Chapter 10

Engineering the Invisible:
Synthesis, Characterization, and Applications of Nanoporous Materials

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ABSTRACT

Nanoporous materials are a major research focus due to their unique structures and diverse applications in catalysis, drug delivery, and environmental remediation. This chapter reviews the synthesis, characterization, and practical applications of nanoporous materials. It examines various synthesis methods, detailing their principles, advantages, and limitations. Key characterization techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD), transmission electron microscopy (TEM), and atomic force microscopy (AFM) are discussed for assessing important properties like surface area and pore size. The chapter also highlights the performance of nanoporous materials in enhancing reaction rates in catalysis, improving drug delivery systems, and aiding in pollutant degradation. Ideally, this chapter contributes to providing researchers and practitioners with the knowledge necessary to advance the further development and application of nanoporous materials in various technological and industrial areas.

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1. INTRODUCTION

Nanoporous materials have attracted significant attention in the scientific community because of their unique structural properties and vast range of applications. Characterized by their pore volume and large surface area, these materials can be engineered at the nanoscale to exhibit specific functionalities that are advantageous in several fields including catalysis, drug delivery, and environmental remediation. According to the International Union of Pure and Applied Chemistry (IUPAC), porous materials are categorized into three distinct groups: (a) microporous materials with pore sizes between 0 and 2 nm; (b) mesoporous materials, with pores between 2 and 50 nm; and (c) macroporous materials, characterized by pores larger than 50 nm (Rouquerol et al., 2011; X. S. Zhao, n.d.). Nanoporous materials fall under the broader category of porous materials, featuring bulky porosities and pore diameters ranging between 1 and 100 nm, offer a significant internal surface area, enabling chemical reactions, molecular adsorption, or controlled drug release. But occasionally, materials with pore sizes as small as 1000 nm are referred to as “nanoporous” (Polarz & Smarsly, 2002) . Nano porous materials have much finer, smaller pores compared to the other categories. This diverse spectrum of materials includes carbon-based substances like activated carbon, carbon nanotubes, polymers, zeolites, zeotypes, metal-organic frameworks, and mesoporous materials such as carbons, silicas, and metal oxides (Lu & Zhao, 2004). This chapter explores the multifaceted world of nanoporous materials, exploring their synthesis, characterization, and practical applications. Techniques such as sol-gel processing, hydrothermal synthesis, and template-assisted methods(Kołodziejczak-Radzimska & Jesionowski, 2014) will be discussed in detail, highlighting their principles, advantages, and limitations. For example, the sol-gel process is noted for its ability to produce highly homogeneous materials with controlled porosity, as demonstrated in the synthesis of titanium dioxide nanoporous films (Zha & Roggendorf, 1991; Bokov et al., 2021). Hydrothermal synthesis, which involves crystallization from high-temperature aqueous solutions under pressure, has been effectively employed to produce zeolites with precise pore structures (Byrappa & Haber, 2001; Cundy & Cox, 2005; T. Gupta et al., 2021; Kołodziejczak-Radzimska & Jesionowski, 2014). Template-assisted methods, which utilize hard and soft templates to shape the pore architecture, have shown great promise in fabricating materials with custom-made properties for specific applications (Stein, 2003).

Following the synthesis discussion, the chapter will explore key characterization techniques essential for analyzing the structural and practical properties of nanoporous materials. Methods like SEM, XRD, and gas adsorption measurements will be emphasized for their roles in determining crucial parameters like pore size, surface area and morphology. SEM and TEM provide detailed pore structure images and distribution, as illustrated in studies of mesoporous carbon. Gas adsorption techniques, like Brunauer-Emmett-Teller (BET) method, are crucial for assessing the pore volume and surface area, which are indicative of the material's potential performance in various applications (Ryoo et al., 1999; Haul, 1982; Ravikovitch & Neimark, 2001; Izhar et al., 2022).

The ability to tailor nanoporous materials for particular applications makes them indispensable in modern technology and industry, particularly their performance in catalysis, drug delivery and environmental remediation. In catalysis, for instance, the large surface area and customizable pore structure of nanoporous materials can significantly enhance reaction rates and selectivity(Yu et al., 2013; Taguchi & Schüth, 2005). According to recent research, mesoporous silica materials can be designed to increase the accessibility of active sites, hence enhancing the efficiency of catalytic reactions. (D. Zhao et al., 1998). By enabling the encapsulation and controlled release of therapeutic agents, these materials are revolutionizing drug delivery systems in the medical field. This improves efficacy and decreases side

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