Supplementary Information (SI) for New Journal of Chemistry.

Supplementary material

Synthesis of high-performance multifunctional electrode material using sweetwood lignin as a precursor

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Experimental

The Koutecky-Levich equation was used to analyze the number of electrons being transferred during the redox reaction [1]:

$$j^{-1} = j_K^{-1} + j_L^{-1} \quad (1)$$

$$j_L = Bw^{1/2} \quad (2)$$

$$B = 0.62nFD^{2/3}\ v^{-1/6}C \quad (3)$$

where j, j_K, and j_L are the measured current density, the kinetic-limiting density, and the diffusion-limiting current density, respectively; ω is the rotation speed in rpm, F is the Faraday constant (96,485 C mol^{-1}), D is the diffusion coefficient of oxygen in 0.1 M KOH (1.9×10^{-5} cm^2 s^{-1}), υ is the kinetic viscosity (0.01 cm^2 s^{-1}), and C is the bulk concentration of oxygen (1.2×10^{-6} mol cm^{-3}) [2]. Based on the above equations, the slope of B^{-1} can be obtained by a linear fitting of j^{-1} vs. $\omega^{-1/2}$, which gives the corresponding n value.

Results and Discussion

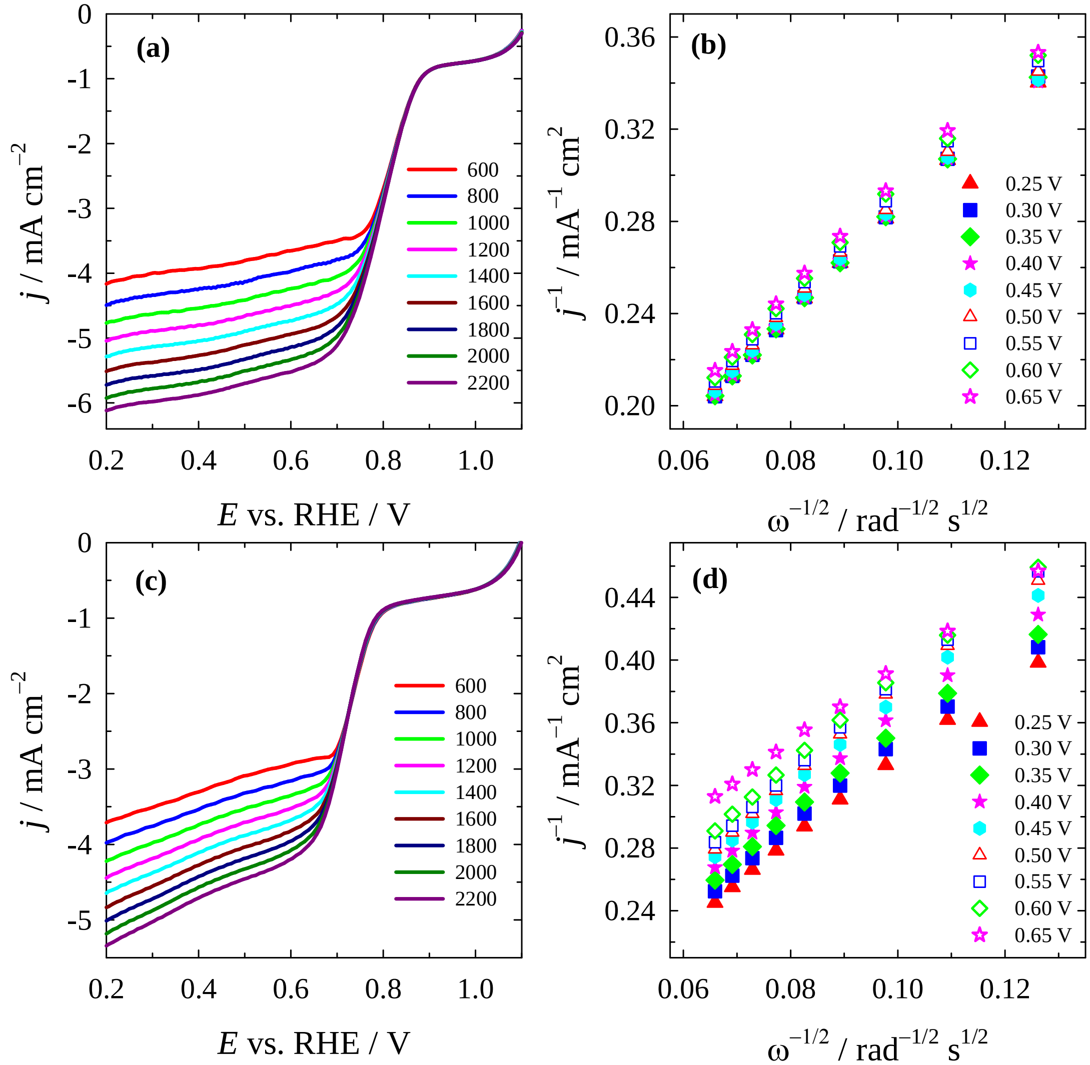

Fig. S1. LSVs recorded on N-AC-L (a) and AC-L (c) in O_2-saturated 0.1 M KOH at 10 mV s^{-1} at different rotation rates. (b, d) The corresponding Koutecky–Levich plots at 0.20-0.60 V electrode potentials.

Table S1. A summary of the ORR performance of current state-of-the-art non-metallic catalysts based on heteroatom-doped carbon and representative advanced biomass-derived catalysts.

Material	**Electro-lyte**	E_{onset}**, V vs. RHE**	$E_{1/2}$**, V vs. RHE**	***n***	j_{lim} ***at*** **1600 rpm, mA cm^{-2}**	**Ref.**
N-AC-L	0.1 M KOH	0.95	0.83	4	5.5	This study
N-doped akaline lignin (N-ALC)	0.1 M KOH	0.96 0.98 for Pt/C	0.84		2.03	[3]
N,P-doped nanocomposite carbon, 0.3 mg cm^{-2}	0.1 M KOH	0.93 for 1.01 Pt/C	0.68	~4	3.8 ~4 for Pt/C	[4]
NSCMS-MLSM	0.1 M KOH		0.83	2	4.78	[5]
n-HPFN@CQDs	0.1 M KOH	0.93	0.85	4	4.6	[6]
2D, N,S-Graphitic sheet 0.64 mg cm^{-2}	0.1 M KOH	1.01	~0.87	3.85	5.1	[7]
N,P-C@GO 0.2 mg cm^{-2}	0.1 M KOH	Close to Pt/C	-	3.7	16.9 17 for Pt/C	[8]
g-C_3N_4@N doped C nanosheet 0.204 mg cm^{-2}	0.1 M KOH	~0.89	0.75 0.73 for Pt/C	3.9-4.0	~3.2-5.8 ~6 for Pt/C	[9]
N-doped graphene nanoribben 0.6 mg cm^{-2}	1 M KOH	0.92 0.94 for Pt/C	0.84 0.85 for Pt/C	3.95	~3-3.5 close to Pt/C	[10]
N, P co-doped C 0.15 mg cm^{-2}	0.1 M KOH	0.94	0.85 Close to Pt/C	~4	~4.25 ~5.5 for Pt/C	[11]
P-doped C_3N_4@C fiber	0.1 M KOH	0.94 0.99 for	0.67 0.8 for Pt-	~4	~10, ~15-20 for	[12]

paper direct electrode		Pt-CFP	CFP		Pt-CFP	
N, P co-doped C 0.2 mg cm^{-2}	0.1 M KOH	0.95	~0.8 V	3.9	~4.98, 4.86 for Pt/C	[13]
N, O, S-tri-doped C 0.203 mg cm^{-2}	0.1 M KOH	0.96	0.74	~4	4.5-6	[14]
B, N co-doped graphene	0.1 M KOH	~0.9		~4	-5.2, close to Pt/C	[15]
N, S co-doped graphene	0.1 M KOH	~0.91		3.3-3.6	~10 Close to Pt/C	[16]
porous *g*-C_3N_4@C 0.17 mg cm^{-2}	0.1 M KOH	>0.9	-	3	~5 ~4 for Pt/C	[17]
N doped C; S, N-doped C from chitosan 0.4 mg cm^{-2}	0.1 M KOH	0.9; 0.93	-	3.9; 4	~12 ~10 for Pt/C	[18]
N doped C from amaranthus	0.1 M KOH	1.196	-	4	4.38 4.66 for Pt/C	[19]
N doped C nanosheet from monkey grass		0.87	-	4	4.9 3.7 for Pt/C	[20]
N doped C from ginko leave 0.71 mg cm^{-2}	0.1 M KOH	~0.9	positive 0.154 V to Pt/C	3.7	5.5 Close to Pt/C	[21]
N doped C from willow leave 0.4 mg cm^{-2}	0.1 M KOH	0.925	-	3.1	~3.7	[22]
Fe@C@N doped C from soybean ~0.5 mg cm^{-2}	0.1 M KOH	0.84	Positive 0.17 V to Pt/C		~2.2 2.5 for Pt/C	[23]
N doped C from bamboo fungi	0.1 M KOH	1.007		3.55	~3.5 ~4 for Pt/C	[24]

Co_3O_4@N doped C from blood powder 0.56 mg cm^{-2}	0.1 M KOH	0.9	Positive 0.05 V to Pt/C	3.93	~6 ~5.5 for Pt/C	[25]
$CoFe_2O_4$@N, P co-doped C from yeast 0.5 mg cm^{-2}	0.1 M KOH	~0.8		3.56	~5.6	[26]
N doped C from bacillus subtilis	0.1 M KOH	0.93		3.96	~5	[27]

Table S2. Electrochemical performance comparison among carbon materials in aqueous electrolytes.

Sample	Surface area, $m^2\ g^{-1}$	Specific capacitance ($F\ g^{-1}$) / scan rate ($mV\ s^{-1}$)	Electrolyte	Ref.
AC (activated carbon)	-	22.3 / 2	4 M $NaNO_3$-EG	[28]
AC (activated carbon)	2066	116 / 2	1 M $NaNO_3$	[29]
Graphene/CNF	-	74 / 1	1.4 M Li_2SO_4 (70%) + ethylene glycol (30%)	[30]
Microporous AC	2244	116 / 2	2 M Li_2SO_4	[31]
NCS-700 (nitrogen-doped porous carbon nanosheets)	1497.4	64.4 / 2	1 M Na_2SO_4	[32]
VN/MWCNT	-	160.3 / 2	0.5 M Na_2SO_4	[33]
AC (derived from banana fibers)	1097	74[a]	1 M Na_2SO_4	[34]
Castor shell	1468	65[a]	1 M Na_2SO_4	[35]
AC-800-3 (derived from torreya grandis shell)	2100.8	142.6 / 50	0.5 M Na_2SO_4	[36]
N-AC-L (derived from sweetwood lignin)	2690	106 / 5	1 M Na_2SO_4	This study

[a] Two electrode measurements

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