Preparation of High Performance Supercapacitor Material by Fast Pyrolysis of Corn Gluten Meal Waste

Bin-Hai Cheng[a,b], Ke Tian[a], Raymond J. Zeng[a,b], Hong Jiang[a,*]

[a] CAS Key Laboratory of Urban Pollutant Conversion, Department of Chemistry, University of Science and Technology of China, Hefei 230026, China

[b] School of Life Sciences, University of Science and Technology of China, Hefei 230026, China

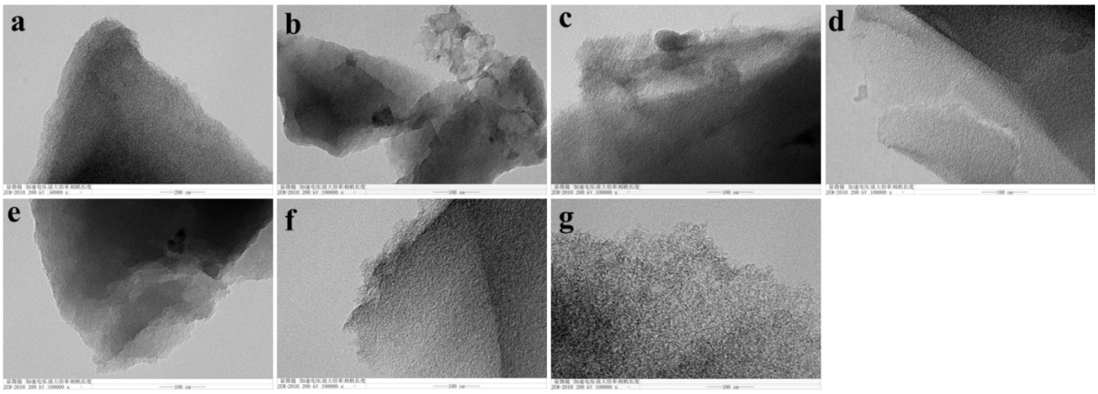

Fig. S1 TEM images of PCMs synthesized under different conditions. a-d) TEM images of $PCM_{H600-900}$; e-g) TEM images of $PCM_{P300-500}$.

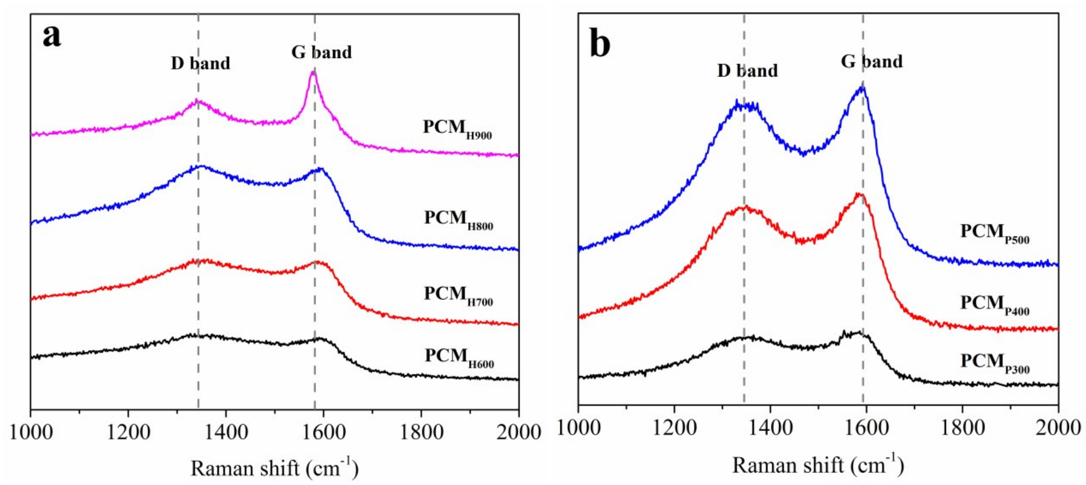

Fig. S2 Raman spectrum of a) $PCM_{H600-900}$, and b) $PCM_{P300-500}$.

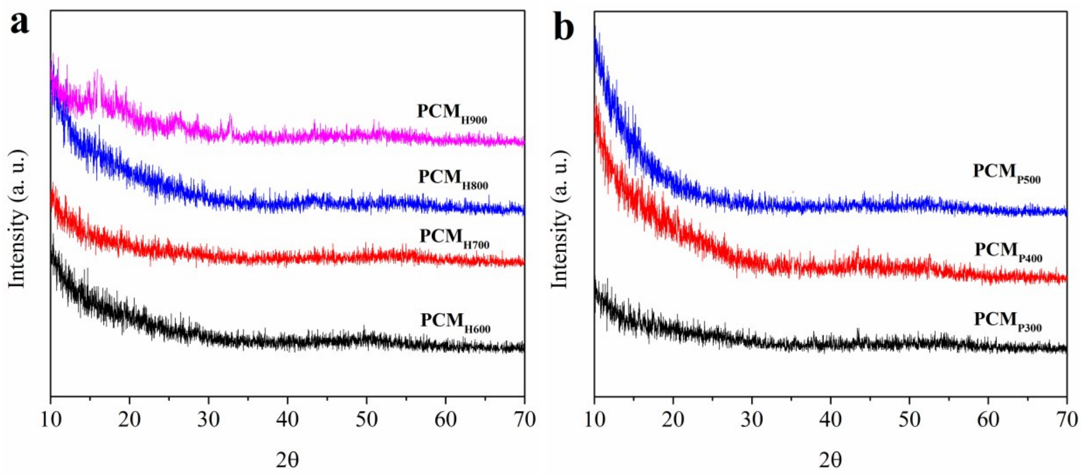

Fig. S3 XRD pattern of a) PCM$_{H600-900}$, and b) PCM$_{P300-500}$.

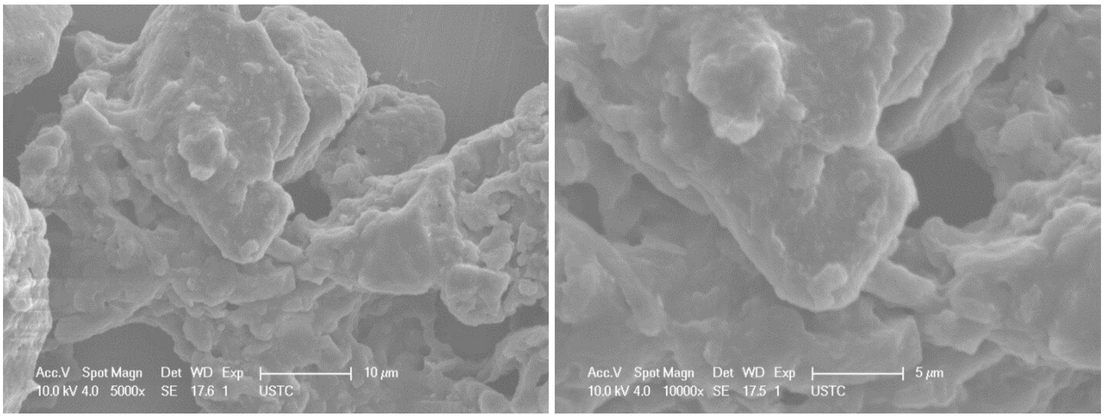

Fig. S4 SEM image of the CGM.

The elemental analysis shows the C, H, N and O contents in PCMs (Table 1). The contents of heteroatoms (N, O) in the bulk materials are 8.5~29.6% (N), 0.7~1.5% (O), and gradually decrease with increasing of pyrolysis temperature.The X-rayphotoelectron spectrometer (XPS) was used to identify the surface elemental composition ofthe porous carbons obtained underdifferent process. The high-resolution XPS spectra of N1sand O1s were collected to understand the formed N−C and O−C bonding. Nitrogen atoms werefound in four different contributions in the carbon matrix:[1]pyridinic-N (N1, 398.0eV), pyrrolic-N (N2, 399.6eV), quaternary-N (N3, 400.8 eV) andoxidized-N (N4, 402.5 eV) (Figure S1b). Oxygen atoms werefound in three different contributions in the carbon matrix:[1]carbonyl oxygen of Keto and quinone (O1, 530.8eV), noncarbonyl (ether-type) oxygen atoms in esters and anhydrides (O2, 531.8eV), and oxygen atoms in carboxylic groups (O3, 533.0eV) (Figure S1c).These nitrogen and oxygen functional groups on the surface of PCMs coupled with high specific surface area offer a strong tendency to deliver exciting electrochemical performance. Therefore, these PCMs derived from CGM could be promising electrode materials for high power density supercapacitors.

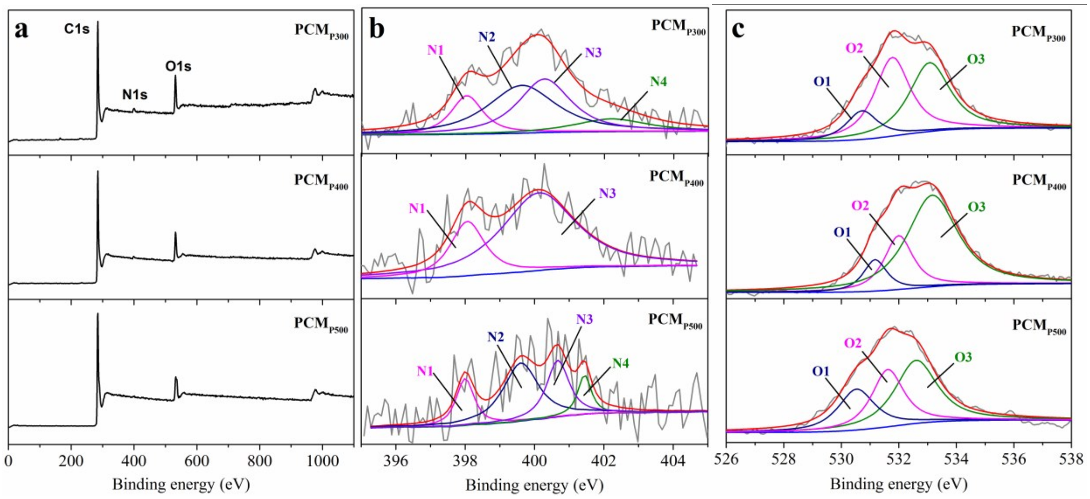

Figure S5. a) XPS survey spectra of the PCMs; b) XPS N1s spectra of the PCMs; c) XPS O1s spectra of the PCMs.

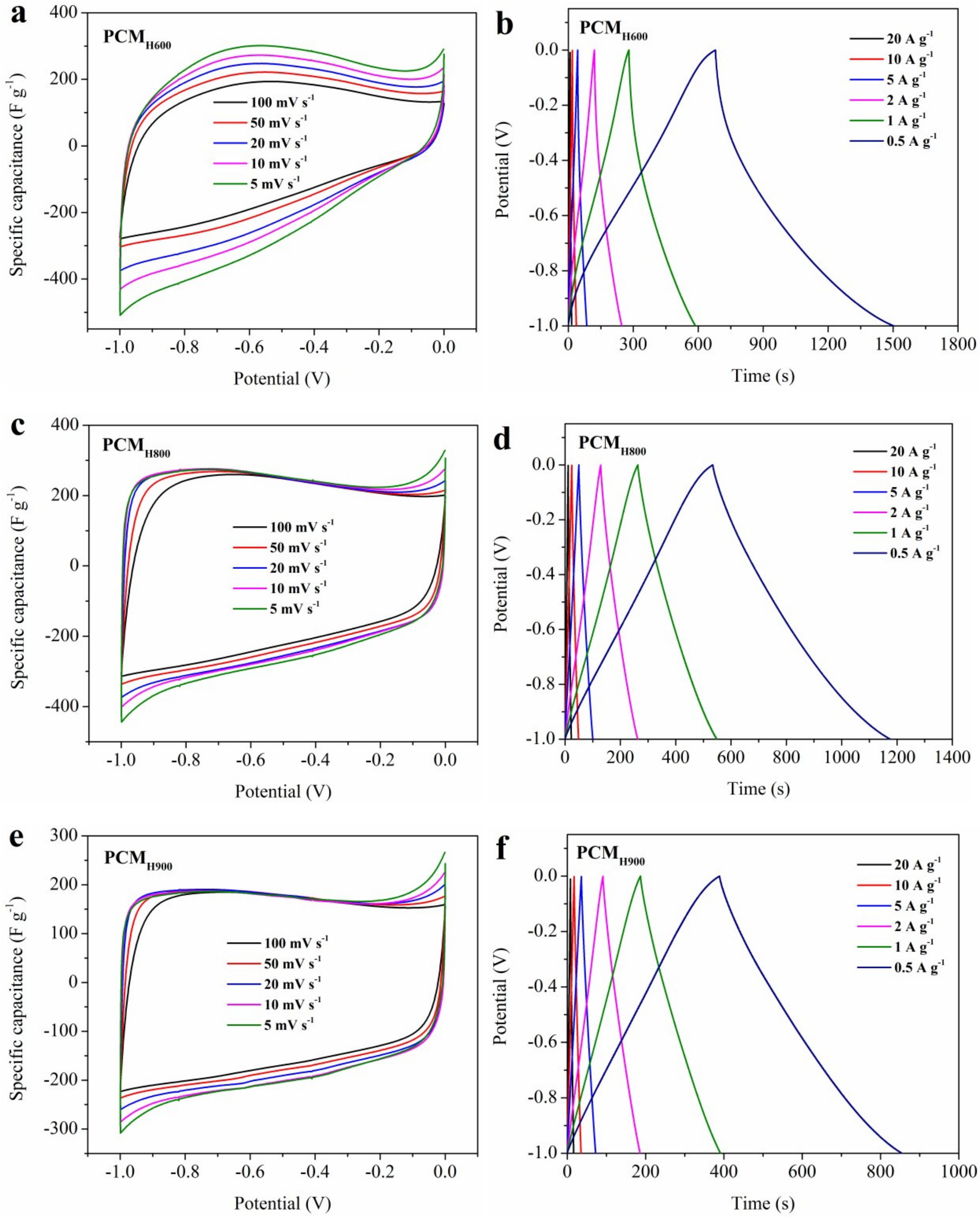

Figure S6. CV curves at different scan rates of a) PCM$_{H600}$, c) PCM$_{H800}$, e) PCM$_{H900}$; GCD profiles under different current densities of b) PCM$_{H600}$, d) PCM$_{H800}$, f) PCM$_{H900}$.

Table S1. Comparison of specific capacitance between the PCM_{P500} and other EDLCs.

Supercapacitor materials	Specific surface area ($m^2\ g^{-1}$)	Pore volume ($cm^3\ g^{-1}$)	Max. capacitance ($F\ g^{-1}$)	Scan rate or current density	Electrolyte	Cycle number	Stability	Ref.
Nitrogen-Containing Hydrothermal Carbons	598	0.34	220	0.1 A g^{-1}	6 M KOH	-	-	[2]
HTC of Natural Organic Chemicals	2967	1.35	236	1 mV s^{-1}	$TEABF_4$ / AN	-	-	[3]
Activation of Graphene a-MEGO	~3100	2.14	165	1.4 A g^{-1}	$TEABF_4$ / AN	10 000	97%	[4]
Nitrogen-Doped Porous Carbon Nanofibers	562	0.51	202	1 A g^{-1}	6 M KOH	3 000	97%	[5]
Nitrogen-Doped Carbon Monolith	679	0.46	246	1 mV s^{-1}	6 M KOH	-	-	[6]
Hierarchical Porous Graphene-Like Networks	1810	1.22	305	0.5 A g^{-1}	6 M KOH	15 000	~100%	[7]
Functionalized 3D Hierarchical Porous Carbon	2870	2.19	318	0.5 A g^{-1}	6 M KOH	10 000	95.8%	[8]
3D Micro-porous Conducting Carbon Beehive	1327	-	254	0.5 A g^{-1}	1 M H_2SO_4	5 000	90%	[9]
Highly Porous Interconnected Carbon Nanosheets	~2200	1.30	150	1 mV s^{-1}	1 M $TEABF_4$ / AN	10 000	90-94%	[10]
Oxygen- and Nitrogen-Enriched 3D Porous Carbon	1003	0.62	440	0.5 A g^{-1}	6 M KOH	10 000	92.3%	[1]
Microporous Doped Carbon	1680	0.86	340	2 mV s^{-1}	1 M H_2SO_4	-	-	[11]
Carbon Materials by Direct Pyrolysis of Seaweeds	1300	-	264	2 mV s^{-1}	1 M H_2SO_4	-	-	[12]
Functional MicroporousCarbon from Dead Leaves	1230		400	0.5 A g^{-1}	1 M H_2SO_4	-	-	[13]
Carbon Materials from High Ash Biochar	3310	1.85	260	0.6 A g^{-1}	6 M KOH	2 000	99%	[14]
Porous Graphitic Carbon NanosheetfromCornstalk Biomass	540	0.48	213	1 A g^{-1}	6 M KOH	6 000	98%	[15]
Porous 3D Carbon from Rice Bran	2475	1.21	265	10 A g^{-1}	6 M KOH	10 000	-	[16]
Human Hair-Derived Carbon Flakes	1306	0.90	340	1 A g^{-1}	6 M KOH	20 000	98%	[17]
Porous Carbon from BiowasteCorncob Residue	1210	0.67	314	5 mV s^{-1}	6 M KOH	-	-	[18]
PCM_{P500}	**3485**	**2.03**	**465**	**0.5 A g^{-1}**	**6 M KOH**	**10000**	**93%**	**This work**

REFERENCES

1. Li, J.; Liu, K.; Gao, X.; Yao, B.; Huo, K.; Cheng, Y.; Cheng, X.; Chen, D.; Wang, B.; Sun, W.; Ding, D.; Liu, M.; Huang, L., Oxygen- and Nitrogen-Enriched 3D Porous Carbon for Supercapacitors of High Volumetric Capacity. *ACS Appl. Mater Interfaces* **2015**.
2. Zhao, L.; Fan, L.-Z.; Zhou, M.-Q.; Guan, H.; Qiao, S.; Antonietti, M.; Titirici, M.-M., Nitrogen-Containing Hydrothermal Carbons with Superior Performance in Supercapacitors. *Adv. Mater.* **2010,***22*, (45), 5202-5206.
3. Wei, L.; Sevilla, M.; Fuertes, A. B.; Mokaya, R.; Yushin, G., Hydrothermal Carbonization of Abundant Renewable Natural Organic Chemicals for High-Performance Supercapacitor Electrodes. *Adv. Energy Mater.* **2011,***1*, (3), 356-361.
4. Zhu, Y.; Murali, S.; Stoller, M. D.; Ganesh, K. J.; Cai, W.; Ferreira, P. J.; Pirkle, A.; Wallace, R. M.; Cychosz, K. A.; Thommes, M.; Su, D.; Stach, E. A.; Ruoff, R. S., Carbon-Based Supercapacitors Produced by Activation of Graphene. *Science* **2011,***332*, (6037), 1537-1541.
5. Chen, L.-F.; Zhang, X.-D.; Liang, H.-W.; Kong, M.; Guan, Q.-F.; Chen, P.; Wu, Z.-Y.; Yu, S.-H., Synthesis of Nitrogen-Doped Porous Carbon Nanofibers as an Efficient Electrode Material for Supercapacitors. *ACS Nano* **2012,***6*, (8), 7092-7102.
6. Wang, D.-W.; Li, F.; Yin, L.-C.; Lu, X.; Chen, Z.-G.; Gentle, I. R.; Lu, G. Q.; Cheng, H.-M., Nitrogen-Doped Carbon Monolith for Alkaline Supercapacitors and Understanding Nitrogen-Induced Redox Transitions. *Chem-Eur J.* **2012,***18*, (17), 5345-5351.
7. Li, Y.; Li, Z.; Shen, P. K., Simultaneous Formation of Ultrahigh Surface Area and Three-Dimensional Hierarchical Porous Graphene-Like Networks for Fast and Highly Stable Supercapacitors. *Adv. Mater.* **2013,***25*, (17), 2474-2480.
8. Qie, L.; Chen, W.; Xu, H.; Xiong, X.; Jiang, Y.; Zou, F.; Hu, X.; Xin, Y.; Zhang, Z.; Huang, Y., Synthesis of functionalized 3D hierarchical porous carbon for high-performance supercapacitors. *Energy Environ. Sci.* **2013,***6*, (8), 2497-2504.
9. Puthusseri, D.; Aravindan, V.; Madhavi, S.; Ogale, S., 3D micro-porous conducting carbon beehive by single step polymer carbonization for high performance supercapacitors: the magic of in situ porogen formation. *Energy Environ. Sci.* **2014,***7*, (2), 728-735.
10. Sevilla, M.; Fuertes, A. B., Direct Synthesis of Highly Porous Interconnected Carbon Nanosheets and Their Application as High-Performance Supercapacitors. *ACS Nano* **2014,***8*, (5), 5069-5078.
11. Ania, C. O.; Khomenko, V.; Raymundo-Piñero, E.; Parra, J. B.; Béguin, F., The Large Electrochemical Capacitance of Microporous Doped Carbon Obtained by Using a Zeolite Template. *Adv. Funct. Mater.* **2007,***17*, (11), 1828-1836.
12. Raymundo-Piñero, E.; Cadek, M.; Béguin, F., Tuning Carbon Materials for Supercapacitors by Direct Pyrolysis of Seaweeds. *Adv. Funct. Mater.* **2009,***19*, (7), 1032-1039.
13. Biswal, M.; Banerjee, A.; Deo, M.; Ogale, S., From dead leaves to high energy density supercapacitors. *Energy Environ. Sci.* **2013,***6*, (4), 1249.
14. Jin, H.; Wang, X.; Gu, Z.; Polin, J., Carbon materials from high ash biochar for supercapacitor and improvement of capacitance with HNO3 surface oxidation. *J. Power Sources* **2013,***236*, 285-292.
15. Wang, L.; Mu, G.; Tian, C.; Sun, L.; Zhou, W.; Yu, P.; Yin, J.; Fu, H., Porous Graphitic Carbon Nanosheets Derived from Cornstalk Biomass for Advanced Supercapacitors. *ChemSusChem* **2013,***6*, (5), 880-889.

16. Hou, J.; Cao, C.; Ma, X.; Idrees, F.; Xu, B.; Hao, X.; Lin, W., From rice bran to high energy density supercapacitors: a new route to control porous structure of 3D carbon. *Sci. Rep.* **2014,***4*, 7260.
17. Qian, W.; Sun, F.; Xu, Y.; Qiu, L.; Liu, C.; Wang, S.; Yan, F., Human hair-derived carbon flakes for electrochemical supercapacitors. *Energy Environ. Sci.* **2014,***7*, (1), 379-386.
18. Qu, W.-H.; Xu, Y.-Y.; Lu, A.-H.; Zhang, X.-Q.; Li, W.-C., Converting biowaste corncob residue into high value added porous carbon for supercapacitor electrodes. *Bioresour. Technol.* **2015,***189*, 285-291.