# Sustainable N/S Co-Doped Porous Carbon from Waste Lemon Peels for High-Performance Zinc-Ion Hybrid Supercapacitors

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## 1. Experimental Section

### 1.1. Materials

All chemical reagents (AR grade) were used without further purification with ammonium sulfate ($(NH_4)_2SO_4$ AR, 99%), and ethanol (EtOH, ACS, ≥99.5%, moisture ≤0.2%) were purchased from Aladdin Reagent Company (China). Concentrated hydrochloric acid (HCl) were purchased from B1eijing Chemical Factory (China). Technical grade potassium hydroxide (KOH, 95%) was supplied by Zhejiang Sandu Chemical Co. Nickel foam (NF, thickness: 17 mm) was purchased from Suzhou Xinuo Technology Co. $NaClO_4$ electrolyte (NC-008) was purchased from DoDoChem. Deionized water (DI $H_2O$, 18 MΩ) and high-purity $N_2$ gas were used in this work.

### 1.2. Structural characterization

The microstructure and composition of the samples were characterized by field-emission scanning electron microscopy (SEM, Hitachi S-4700, and Hitachi/Japan) along with energy dispersive X-ray (EDX) spectroscopy, and transmission electron microscopy (TEM, H-800 JEOL JEM2100F, and JEOL/Japan). X-ray diffraction (Rigaku Ultima IV) was performed by using a Rigaku D/max2500VB2 +/PCX diffractometer operating at 40 kV, 40 mA for Co Kα radiation (λ = 1.5406 Å). The phase composition of samples was analyzed using a Raman spectrometer (LabRAM HR Evolution) $N_2$ sorption/desorption isotherms were analyzed at 77 K with Micromeritics ASAP 2020 surface-area analyzer. X-ray photoelectron spectroscopy (XPS) was recorded on a Thermo Scientific ESCALAB 250 spectrometer with operating voltage of 200 eV for the survey and 30 eV for high-resolution analysis at Al K radiation.

## 1.3 Electrochemical Performance

Electrochemical performance of the supercapacitor was assessed utilizing both full-cell (two electrode) and half-cell (three electrode) configurations. In the three-electrode system, the synthesized carbon material functioned as the working electrode, while a Zn/ZnO electrode acted as the reference, and a nickel plate (1 × 1 $cm^2$) served as the counter electrode. The electrolyte solution consisted of 6M KOH. Galvanostatic charge–discharge (GCD) experiments were conducted using a LANHE battery testing system, while cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS) measurements were performed on a CHI1604E electrochemical workstation. All electrochemical tests were carried out within a potential window of 0.4 to 1.4 V versus Zn/ZnO. Initial CV measurements were conducted at a scan rate of 100 mV/s within the fixed potential window. To evaluate the scan rate capability, further measurements were conducted across a range of scan rates from 10 to 1000 mV $s^{-1}$. GCD tests were conducted at current densities ranging from 1 to 500 A $g^{-1}$ to assess the rate performance and specific capacitance of the electrode material. EIS measurements were conducted over a frequency range of 100 kHz to 10 Hz, and the cyclic stability and capacitance retention of the fabricated material were evaluated over 150,000 charge–discharge cycles. The specific capacitance (Cs) of the electrode was calculated from the discharge portion of the GCD curves using the following equation:

$$Cs = \frac{I \times \triangle t}{m \times \triangle V} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (I)$$

where I denote the applied current, Δt is the discharge time, m is the mass of active material, and ΔV the potential window corrected for the IR drop. Symmetric supercapacitor was assembled in CR2032 coin cells with two identical NS-LPC-850 electrodes as both working

and counter electrodes inside an argon-filled glove box, using 6MKOH as the electrolyte. The specific capacitance (Cp), energy density (E), and power density (P) of these devices were determined by the following equations:

$$Cs = \frac{2I \times \triangle t}{m \times \triangle V} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (II)$$

$$E = \frac{C_s \times \triangle V^2}{8 \times 3.6} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (III)$$

$$P = \frac{E.3600}{\triangle t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (IV)$$

Where E represents energy density (Wh $kg^{-1}$) and P is power density (W $kg^{-1}$). We designed a zinc hybrid capacitor (ZHC) with NS-LPC-850 as the active material, in addition to the typical three-electrode arrangement and coin cell construction. This device has a zinc foil anode and an NS-LPC-850 cathode. The electrolyte was composed of 6M KOH and 0.35M ZnO, and the cell was built into a stainless steel CR2032 coin battery. The energy density (E) and power density (P) of the ZHC were estimated using the formulae shown below.

$$E = \frac{V.I. \triangle t}{3.6.(m_1 + m_2)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (V)$$

$$P = \frac{E.3600}{\triangle t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (VI)$$

Where $m_1$ and $m_2$ is the mass of cathode and anode .

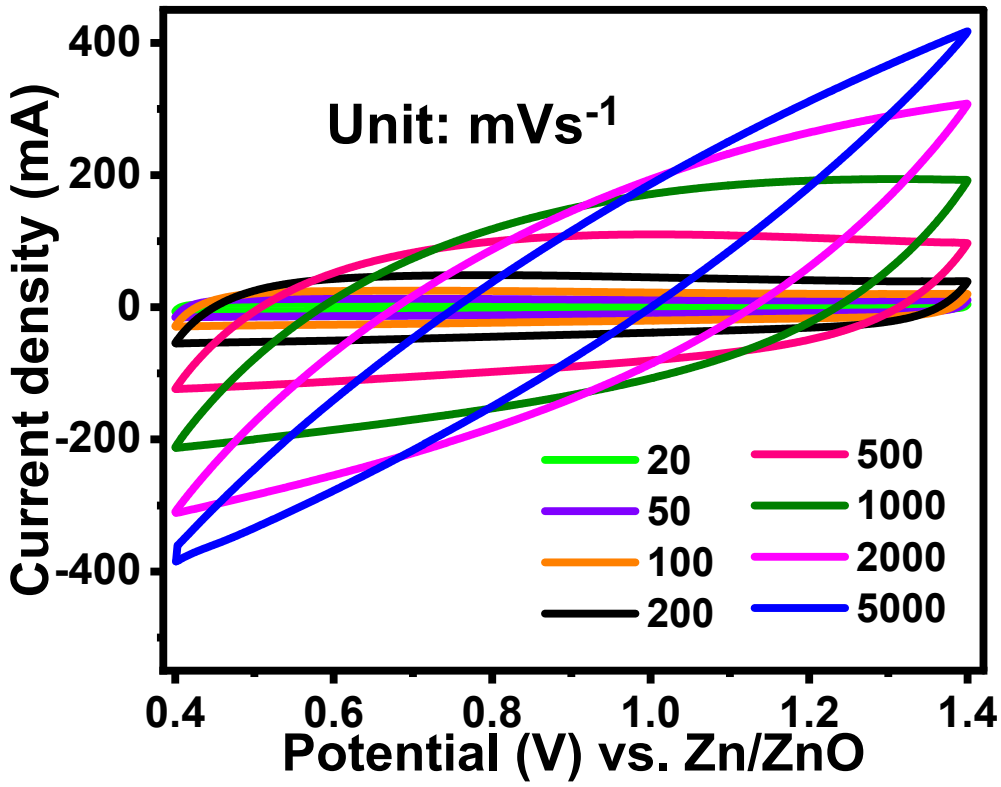


**Figure S1:** CV curves of NS-LPC-850 in a fixed potential window at different scan rate

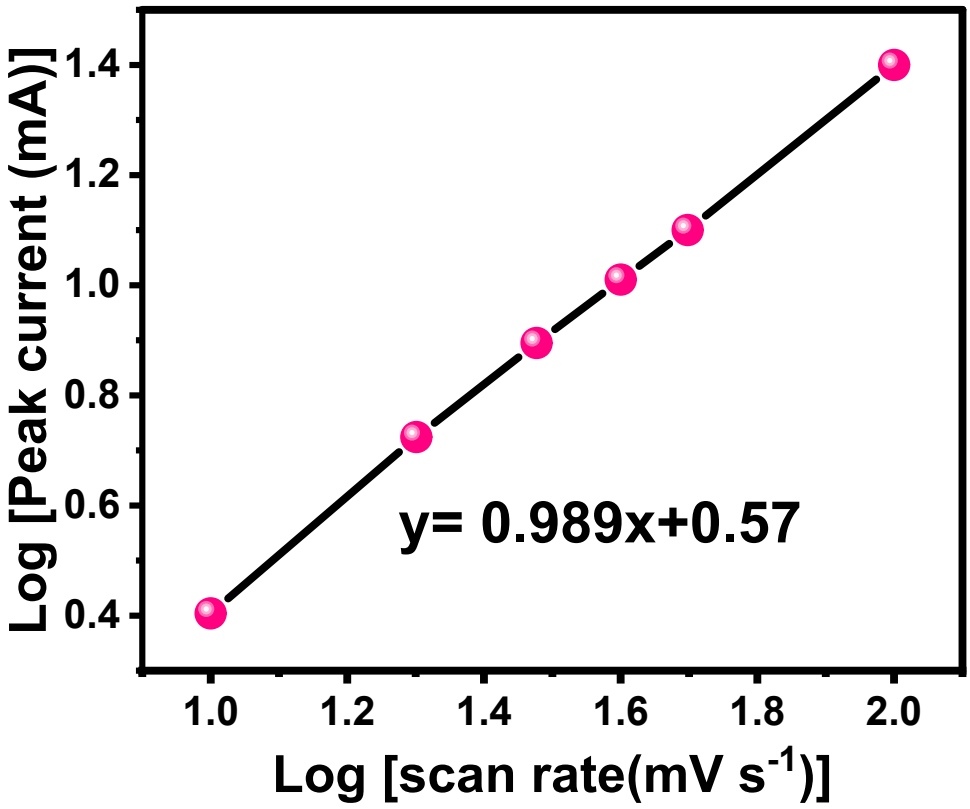


**Figure S2:** Power law graph used to determine the b-value from the coefficient of variation (CV) of NS-LPC-850.