after polyethylene (PE) and polypropylene (PP) [2,3]. Considering that only one PET bottle is recycled for every four PET bottles traded, landfills are overflowing with million tons of discarded PET bottles [4]. Moreover, PET bottles do not biodegrade, instead they photodegrade, taking up to 1000 years for each bottle to decompose [4,5]. Conventionally used plastic recycling methods, such as incineration and mechanical recycling are not economically viable and also raise some environmental concerns [1]. To avoid a global PET waste bottle catastrophe, the production of high value-added products from PET waste bottles has been recognised [6–8]. Since PET was identified as a condensation polymer made by the reaction of terephthalic acid (BDC) and ethylene glycol (EG), PET waste has been repurposed and used for the production of various synthetic materials such as metal-organic frameworks (MOFs) [6,7] and polybutylene terephthalate (PBT) [9], as well as products such as cleaner asphalt pavement materials [8,10] and textile materials [11], among others. Interestingly, due to their high carbon content, the absence of mineral matter and impurities, PET waste has been used in the preparation of nanoporous carbon (NPC) [12]. Owing to their adjustable pore structures and functional groups such as the OH group, nanoporous carbons have attracted attention in energy storage [13], catalysis [14], adsorption [15–17], among other applications. As an example, Ubaidullah, et al. [18] fabricated a high surface area nitrogen doped mesoporous carbon (N-MC) through an economically feasible approach using waste PET plastic bottles through MOF-5 construction. The synthesised N-MC displayed a high specific surface area of $\sim 2243 \text{ m}^2 \text{ g}^{-1}$ with mesopores ($\sim 14 \text{ nm}$), and an excellent electrochemical energy storage performance. The authors concluded that the fabrication of N-MC using PET waste makes it an appealing process for environmental remediation and an efficient low-cost electrode material for supercapacitor applications. Using PET waste-based nanoporous carbon, a pathway to deal with a variety of environmental problems, such as trace metals, pharmaceutical and pesticides contaminations [19–21], among others, might be a possibility.

This chapter, therefore, describes the synthesis strategies, alongside important properties of PET waste-derived nanoporous carbon materials that were discussed prior to their application on the removal of various environmental contaminants.

2. Synthesis strategies for PET waste conversion into nanoporous carbons

PET plastic bottles are among the most valuable types of waste, thus their valorisation into new adsorbent materials has been explored using a variety of methods, including direct carbonisation (physical or chemical activation), hydrothermal carbonisation, and pyrolysis [22]. Subsequently, the common methods responsible for the conversion of PET waste into nanoporous carbon have been briefly described.

2.1 Direct carbonisation

Literature findings have reported intensively that the physical (temperature treatment usually between 500–1000 °C) and chemical activation (using activation agents, such as KOH, NaOH, H_3PO_4 , $ZnCl_2$, and K_2CO_3) enhance the surface properties of carbon-based materials, thus producing highly porous structured carbon-based materials [17,22–24]. To this end, Kaur *et al.* [12] synthesised the O-enriched porous carbonaceous adsorbents by directly carbonising hacked smaller PET waste bottle pieces with high carbon content at different temperatures (500–800 °C) in a tubular furnace under inert atmosphere prior to chemical activation using KOH. Figure 1 displays the SEM images of the adsorbent prepared by direct carbonisation without activation (Figure 1a) and the chemically activated carbon (Figure 1b–e). It can be noted that each carbon chemically activated with KOH displays better development of pores than the inactivated carbon. The best performing material for gas adsorption showed the best pore structure with a BET surface area of $1690 \text{ m}^2\text{g}^{-1}$ and micropore volume of $0.78 \text{ cm}^3 \text{ g}^{-1}$ is displayed in Fig. 1c. The authors ascribed the best performance of this materials to the higher microporosity and basic oxygen functionalities observed after KOH chemical activation.

2.2 Hydrothermal carbonisation

Hydrothermal carbonisation (HTC) has been described as a thermochemical conversion process usually carried out at temperatures between 150–250 °C for the conversion of organic waste to hydrochar with residence times between 0.5 and 8 hours [25,26]. However, this method has been modified for the synthesis of nanoporous carbon from PET waste into a two-step synthetic procedure as reported in the literature [6,12]. The initial step involves the depolymerisation of waste PET bottles that are first cut into small PET flakes, followed by their hydrolysis in a hydrothermal reactor (at 220 °C for 8 hours) with a given ratio of ethylene glycol and deionised water as described on the literature [6]. The product obtained is an organic linker called terephthalic acid (BDC) (shown in Figure 2), which

is then physically activated at temperatures around 700–850 °C to form nanoporous carbon in the second step of the synthesis [12,17].

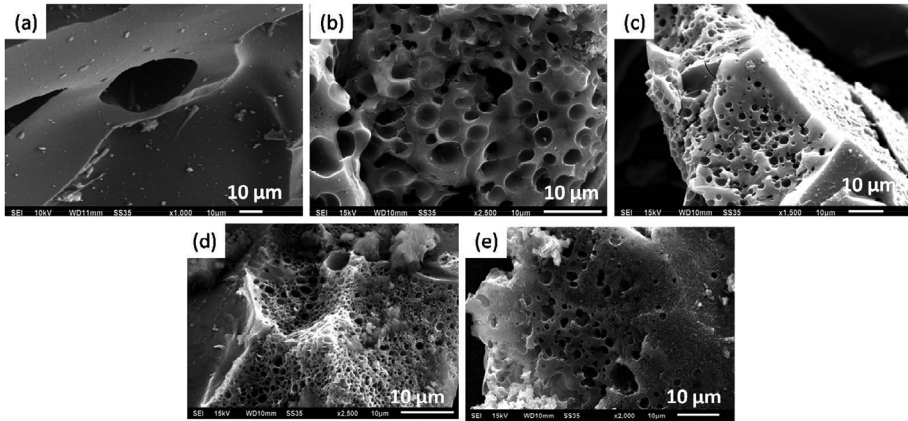


Figure 1: SEM images of nanoporous carbon derived from PET waste. Reprinted with permission from [12]. Copyright 2019, Elsevier.

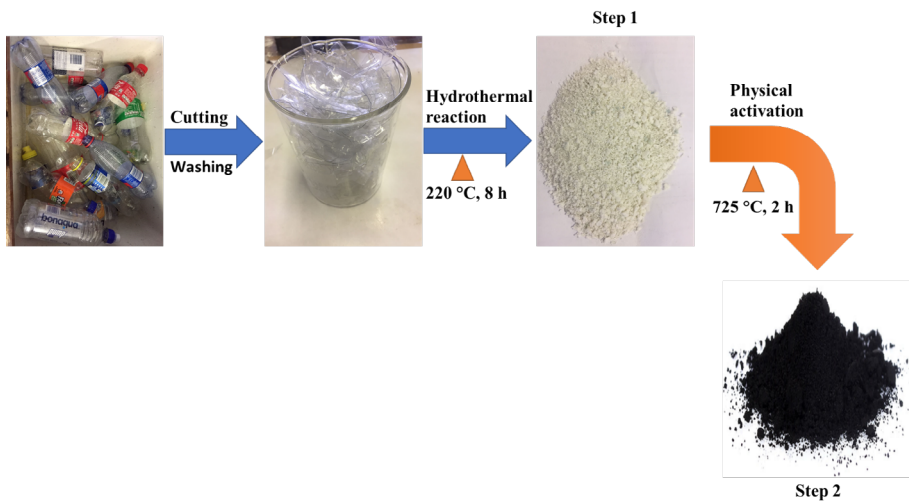


Figure 2: Hydrothermal synthesis and physical activation of PET waste bottles to porous carbon.

3. Properties of PET waste derived nanoporous carbon

Various structural, physical, and chemical properties of nanoporous carbon derived from PET waste have been outlined in the literature. For instance, Wenlong *et al.* [14] reported the nanoporous carbons (NPCs) with various pore structures and morphology control that were prepared

using MgO particles as nanotemplates and PET powders derived from waste PET bottles as a carbon precursor. The controllable porosity was very critical on the hybridisation with platinum particles, leading to the preparation of very small platinum particles. Yuan *et al.* [27] prepared an N-doped microporous carbon through the valorisation of waste PET plastic bottles through a one-pot synthesis. The Nitrogen doping did not only enhance the selectivity of the adsorbent, but also acted as active sites for the adsorption. Wei and Ali [28] proposed a two-steps strategy based on the controlled carbonisation and thermal oxidation in air to convert waste PET into porous carbon materials with high values of surface area and electrical conductivity. The PET- derived carbon materials prepared at different temperatures were found to exhibit an interesting combination of properties, including a high surface area of 644 m²/g, and electron conductivity of 37 S/m observed for the best performing adsorbent material. Subsequently, the structural, physical, and chemical properties observed from these literature studies were summarised in Figure 3.

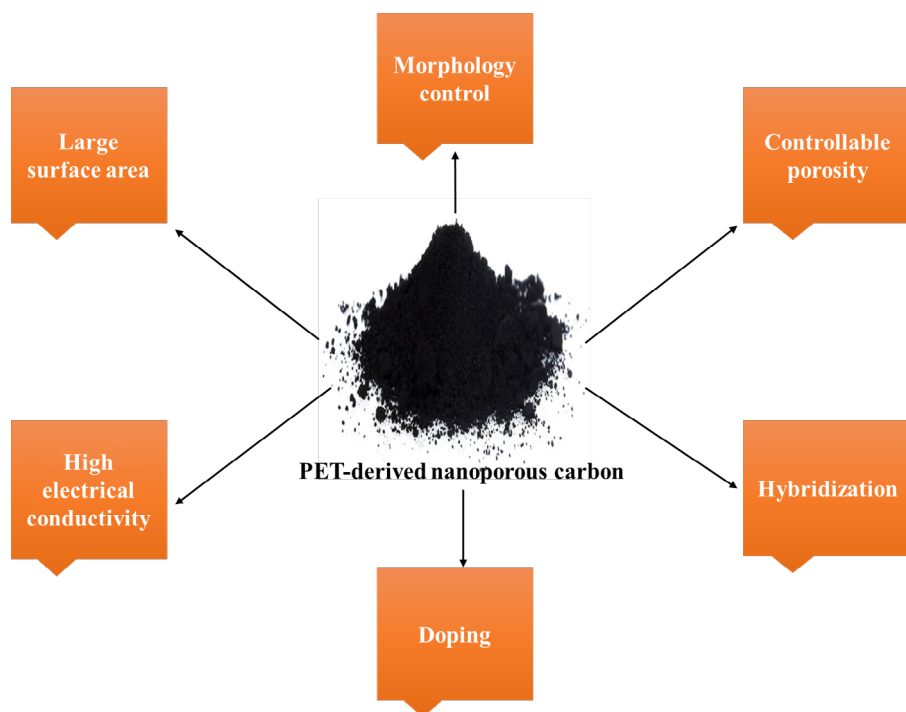


Figure 3: Key properties of PET-derived nanoporous carbon.

4. Application of nanoporous carbon as adsorbents

The global availability of PET waste in large quantities is unsurprisingly visible within the environment. Thus, the valorisation of PET waste as an efficient waste beneficiation strategy leading to the reduction of environmental pollution has attracted interest [6,7,10,27]. Due to the high content of carbon, negligible amounts of inorganic matter in its chemical constitution, high chemical, mechanical, and thermal stability, PET waste has advanced as an excellent porous carbon adsorbent in many gas adsorption applications, specifically in CO₂ adsorption [12,16,22,27,29]. Furthermore, PET waste has been converted to nanoporous carbon adsorbents for various environmental remediation applications ranging from organic dye removal to pesticides and pharmaceuticals removal in wastewater [15,30]. Although very few studies have been conducted for the removal of trace/heavy metals in aqueous environments using PET waste derived nanoporous adsorbents, their interesting structural, physical, and chemical properties seem to be attractive for these studies. To this end, Mendoza-Carrasco et al. [31] developed a waste-treats-waste approach enabling the waste PET to be used as the precursor for the preparation of activated carbons (ACs) by physical activation with steam and chemical activation with potassium hydroxide. Although the SEM images in Figure 4 show that the physically activated carbon (Figure 4a) is agglomerated and appears less porous than the chemically activated carbon (Figure 4b), the BET surface areas reached 1235 m² g⁻¹ with physical activation and 1002 m² g⁻¹ with chemical activation. The authors declared the formation of micro to mesoporous structures with physical activation and microporous structures with chemical activation. The selected AC samples were used to study the adsorption process for both p-nitrophenol and Fe(III) in aqueous solution, individually and simultaneously from the kinetic and equilibrium standpoint. Concerning the simultaneous adsorption of p-nitrophenol and Fe(III) in aqueous solution, both the PET derived ACs exhibited a better adsorption behaviour towards p-nitrophenol than commercial AC, both in terms of adsorption rate and adsorption capacity. Thus, the PET waste-derived AC adsorbents did not perform well for the adsorption of Fe(III) ions due to the p-nitrophenol already taking the active sites within the adsorbent, indicating that Fe(III) ions need to be studied without the presence of their organic counterpart.

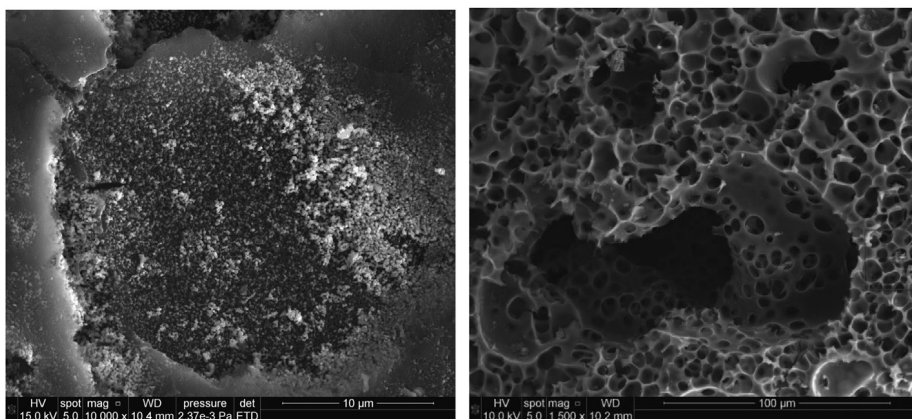


Figure 4: SEM images of PET waste-derived activated carbon prepared using (a) physical activation and (b) chemical activation. Reprinted with permission from [31]. Copyright 2016, Elsevier.

5. Challenges and future prospects

- Due to its high carbon contents, low nitrogen and sulfur contents, PET waste appears to be a suitable material to be used as the precursor in the preparation of nanoporous carbon materials, however, problems occur when mixing PET bottles by colour, as these introduce unwanted organic compounds during the synthesis procedures.
- The caps of PET bottles are usually made from polyolefins and have to be recycled separately, adding to the problems of coloured bottles in the mix.
- Considering that there have been very few studies utilising the structural, physical, and chemical properties of PET waste-derived nanoporous carbon for the removal of metals in aqueous systems (river water, wastewater, drinking water, etc.), this area paves new avenues for solving some of the environmental problems the world faces.

6. Conclusion

This chapter highlights the potential of utilising PET waste-derived nanoporous carbon adsorbents for the removal of environmental contaminants in aqueous environments. The subsequent literature discussed shows that the waste-treats-waste concept might be viable for the removal of contaminants from the environmental viewpoint. It is evident that the locally available PET waste can act as inexpensive precursor materials for the preparation of porous carbon adsorbents for the aqueous environment remediation. However, it is also evident that

more investigations are needed in order to assess the effectiveness of the PET waste-derived porous carbon materials as adsorbents for the removal of various environmental pollutants, thus proving if this is a sustainable concept to pursue.

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