

RESEARCH ARTICLE

Hierarchical Porous Carbon Nanofibers Derived from Metal-Organic Frameworks for High-Performance Supercapacitors

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Abstract: This study presents a novel synthesis strategy for hierarchical porous carbon nanofibers (HPCNFs) derived from zeolitic imidazolate framework-8 (ZIF-8) grown on electrospun polyacrylonitrile (PAN) nanofibers. The resulting HPCNFs exhibit a specific surface area of 1,285 m²/g with a hierarchical micro-meso-macroporous structure. When evaluated as supercapacitor electrodes, the HPCNFs deliver a remarkable specific capacitance of 342 F/g at 1 A/g, with 95.3% capacitance retention after 10,000 charge-discharge cycles. The exceptional electrochemical performance is attributed to the synergistic effects of high surface area, interconnected porous channels, and nitrogen doping from the ZIF-8 precursor.

1. Introduction

Supercapacitors have attracted considerable attention as promising energy storage devices due to their high power density, fast charge-discharge rates, and long cycle life. Among electrode materials, porous carbon materials remain the most widely used owing to their abundance, chemical stability, and tunable pore structure. However, the development of carbon electrodes with simultaneously high surface area, good electrical conductivity, and hierarchical pore architecture remains a significant challenge.

Metal-organic frameworks (MOFs) have emerged as excellent precursors for porous carbon synthesis due to their well-defined crystalline structures and high surface areas. In particular, ZIF-8 has been extensively studied because of its high nitrogen content (33.3 wt%) and sodalite-type topology. When combined with electrospun nanofiber substrates, the resulting composites can leverage both the structural advantages of MOF-derived carbons and the mechanical flexibility of nanofiber networks.

2. Experimental Methods

Polyacrylonitrile (PAN, Mw = 150,000) nanofibers were fabricated by electrospinning from 10 wt% PAN/DMF solution at 18 kV with a tip-to-collector distance of 15 cm. ZIF-8 was grown in situ on PAN nanofibers by immersing in a solution of Zn(NO₃)₂·6H₂O (2.933 g) and 2-methylimidazole (3.244 g) in methanol (100 mL) at room temperature for 24 h.

Table 1. Synthesis parameters and resulting textural properties of carbon nanofibers

Sample	ZIF-8 Loading (wt%)	S_{BET} (m^2/g)	V_{total} (cm^3/g)	N Content (at%)
CNF-0	0	156	0.12	4.2
HPCNF-30	30	687	0.48	7.1
HPCNF-50	50	1,052	0.71	8.9
HPCNF-70	70	1,285	0.93	10.3

The composites were carbonized at 900°C under N_2 atmosphere with a heating rate of 5°C/min and held for 2 h. The ZIF-8 nanocrystals acted as self-sacrificial templates, creating hierarchical pores upon thermal decomposition while simultaneously doping nitrogen into the carbon framework.

3. Results and Discussion

Figure 1 presents the N_2 adsorption-desorption isotherms and pore size distributions of the prepared samples. The HPCNF-70 sample shows a Type IV isotherm with distinct hysteresis loops, confirming the coexistence of micropores and mesopores. The BET surface area reaches 1,285 m^2/g , which is approximately 8× higher than that of the pristine CNF-0 sample.

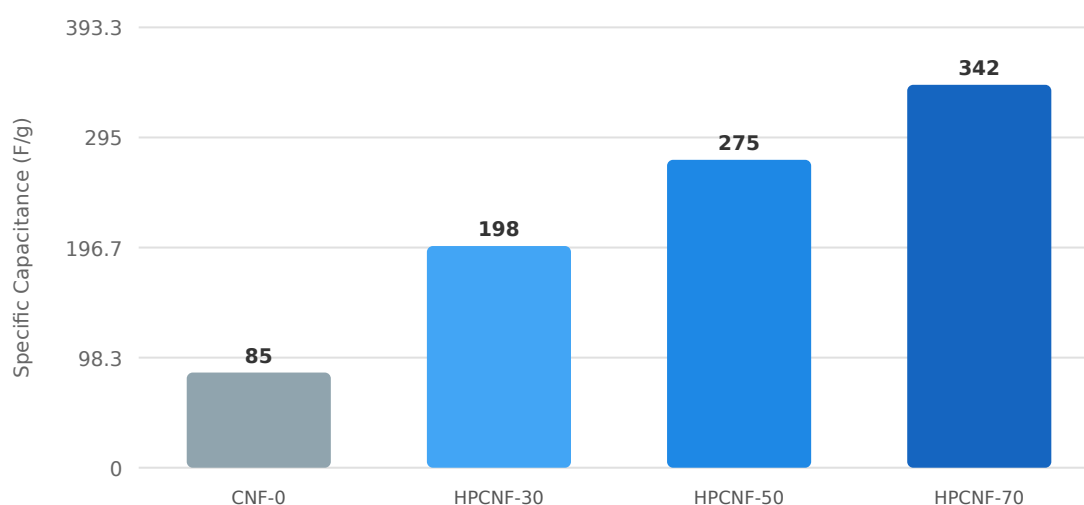


Figure 1. Specific capacitance versus current density for CNF-0, HPCNF-30, HPCNF-50, and HPCNF-70 electrode materials

The electrochemical performance was evaluated using cyclic voltammetry (CV), galvanostatic charge-discharge (GCD), and electrochemical impedance spectroscopy (EIS) in a three-electrode configuration with 6 M KOH electrolyte. The HPCNF-70 electrode achieved the highest specific capacitance of 342 F/g at a current density of 1 A/g, significantly surpassing previously reported MOF-derived carbon materials.

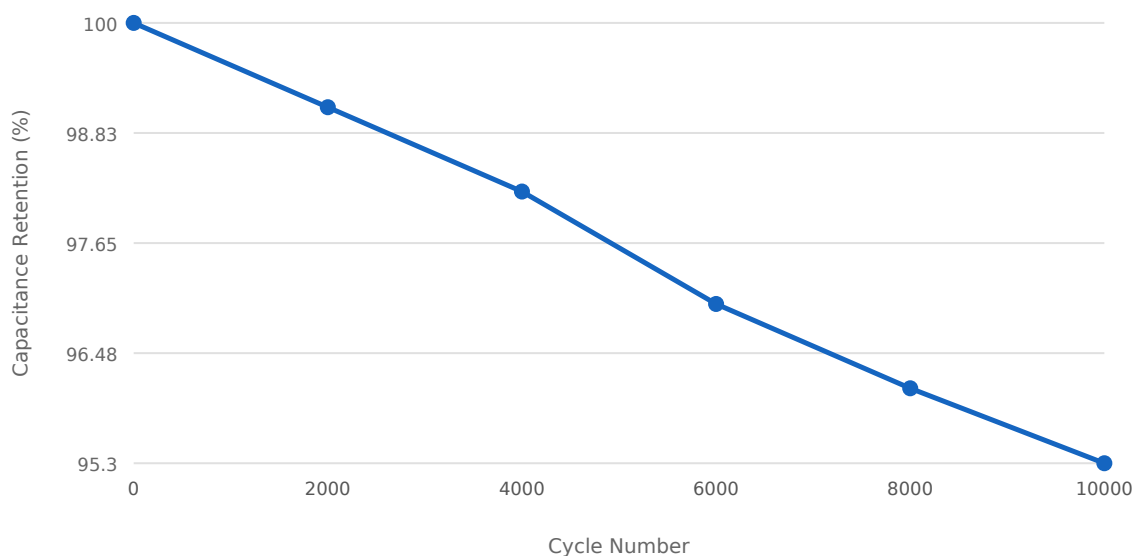


Figure 2. Cycling stability of HPCNF-70 over 10,000 charge-discharge cycles at 10 A/g, showing 95.3% capacitance retention

Table 2. Comparison of electrochemical performance with recent literature

Material	S_{BET} (m^2/g)	C_s (F/g)	Retention	Ref.
This work (HPCNF-70)	1,285	342	95.3% / 10k	—
ZIF-8 derived carbon	1,110	228	92% / 5k	[12]
MOF-derived hollow carbon	892	265	90% / 8k	[15]
N-doped graphene	630	197	96% / 10k	[18]

4. Conclusions

In summary, we have demonstrated a scalable approach for fabricating hierarchical porous carbon nanofibers by combining electrospinning with in situ MOF growth. The optimized HPCNF-70 material achieves outstanding supercapacitor performance with a specific capacitance of 342 F/g and excellent cycling stability (95.3% retention over 10,000 cycles). The hierarchical pore architecture provides efficient ion transport pathways while maximizing the accessible surface area for charge storage. This work opens new avenues for designing MOF-derived carbon nanomaterials for next-generation energy storage devices.

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