# Enhanced capacity of aluminum-ion batteries by adjusting the average pore size of the porous carbon cathodes

*Yifeng Chen[a], Hiroo Suzuki[a], Shu Fukumoto[a], Chiyu Nakano[b], Takeshi Nishikawa[a], Shigeyuki Umezawa[c], Yasuhiko Hayashi[a]*

[a]Graduate School of Environmental, Life, Natural Science, and Technology, Okayama University, Okayama 700-8530, Japan

[b]Department of Comprehensive Technical Solutions, Okayama University, Okayama 700-8530, Japan

[c]Seiwa Electric Mfg. Co., Ltd., Kyoto 610-0192, Japan

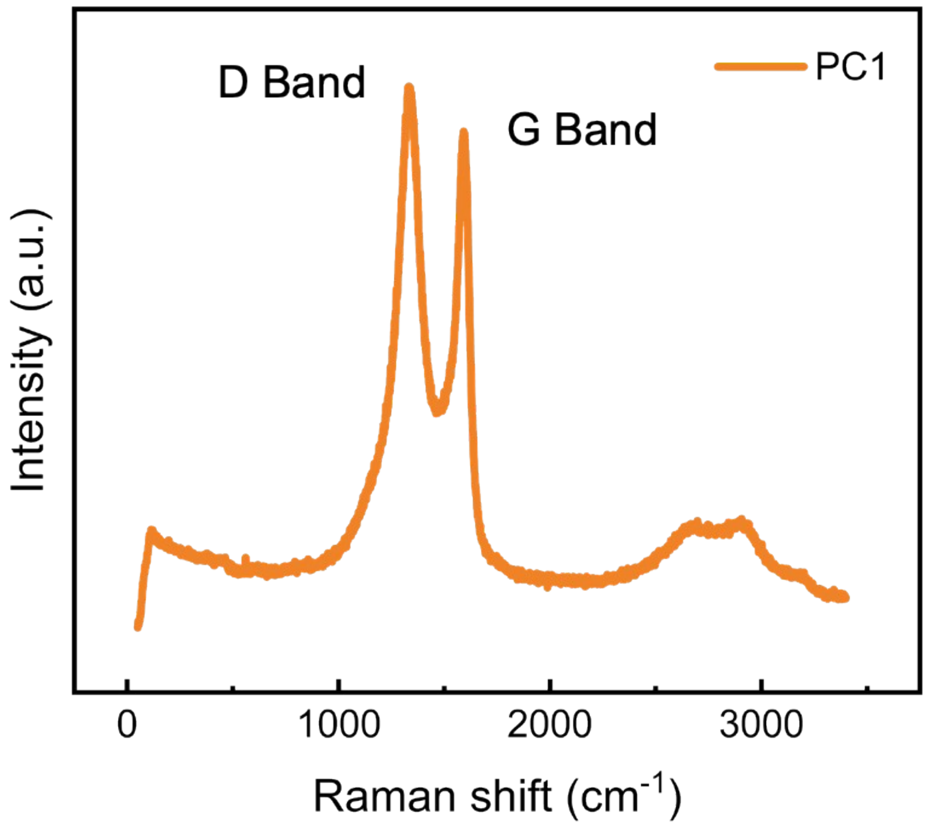



**Fig. S1** Raman spectra of PC1

PC1 (YP50F) was commercially purchased and directly used as a cathode material

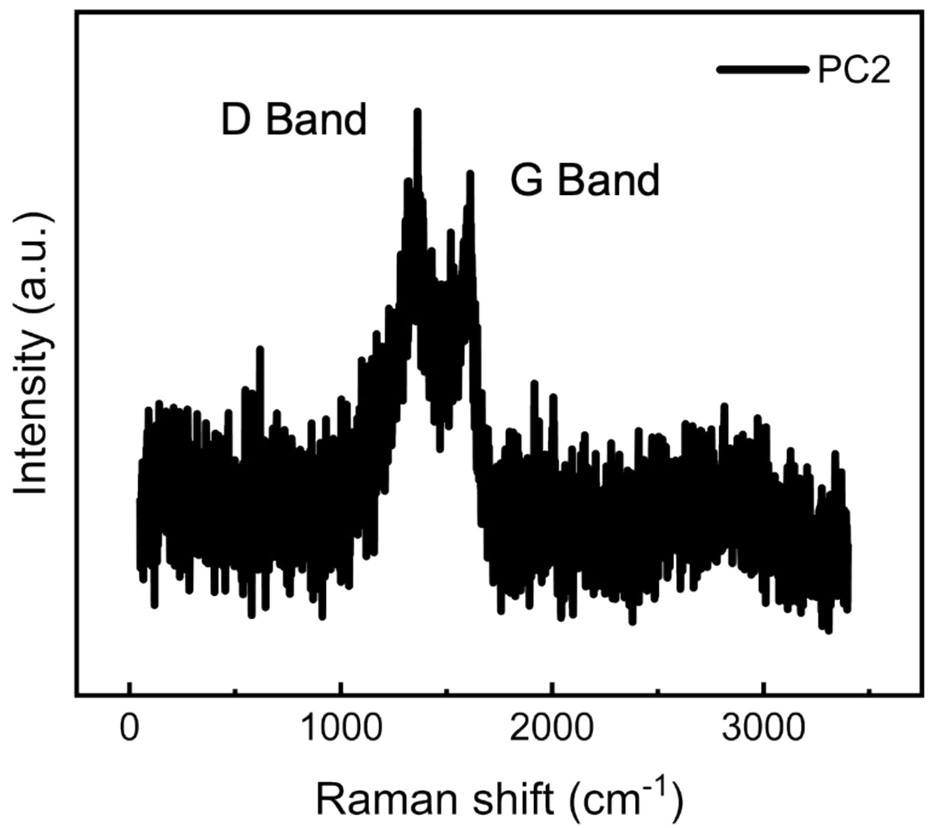



**Fig. S2** Raman spectra of PC2

PC2 (MSP-20) was commercially purchased and directly used as a cathode material

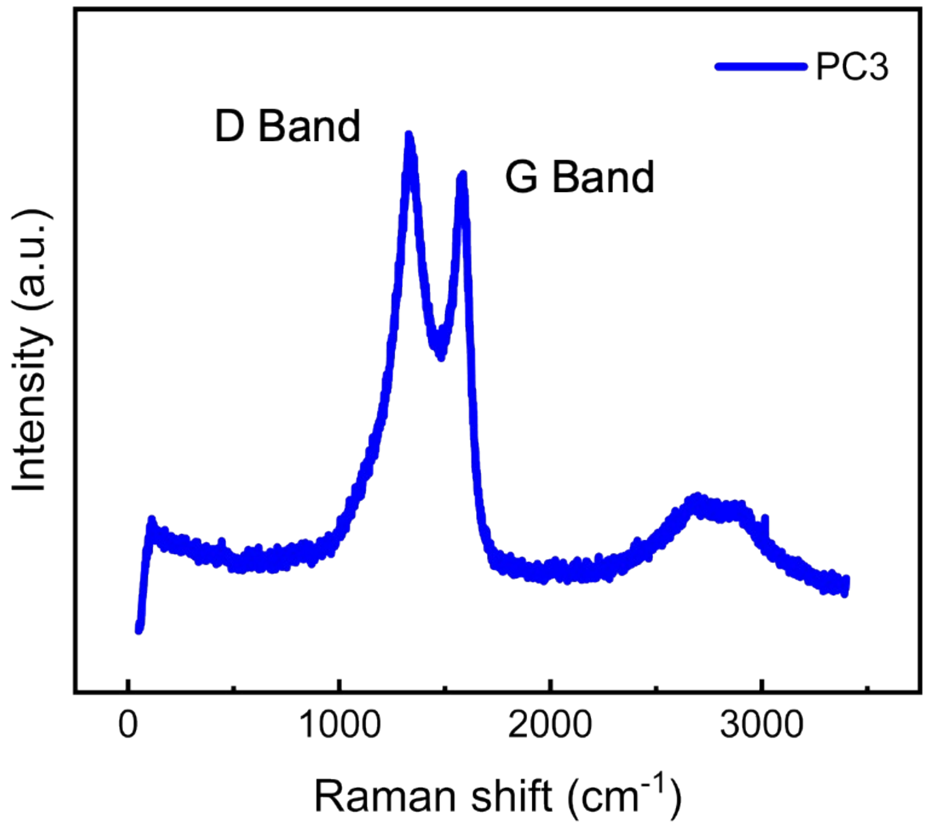



**Fig. S3** Raman spectra of PC3

PC3 (MSA-20) was commercially purchased and directly used as a cathode material

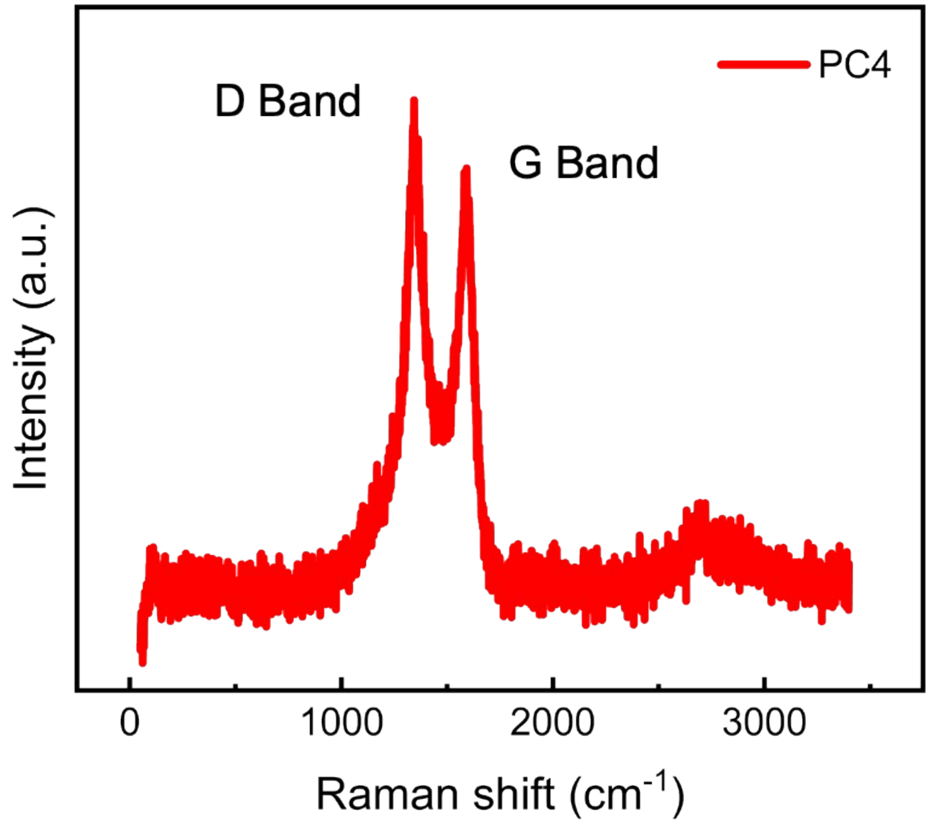



**Fig. S4** Raman spectra of PC4

PC4 (MSC-30) was commercially purchased and directly used as a cathode material

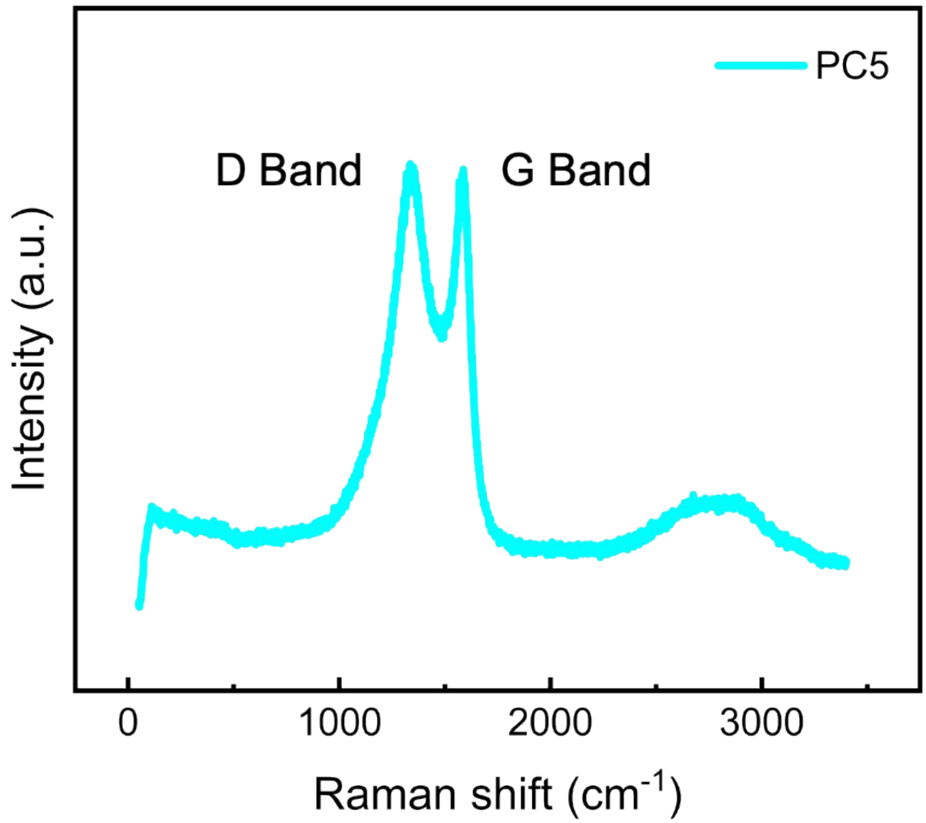



**Fig. S5** Raman spectra of PC5

PC5 (CNovel 20 nm) was commercially purchased and directly used as a cathode material

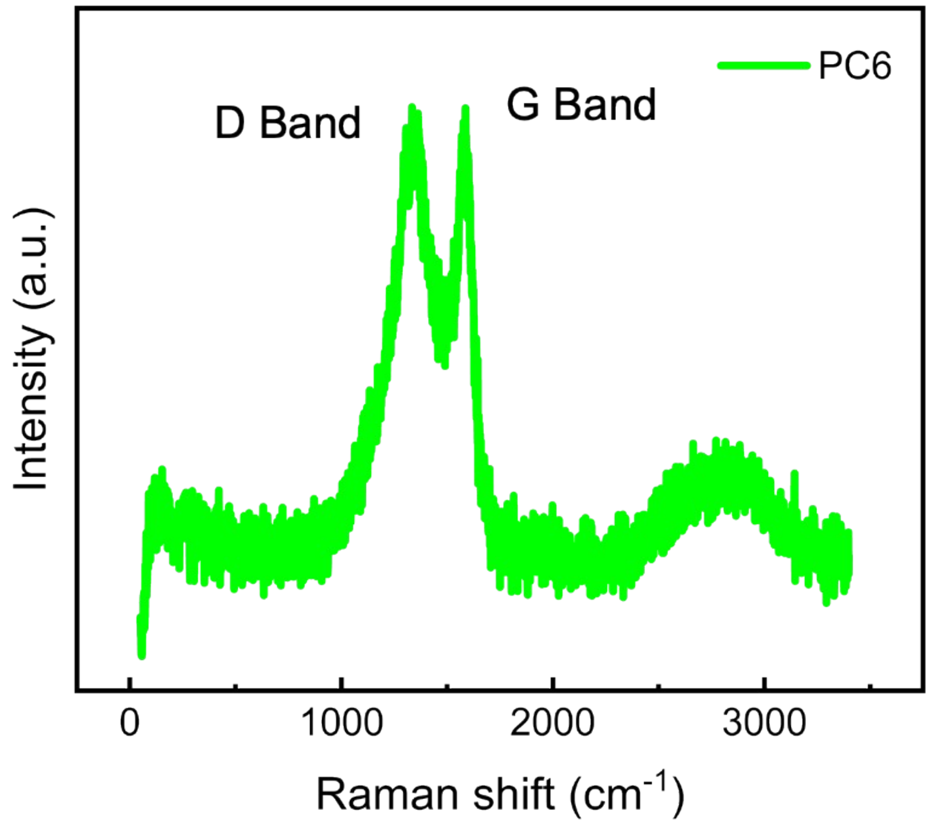



**Fig. S6** Raman spectra of PC6

PC6 (CNovel MJ4 010-00) was commercially purchased and directly used as a cathode material

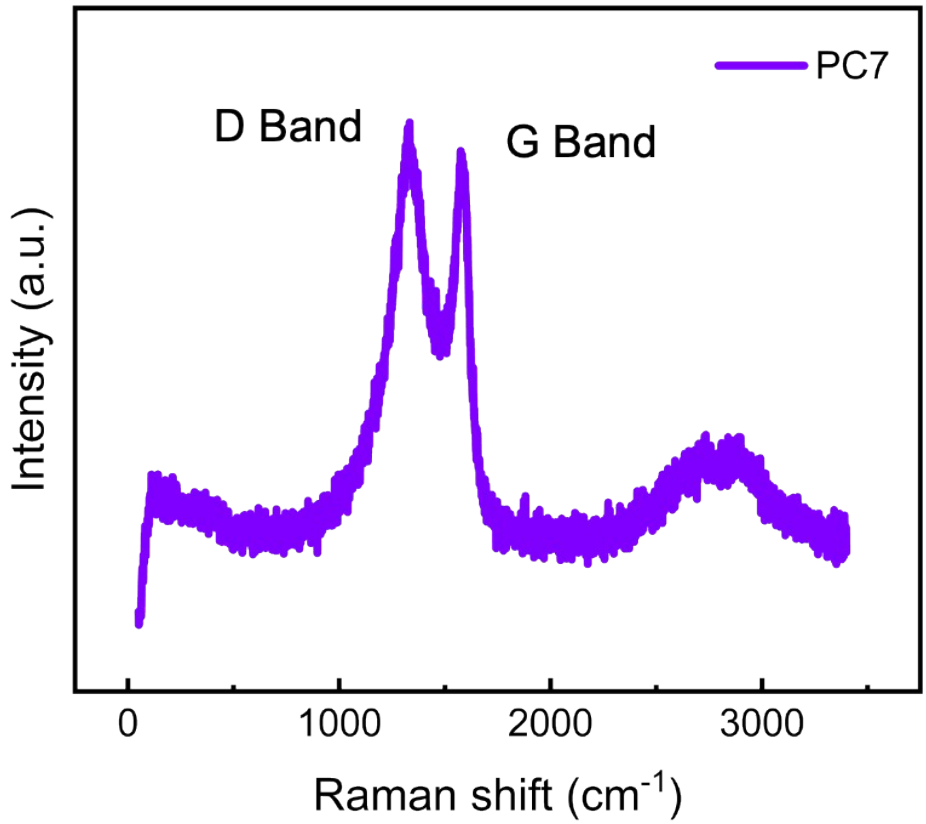



**Fig. S7** Raman spectra of PC7

PC7 (CNovel MH-00) was commercially purchased and directly used as a cathode material

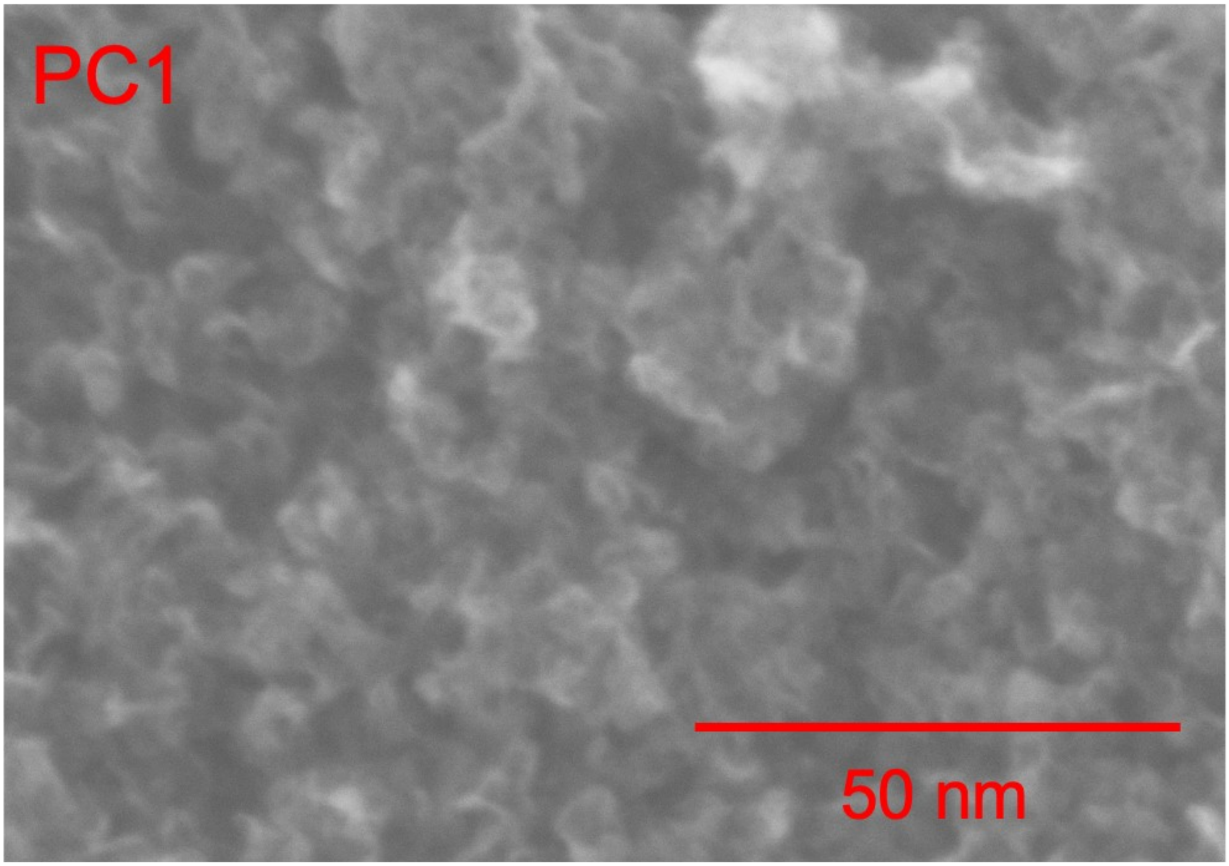



**Fig. S8** Field emission scanning electron microscope image of the top view of PC1

PC1 (YP50F) was commercially purchased and directly used as a cathode material

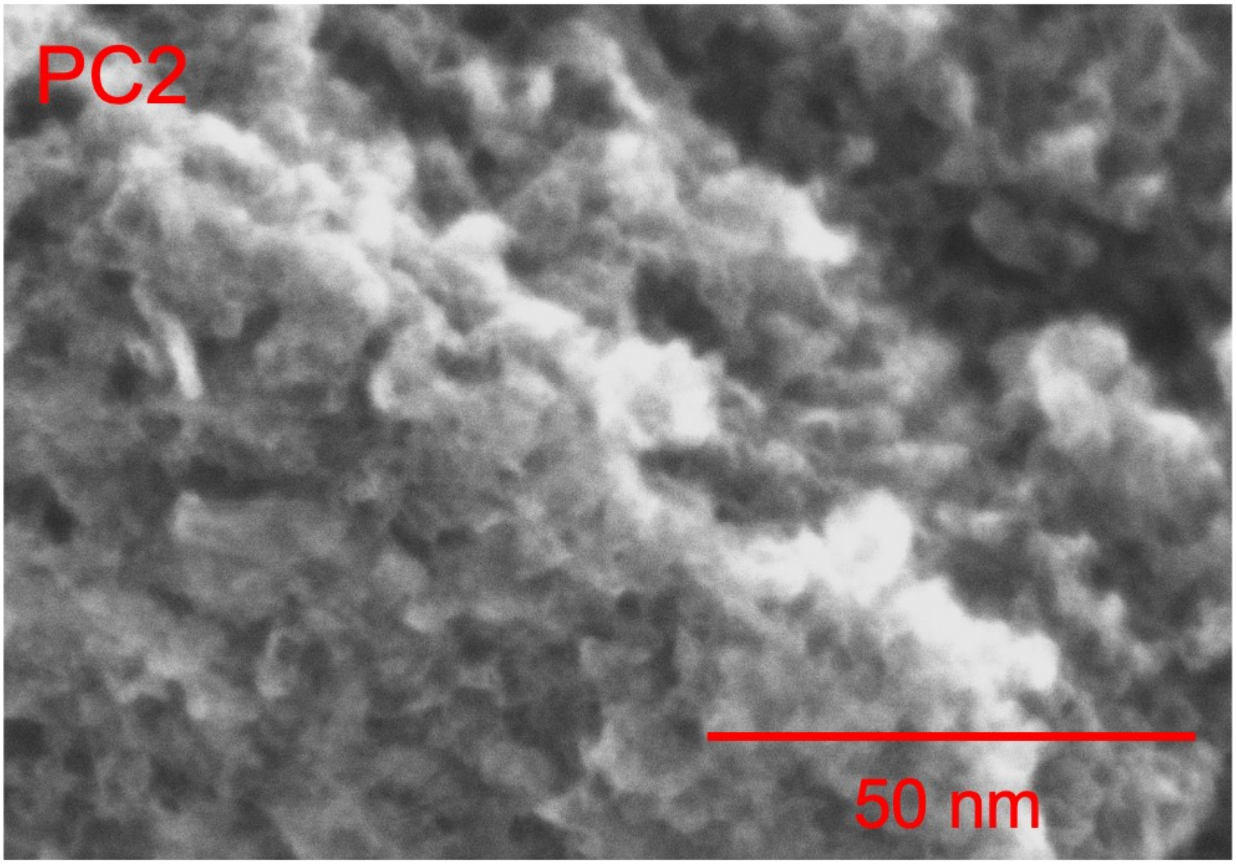



**Fig. S9** Field emission scanning electron microscope image of the top view of PC2

PC2 (MSP-20) was commercially purchased and directly used as a cathode material

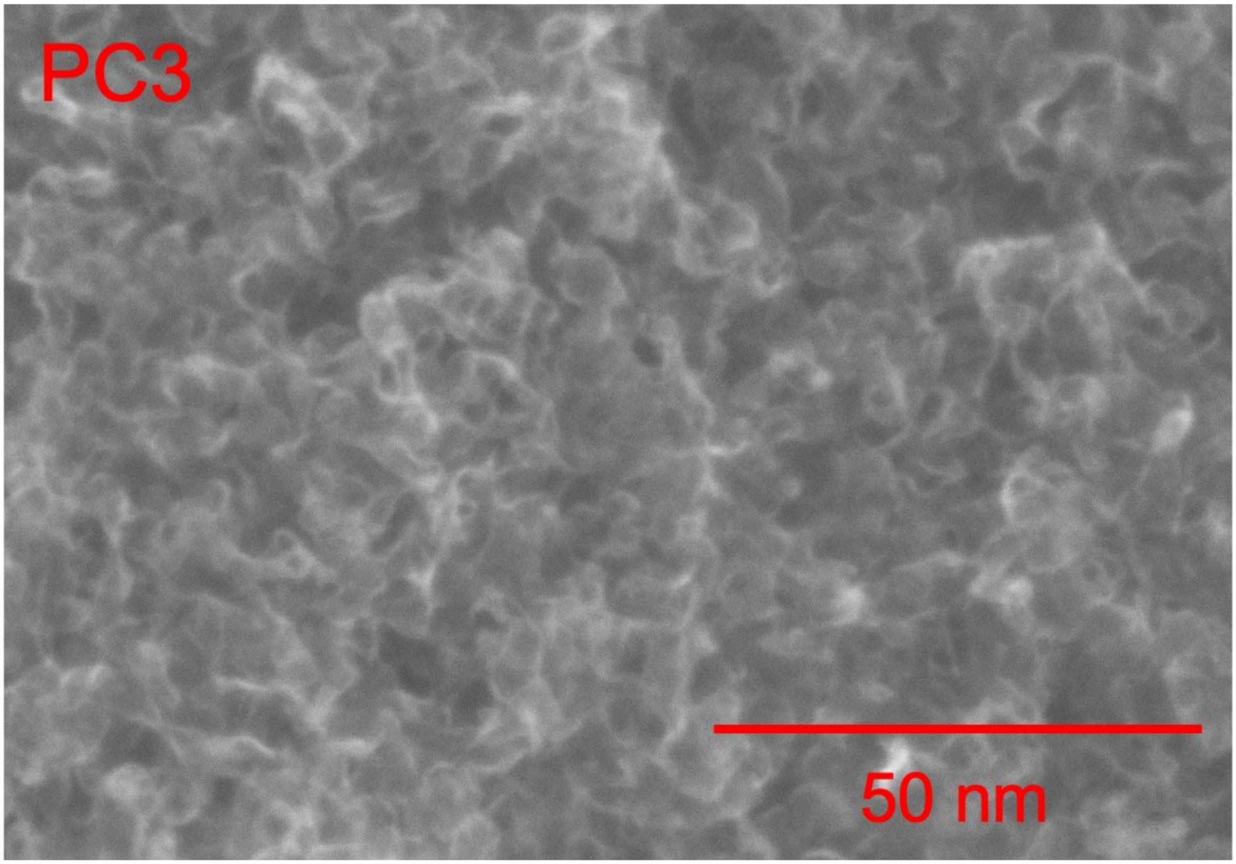



**Fig. S10** Field emission scanning electron microscope image of the top view of PC3

PC3 (MSA-20) was commercially purchased and directly used as a cathode material

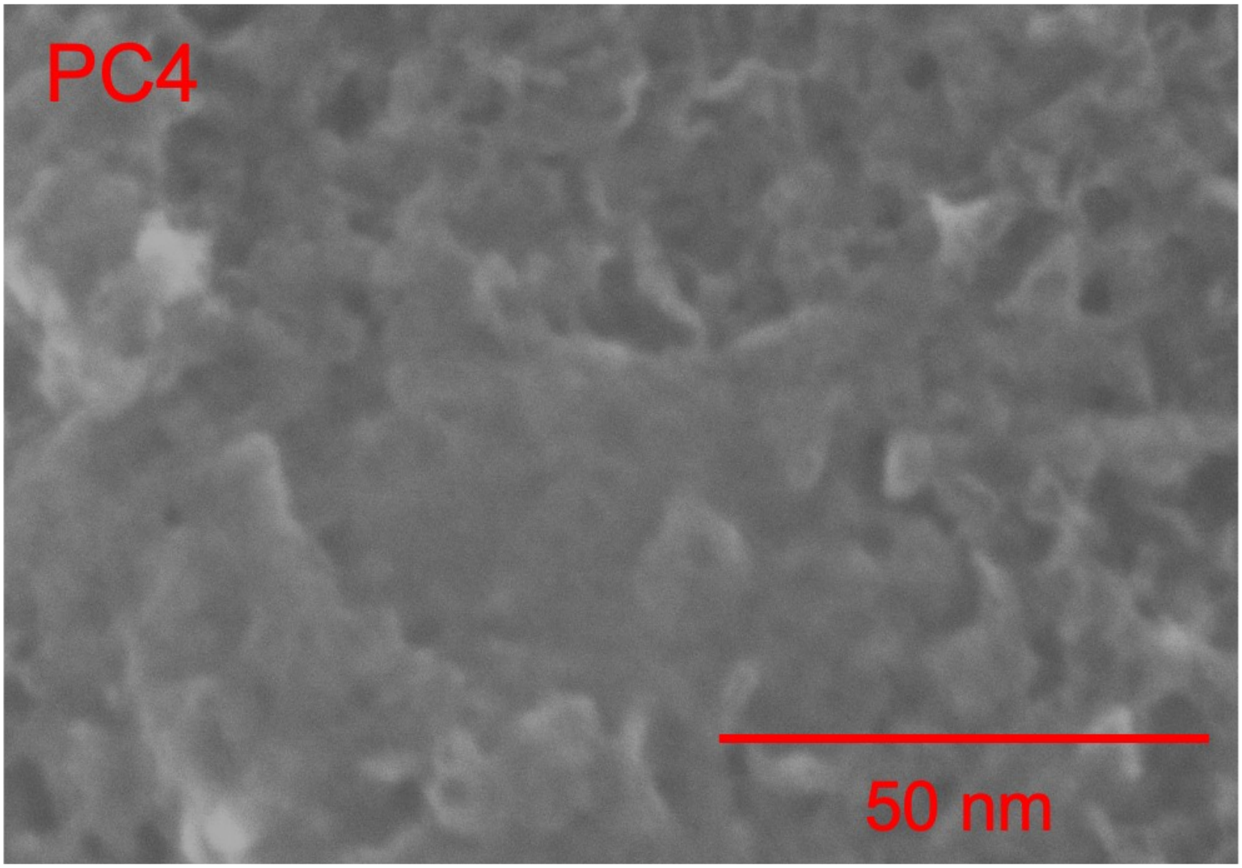



**Fig. S11** Field emission scanning electron microscope image of the top view of PC4

PC4 (MSC-30) was commercially purchased and directly used as a cathode material

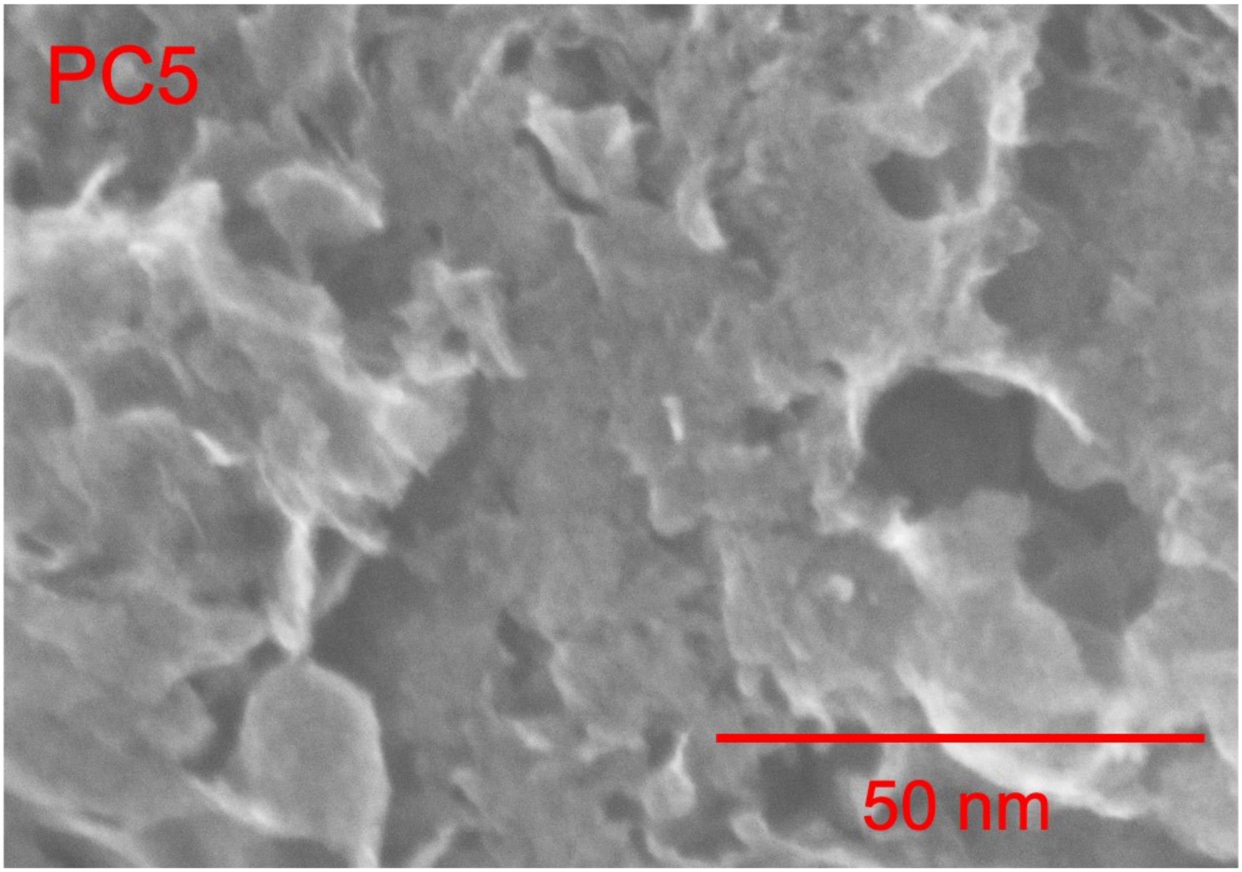



**Fig. S12** Field emission scanning electron microscope image of the top view of PC5

PC5 (CNovel 20 nm) was commercially purchased and directly used as a cathode material

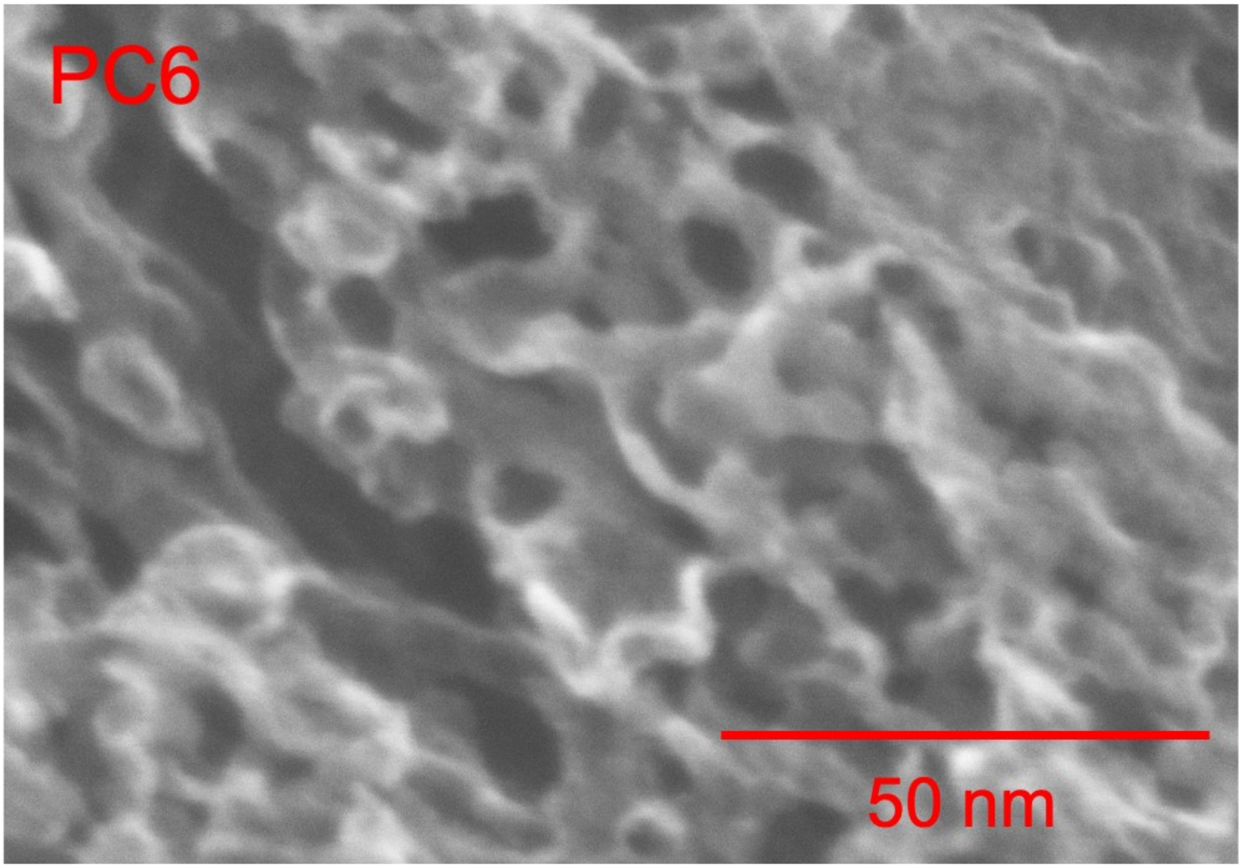



**Fig. S13** Field emission scanning electron microscope image of the top view of PC6

PC6 (CNovel MJ4 010-00) was commercially purchased and directly used as a cathode material

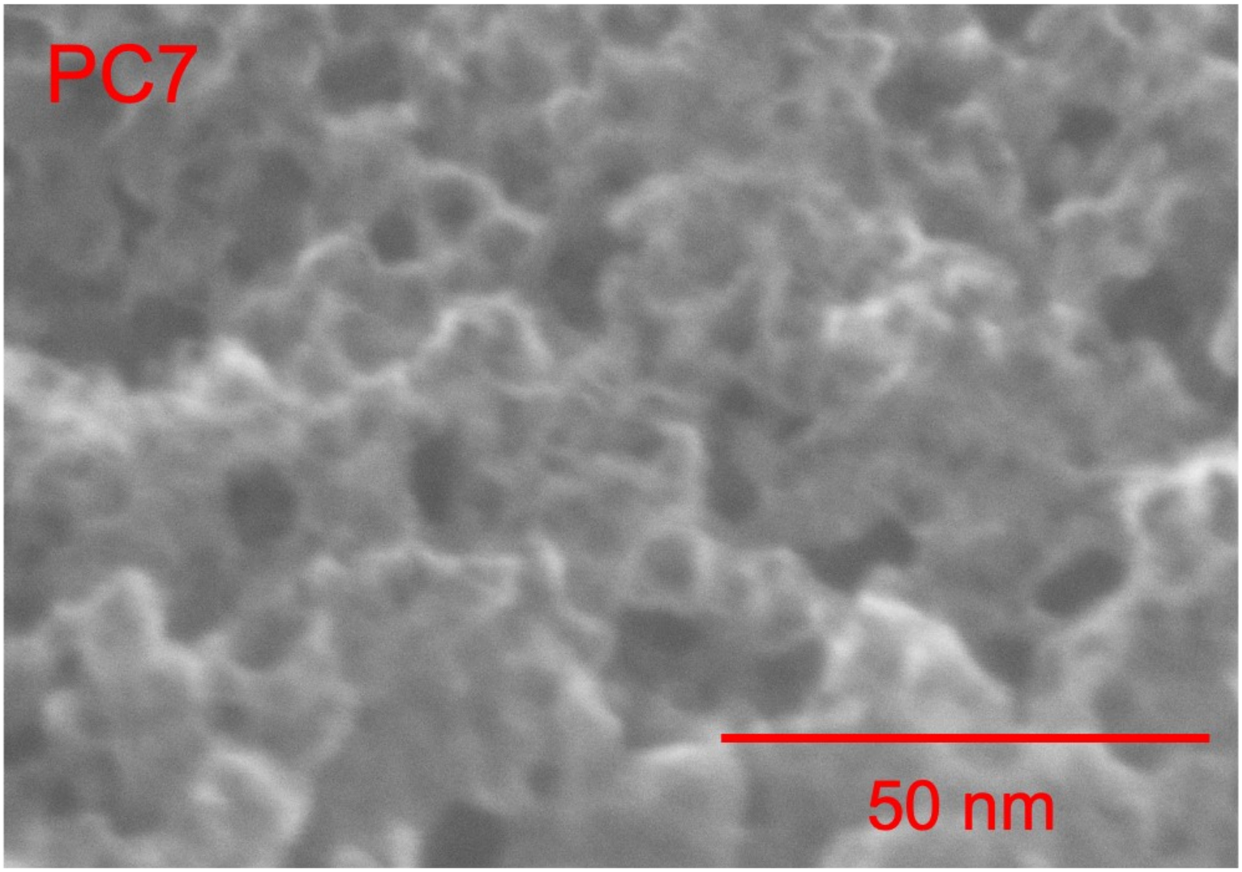



**Fig. S14** Field emission scanning electron microscope image of the top view of PC7

PC7 (CNovel MH-00) was commercially purchased and directly used as a cathode material

**Table S1** Specific surface area and pore structure characteristics of PC1, PC2, PC3, PC4, PC5, PC6 and PC7, along with the capacity at a current density of 0.1 A/g and the ratio of capacity to specific surface area.

| Sample | Average pore width (nm) | Specific surface area ($m^2/g$) | Capacity at 0.1 A/g (mAh/g) | Capacity/Specific surface area |
|---|---|---|---|---|
| PC1 | 1.09 | 1616 | 44.48 | 0.03 |
| PC2 | 1.09 | 2266 | 9.48 | 0.01 |
| PC3 | 2.60 | 2514 | 103.66 | 0.04 |
| PC4 | 2.48 | 3299 | 137.81 | 0.04 |
| PC5 | 19.6 | 709 | 70.79 | 0.10 |
| PC6 | 8.45 | 1031 | 118.81 | 0.12 |
| PC7 | 4.43 | 1500 | 128.79 | 0.09 |

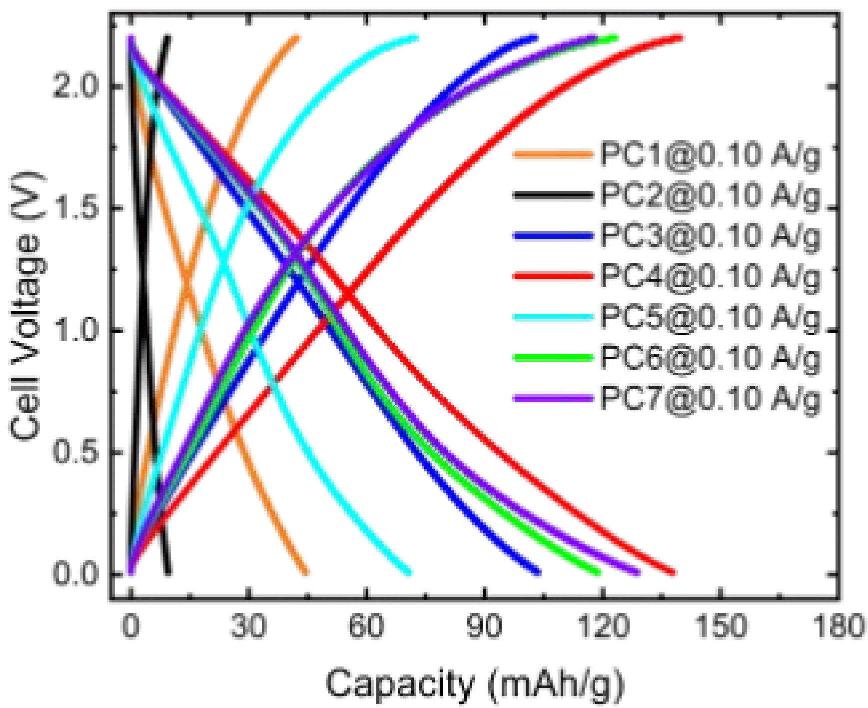



**Fig. S15** Discharge capability of aluminum-ion batteries with PC1, PC2, PC3, PC4, PC5, PC6, and PC7 as cathode materials at a current density of 0.10 A/g

PC1 (YP50F), PC2 (MSP-20), PC3 (MSA-20), PC4 (MSC-30), PC5 (CNovel 20 nm), PC6 (CNovel MJ4 010-00), and PC7 (CNovel MH-00) were commercially purchased and directly used as cathode materials

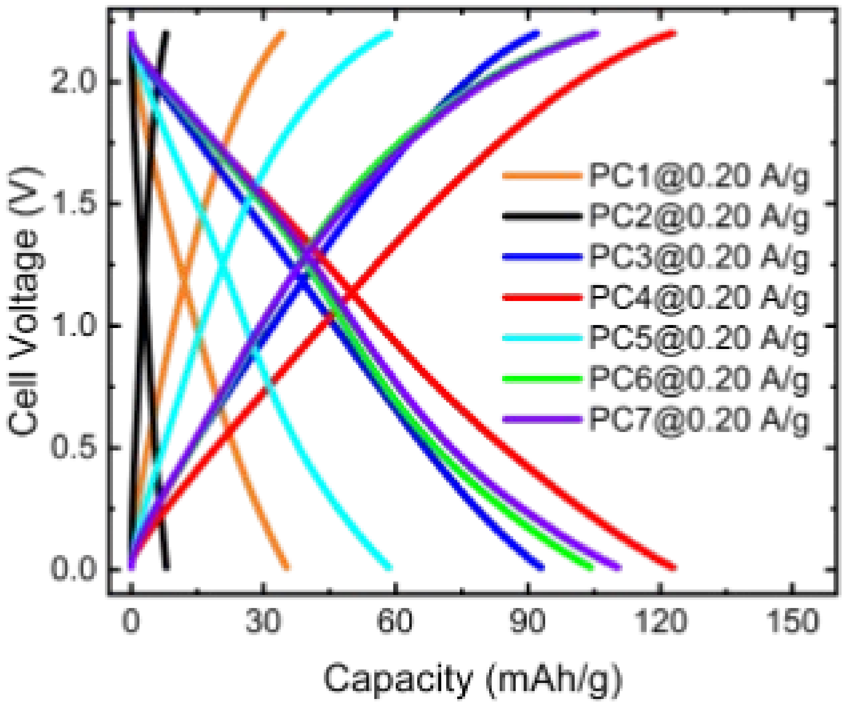



**Fig. S16** Discharge capability of aluminum-ion batteries with PC1, PC2, PC3, PC4, PC5, PC6, and PC7 as cathode materials at a current density of 0.20 A/g

PC1 (YP50F), PC2 (MSP-20), PC3 (MSA-20), PC4 (MSC-30), PC5 (CNovel 20 nm), PC6 (CNovel MJ4 010-00), and PC7 (CNovel MH-00) were commercially purchased and directly used as cathode materials

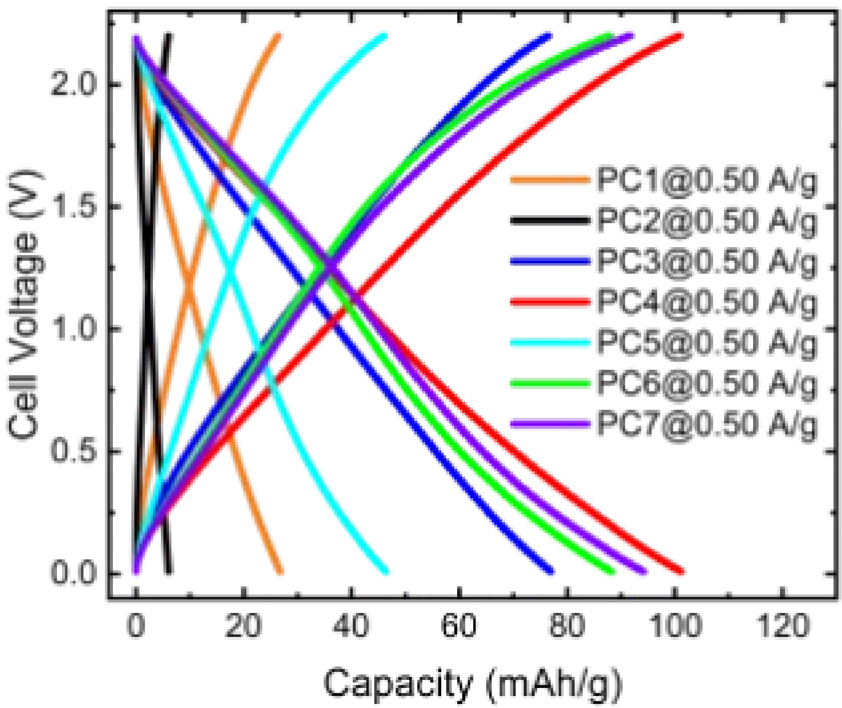



**Fig. S17** Discharge capability of aluminum-ion batteries with PC1, PC2, PC3, PC4, PC5, PC6, and PC7 as cathode materials at a current density of 0.50 A/g

PC1 (YP50F), PC2 (MSP-20), PC3 (MSA-20), PC4 (MSC-30), PC5 (CNovel 20 nm), PC6 (CNovel MJ4 010-00), and PC7 (CNovel MH-00) were commercially purchased and directly used as cathode materials

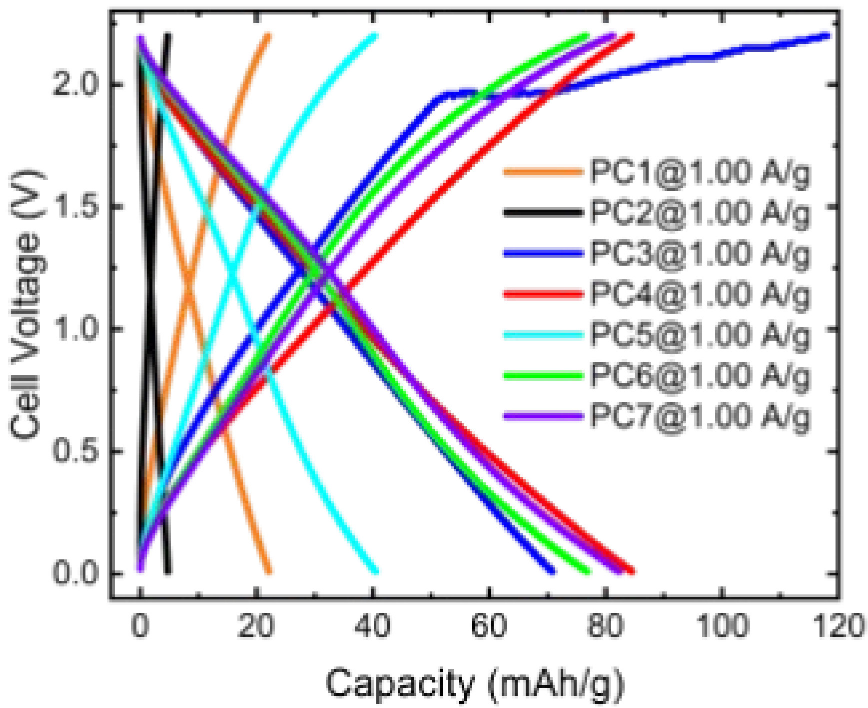



**Fig. S18** Discharge capability of aluminum-ion batteries with PC1, PC2, PC3, PC4, PC5, PC6, and PC7 as cathode materials at a current density of 1.00 A/g

PC1 (YP50F), PC2 (MSP-20), PC3 (MSA-20), PC4 (MSC-30), PC5 (CNovel 20 nm), PC6 (CNovel MJ4 010-00), and PC7 (CNovel MH-00) were commercially purchased and directly used as cathode materials

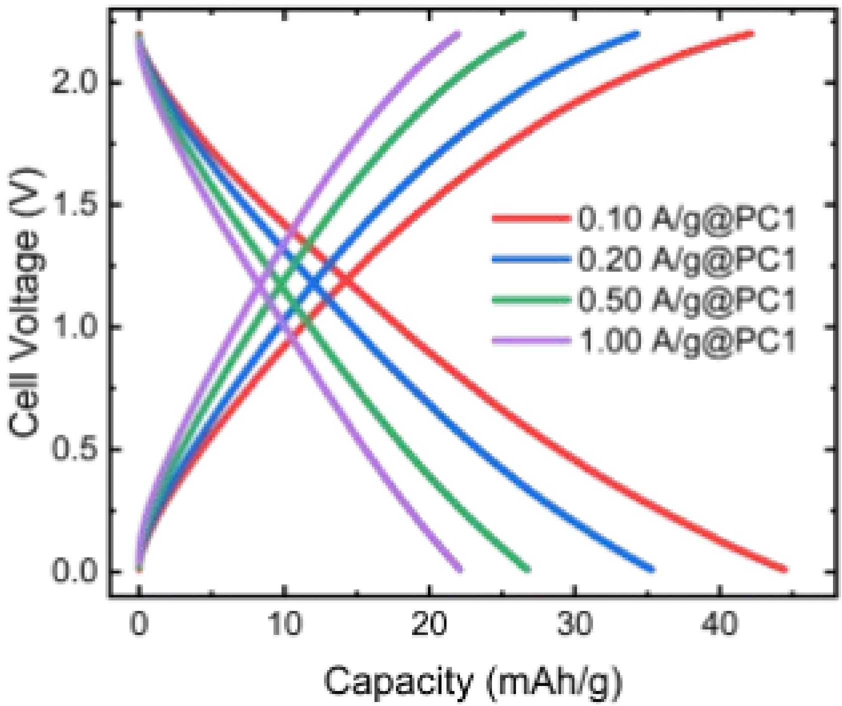



**Fig. S19** Galvanostatic charge and discharge curves of an aluminum-ion battery with the cathode material of PC1 at a series of current densities

PC1 (YP50F) was commercially purchased and directly used as a cathode material

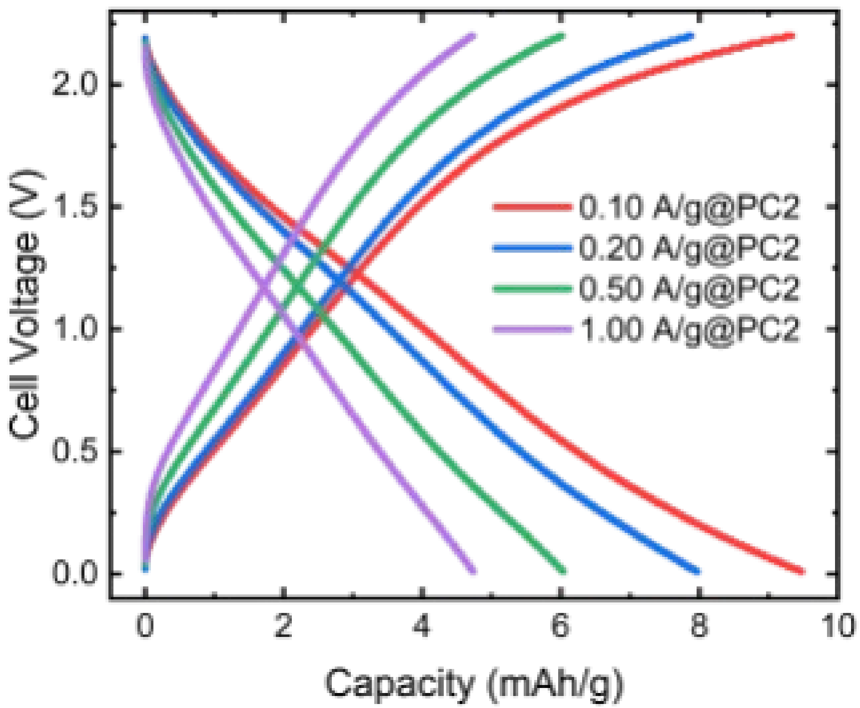



**Fig. S20** Galvanostatic charge and discharge curves of an aluminum-ion battery with the cathode material of PC2 at a series of current densities

PC2 (MSP-20) was commercially purchased and directly used as a cathode material

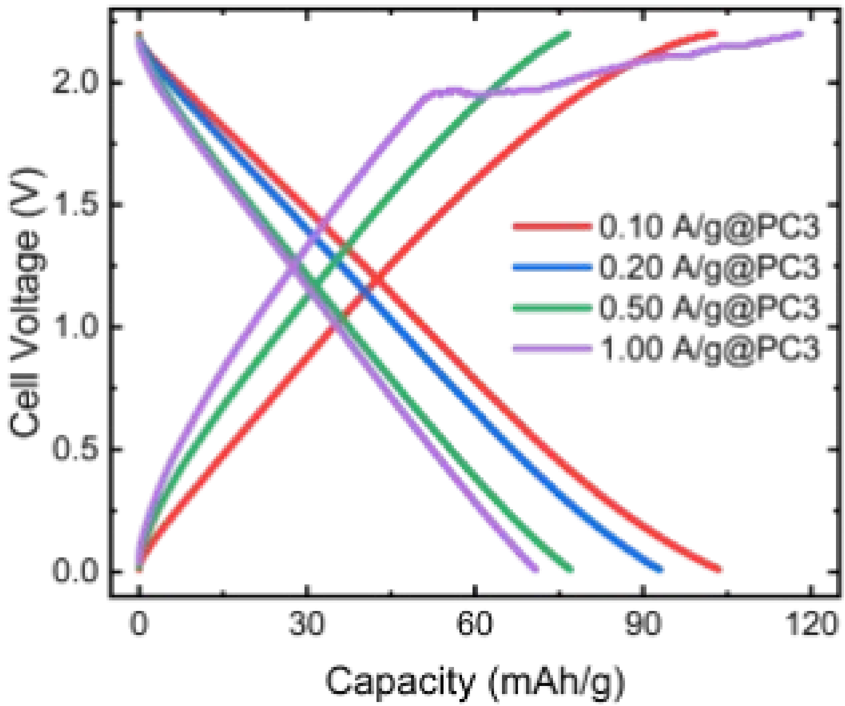



**Fig. S21** Galvanostatic charge and discharge curves of an aluminum-ion battery with the cathode material of PC3 at a series of current densities

PC3 (MSA-20) was commercially purchased and directly used as a cathode material

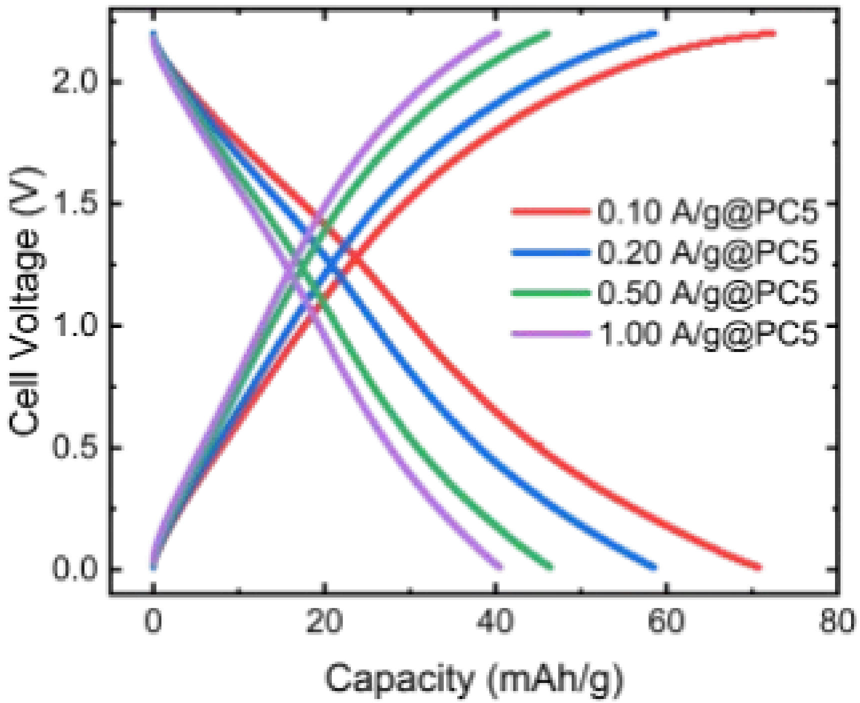



**Fig. S22** Galvanostatic charge and discharge curves of an aluminum-ion battery with the cathode material of PC5 at a series of current densities

PC5 (CNovel 20 nm) was commercially purchased and directly used as a cathode material

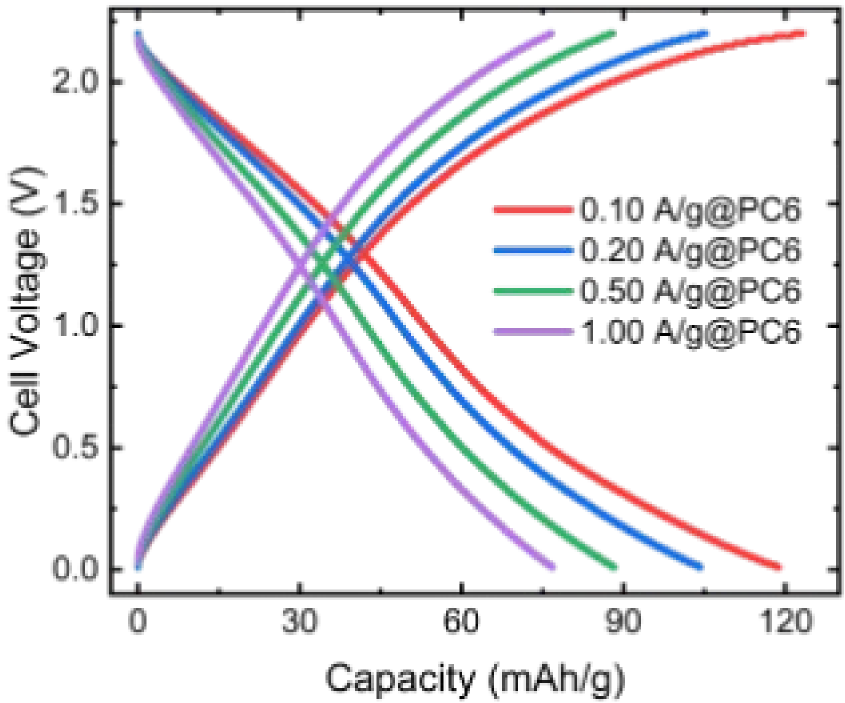



**Fig. S23** Galvanostatic charge and discharge curves of an aluminum-ion battery with the cathode material of PC6 at a series of current densities

PC6 (CNovel MJ4 010-00) was commercially purchased and directly used as a cathode material

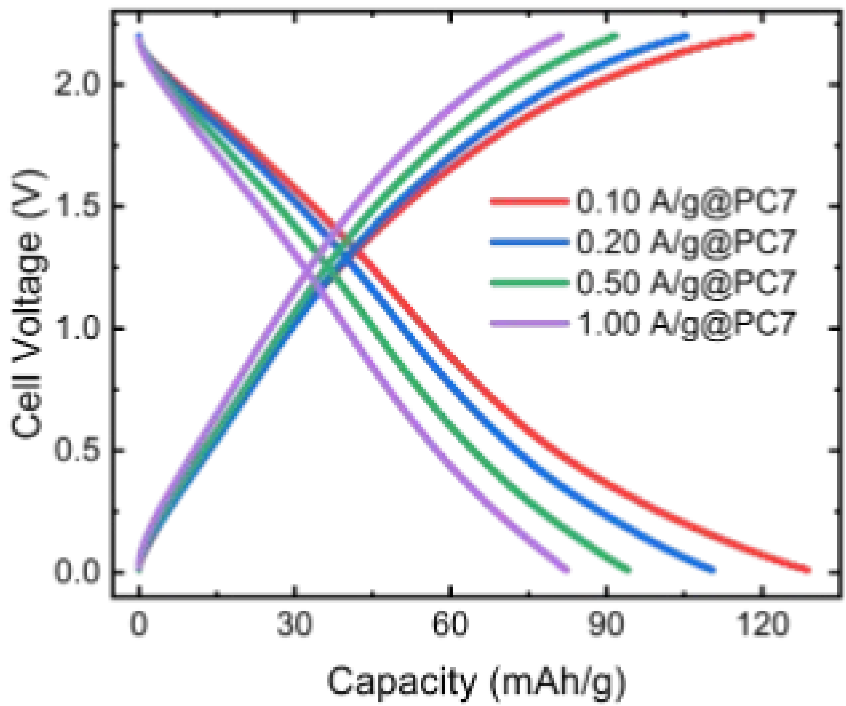



**Fig. S24** Galvanostatic charge and discharge curves of an aluminum-ion battery with the cathode material of PC7 at a series of current densities

PC7 (CNovel MH-00) was commercially purchased and directly used as a cathode material

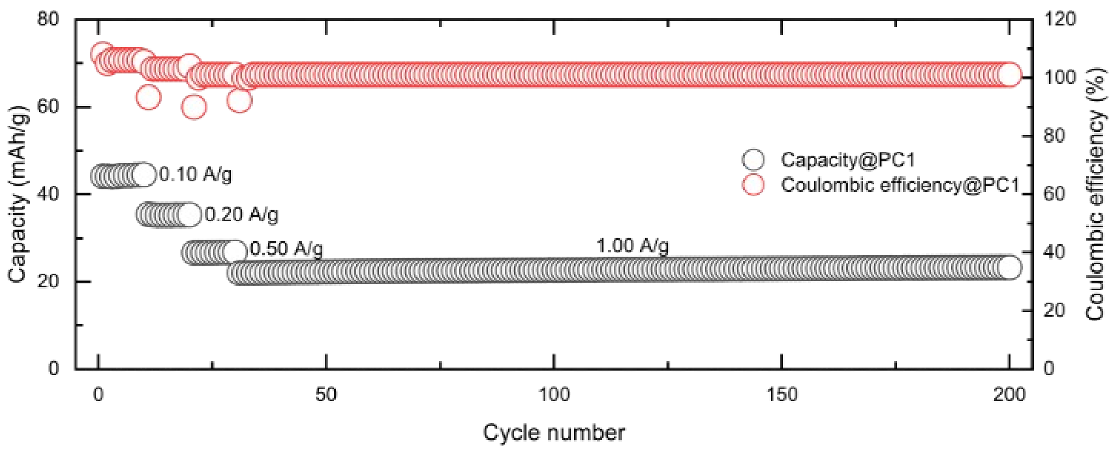



**Fig. S25** Discharge capability and coulombic efficiency of an aluminum-ion battery with the cathode material of PC1 at a series of current densities

PC1 (YP50F) was commercially purchased and directly used as a cathode material

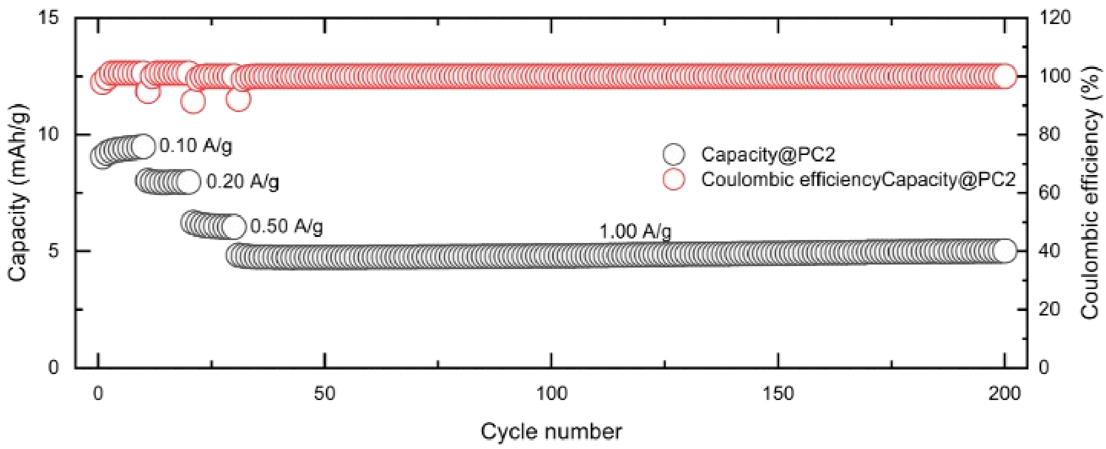



**Fig. S26** Discharge capability and coulombic efficiency of an aluminum-ion battery with the cathode material of PC2 at a series of current densities

PC2 (MSP-20) was commercially purchased and directly used as a cathode material

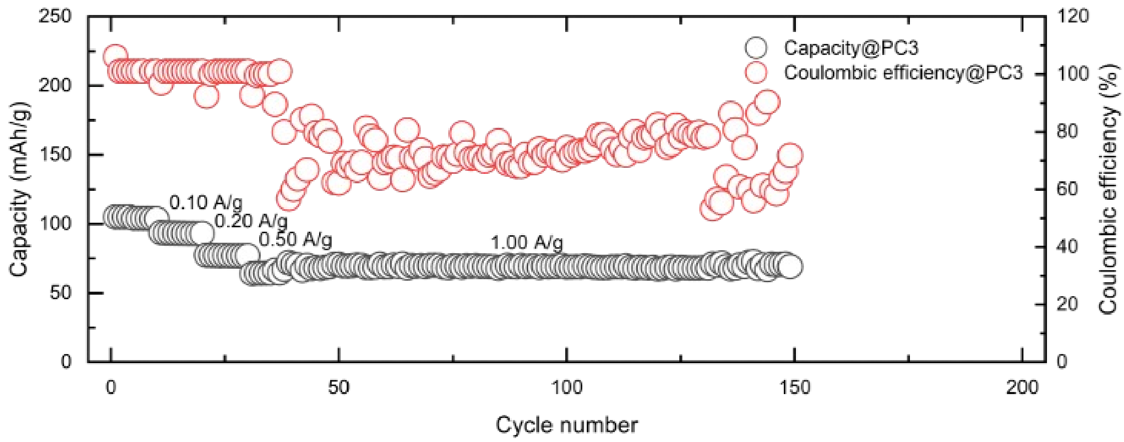



**Fig. S27** Discharge capability and coulombic efficiency of an aluminum-ion battery with the cathode material of PC3 at a series of current densities

PC3 (MSA-20) was commercially purchased and directly used as a cathode material

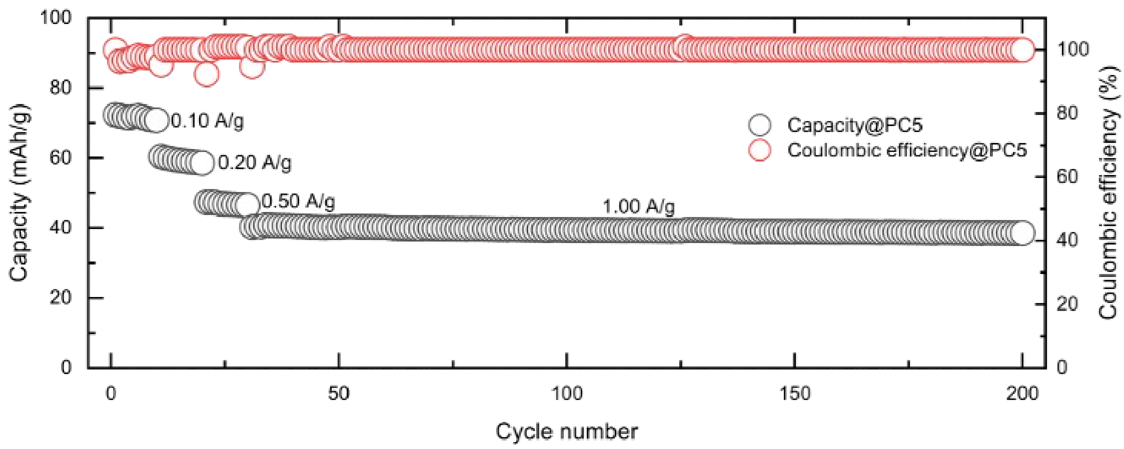



**Fig. S28** Discharge capability and coulombic efficiency of an aluminum-ion battery with the cathode material of PC5 at a series of current densities

PC5 (CNovel 20 nm) was commercially purchased and directly used as a cathode material

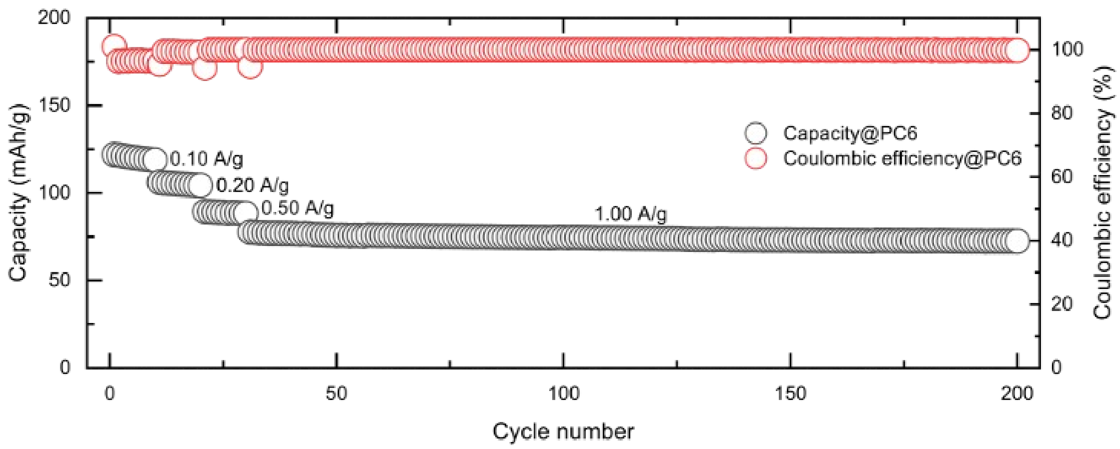



**Fig. S29** Discharge capability and coulombic efficiency of an aluminum-ion battery with the cathode material of PC6 at a series of current densities

PC6 (CNovel MJ4 010-00) was commercially purchased and directly used as a cathode material

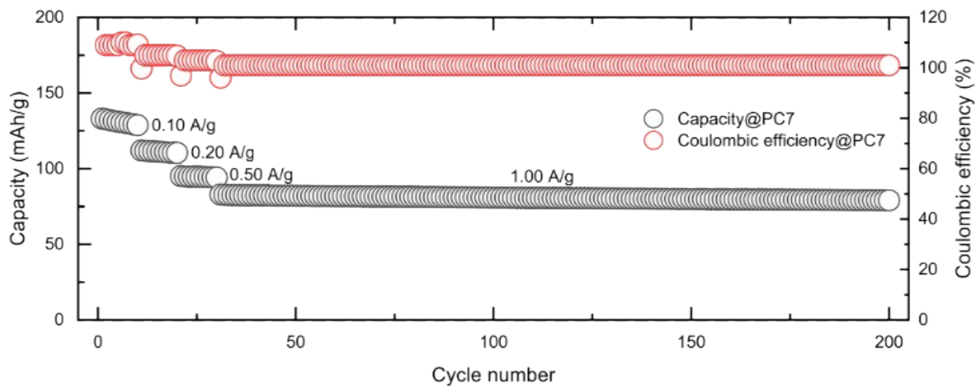
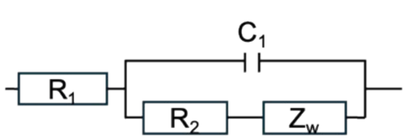



**Fig. S30** Discharge capability and coulombic efficiency of an aluminum-ion battery with the cathode material of PC7 at a series of current densities

PC7 (CNovel MH-00) was commercially purchased and directly used as a cathode material

**Table S2** The fitting values of $R_1$, $R_2$, $Z_w$-R, $Z_w$-T, $Z_w$-P and $C_1$ for PC1, PC2, PC3, PC4, PC5, PC6 and PC7, along with the real part of impedance at 0.1 Hz that roughly corresponds to the $Z_w+R_1+R_2$.

| Sample | The fitting values of $R_1$ ($\Omega$) | The fitting values of $R_2$ ($\Omega$) | The fitting values of $Z_w$-R ($\Omega$) | The fitting values of $Z_w$-T | The fitting values of $Z_w$-P | The fitting values of $C_1$ | The real part of impedance at 0.1 Hz ($\Omega$) |
|---|---|---|---|---|---|---|---|
| PC1 | 2.113 | 0.7356 | 4.688 | 0.10196 | 0.36671 | 0.00011151 | 20.5 |
| PC2 | 2.194 | 0.61106 | 5.578 | 0.14214 | 0.36463 | 0.00011891 | 18.2 |
| PC3 | 2.446 | 0.48036 | 4.909 | 1.246 | 0.39047 | 0.00030301 | 6.52 |
| PC4 | 1.812 | 0.22684 | 4.99 | 1.289 | 0.29148 | 0.00019475 | 7.21 |
| PC5 | 2.547 | 1.151 | 75.47 | 25.55 | 0.55218 | 0.00049315 | 13.6 |
| PC6 | 2.325 | 0.91136 | 28.64 | 6.194 | 0.48155 | 0.00034412 | 12.8 |
| PC7 | 2.289 | 0.29664 | 3.911 | 0.34656 | 0.32775 | 0.00019481 | 10.5 |




Equivalent circuit

$$Z = R \cdot \frac{coth\left[(j \cdot T \cdot \omega)^P\right]}{(j \cdot T \cdot \omega)^P}$$

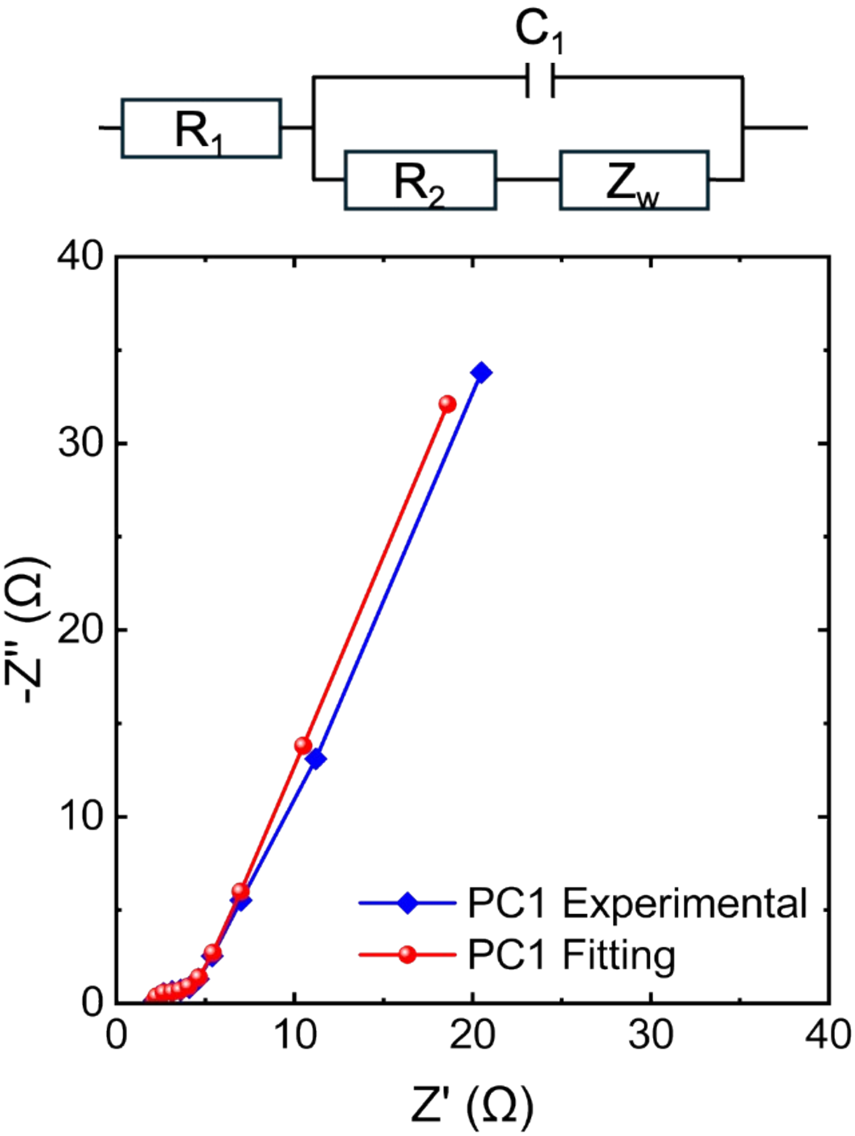



**Fig. S31** Nyquist plot of PC1 at 2.2 V and at an amplitude of 10.0 mV and frequencies ranging from 1.0 MHz to 0.1 Hz and the fitted curve of PC1

PC1 (YP50F) was commercially purchased and directly used as a cathode material

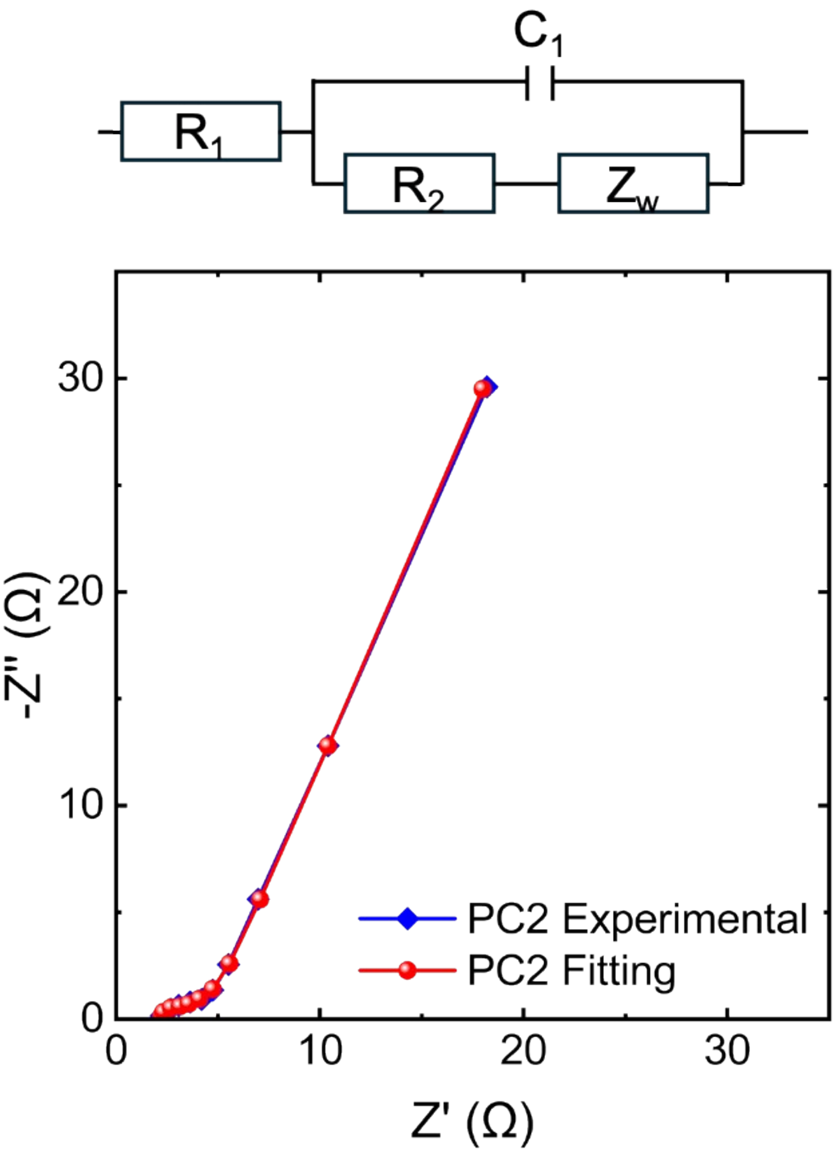



**Fig. S32** Nyquist plot of PC2 at 2.2 V and at an amplitude of 10.0 mV and frequencies ranging from 1.0 MHz to 0.1 Hz and the fitted curve of PC2

PC2 (MSP-20) was commercially purchased and directly used as a cathode material

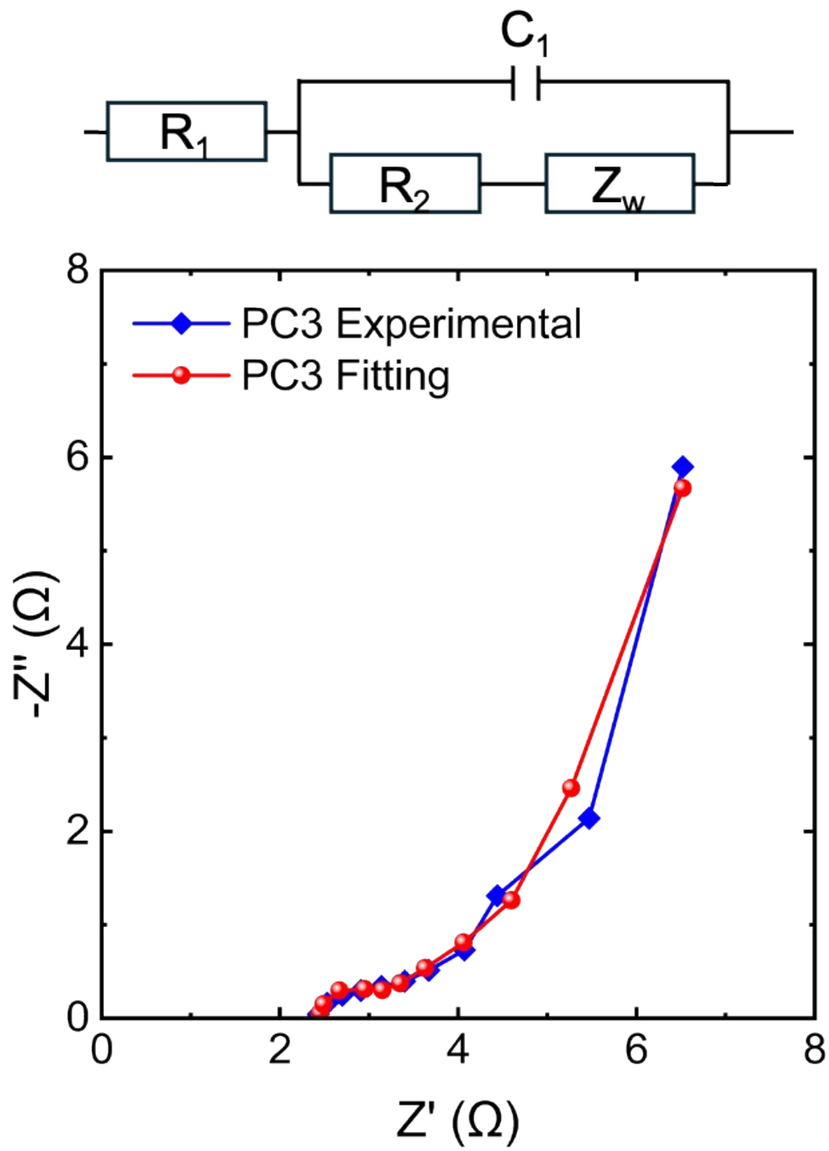



**Fig. S33** Nyquist plot of PC3 at 2.2 V and at an amplitude of 10.0 mV and frequencies ranging from 1.0 MHz to 0.1 Hz and the fitted curve of PC3

PC3 was commercially purchased and directly used as a cathode material

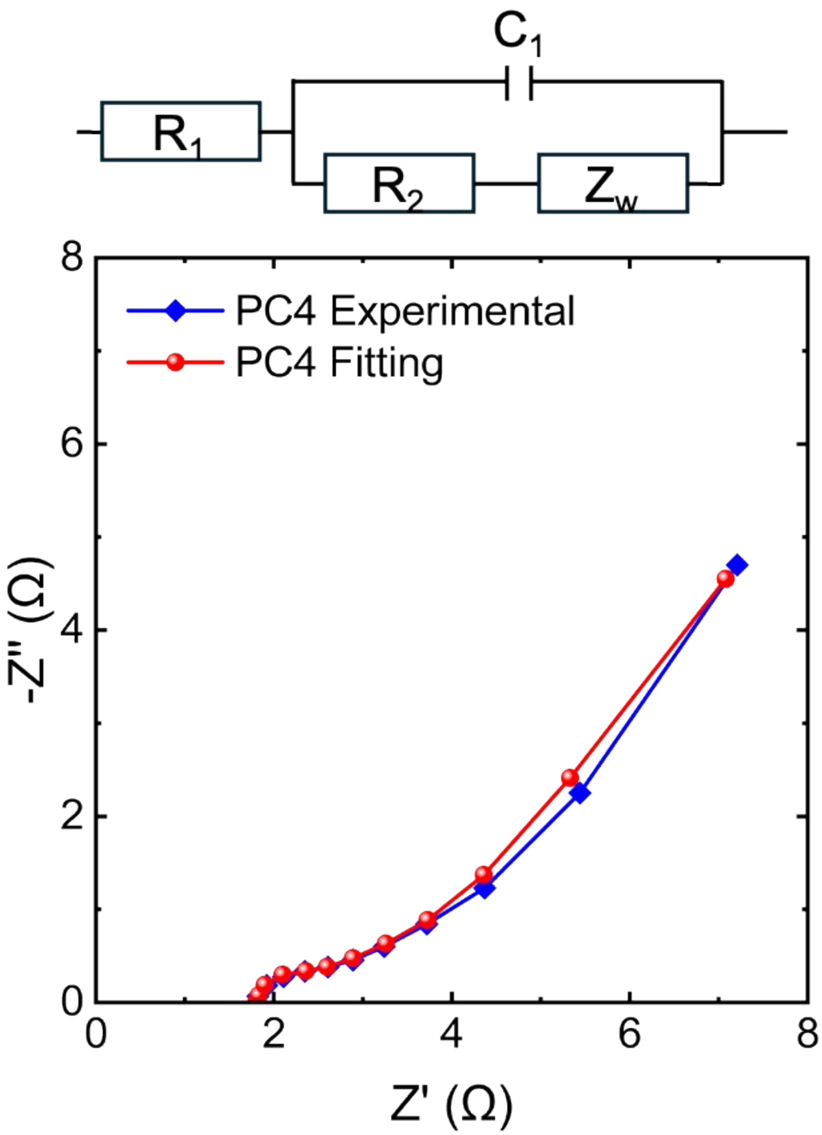



**Fig. S34** Nyquist plot of PC4 at 2.2 V and at an amplitude of 10.0 mV and frequencies ranging from 1.0 MHz to 0.1 Hz and the fitted curve of PC4

PC4 (MSC-30) was commercially purchased and directly used as a cathode material

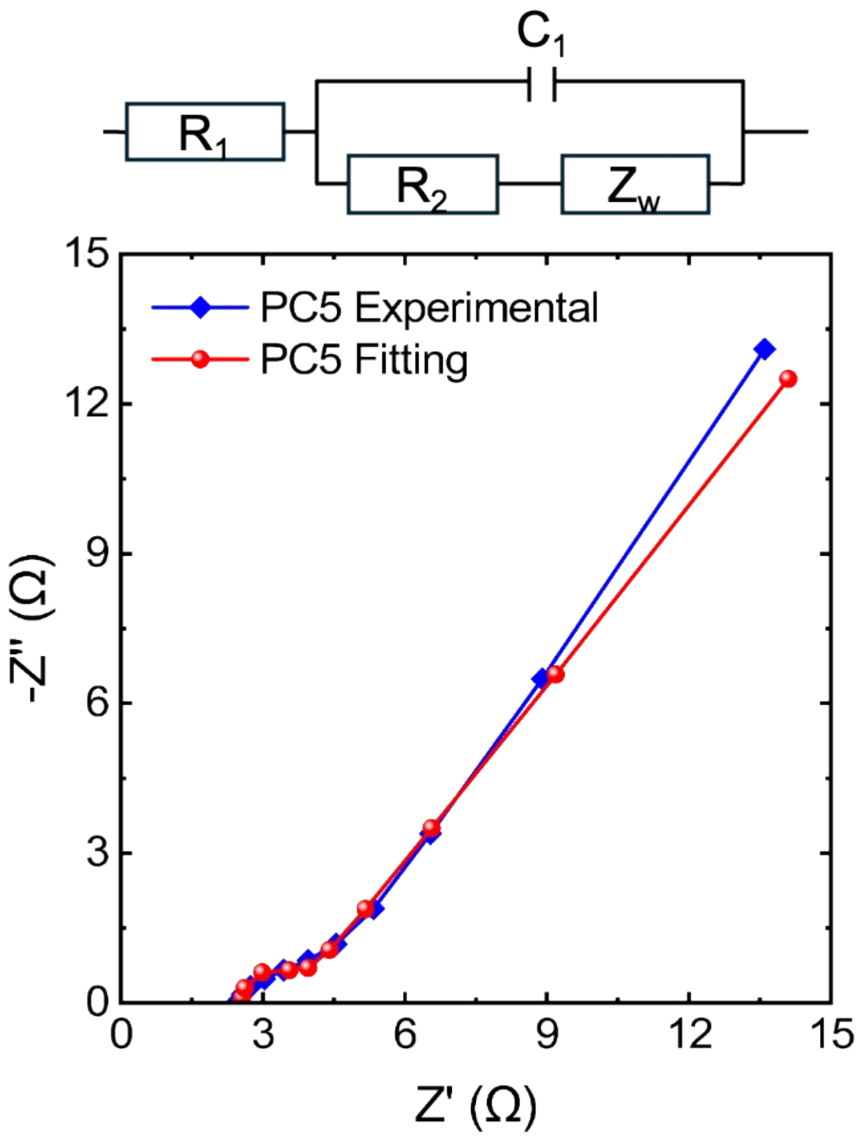



**Fig. S35** Nyquist plot of PC5 at 2.2 V and at an amplitude of 10.0 mV and frequencies ranging from 1.0 MHz to 0.1 Hz and the fitted curve of PC5

PC5 (CNovel 20 nm) was commercially purchased and directly used as a cathode material

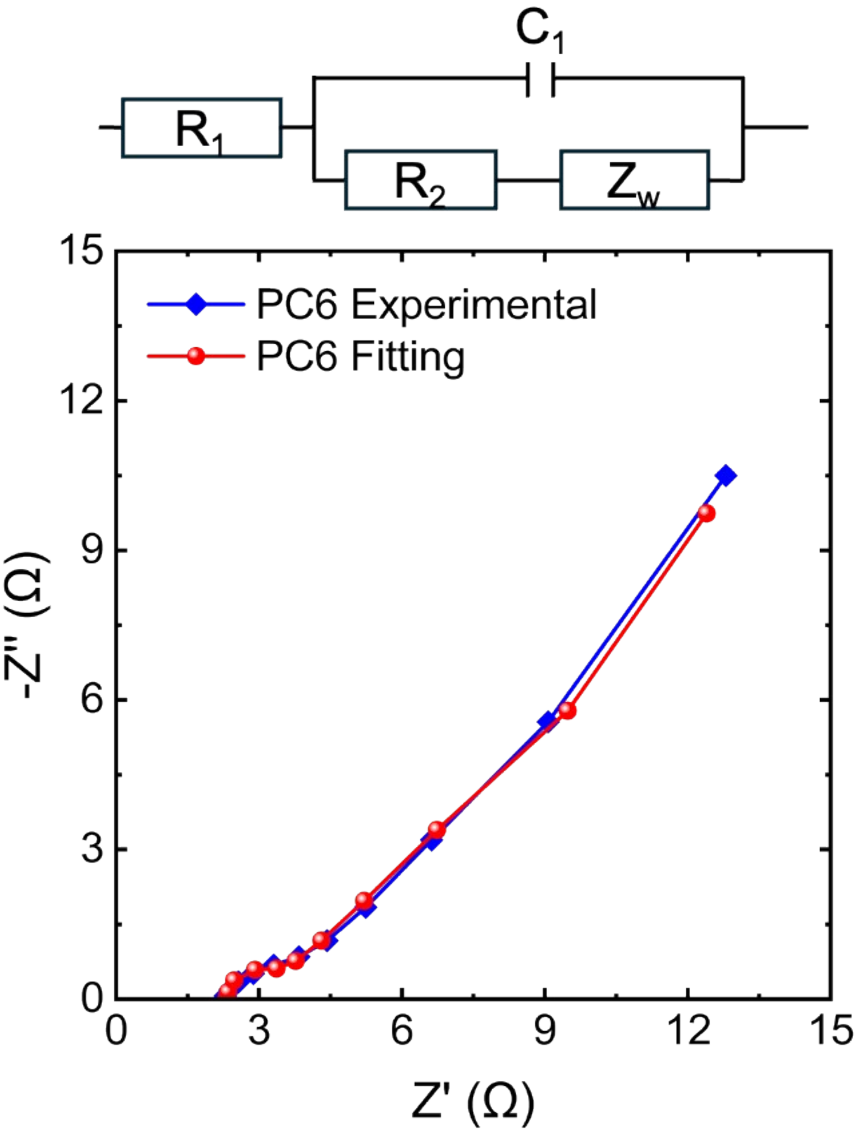



**Fig. S36** Nyquist plot of PC6 at 2.2 V and at an amplitude of 10.0 mV and frequencies ranging from 1.0 MHz to 0.1 Hz and the fitted curve of PC6

PC6 (CNovel MJ4 010-00) was commercially purchased and directly used as a cathode material

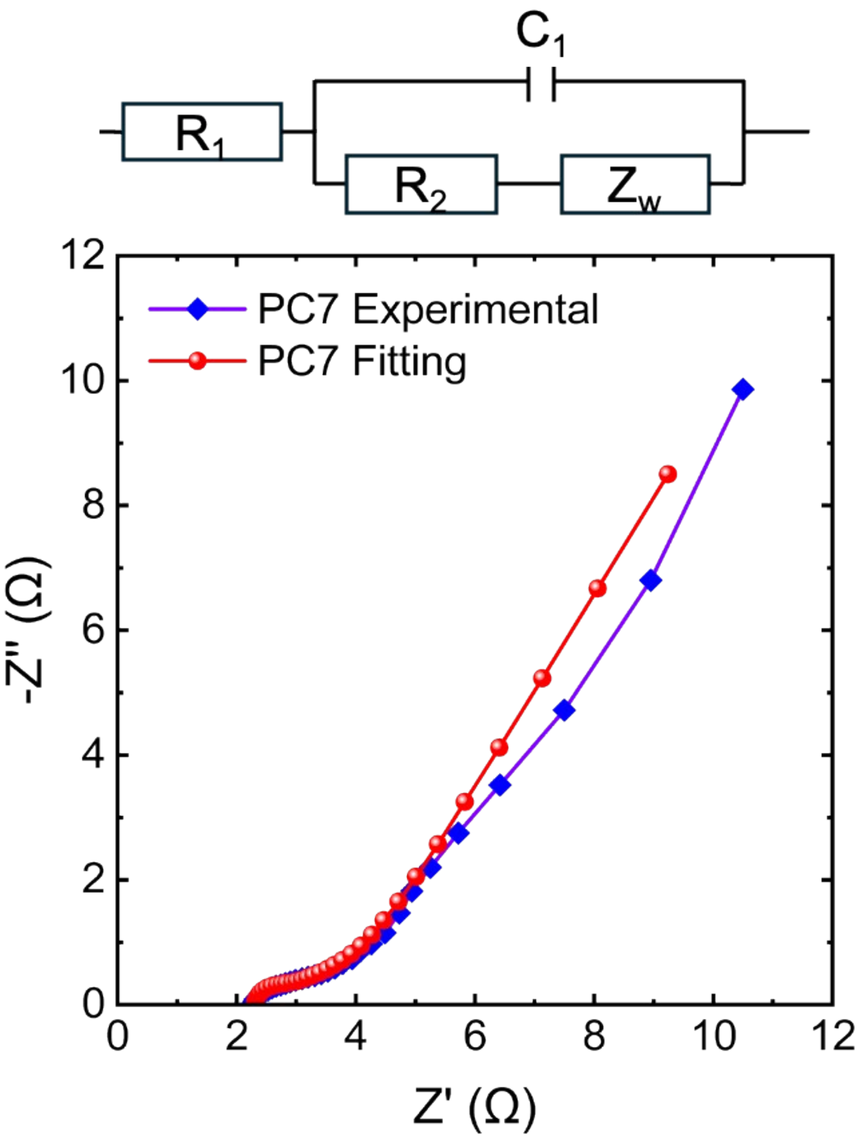



**Fig. S37** Nyquist plot of PC7 at 2.2 V and at an amplitude of 10.0 mV and frequencies ranging from 1.0 MHz to 0.1 Hz and the fitted curve of PC7

PC7 (CNovel MH-00) was commercially purchased and directly used as a cathode material