

Enhanced Faradaic Pseudo-capacitance in reduced π -conjugated carbon network anchored with Strontium Tungstate Nano-Hybrids for High-Energy Supercapacitors

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1. Material

The following items were bought from Sigma Aldrich: graphite powder ($\geq 99.99\%$, Product No. 496596), potassium permanganate ($\geq 99.0\%$, Product No. 223468), sodium tungstate dihydrate ($\text{Na}_2\text{WO}_4 \cdot 2\text{H}_2\text{O}$, $\geq 99.0\%$, Product No. 223336), nitric acid (70%, Product No. 438073), sulphuric acid (95–98%, Product No. 258105), hydrogen peroxide (30% in H_2O_2 , Product. No. 216763), Strontium chloride hexahydrate ($\text{SrCl}_2 \cdot 6\text{H}_2\text{O}$, 99.99%, Product No. 203874), NaOH (Bio reagent, Product No. U5378), hydrochloric acid (37%, Product No. 258148), polyvinylidene difluoride (PVDF, average Mw $\sim 534,000$, Product No. 182702), n-methyl pyrrolidinone (NMP $\geq 99.0\%$, Product No. 443778), and carbon black (conductive, Product No. 940232). All the experiments utilised deionised (DI) water obtained from a Millipore water system.

1.1. Materials and Characterisation

High-resolution scanning electron microscopy (HR-SEM, Thermo Scientific Apreo S) and transmission electron microscopy (TEM, JEM-2100 Plus, JEOL) were used to explore the morphological, chemical and surface properties, and the selected-area electron diffraction (SAED) patterns of the produced SrWO_4 and reduced graphene oxide (rGO). Energy-dispersive spectroscopy (EDS; JEOL JSM-2100 Plus and Thermo Scientific Apreo S) was used for chemical and elemental composition analysis. X-ray diffraction spectroscopy (XRD-X'pert powder XRD system, Malvern PANalytical, United Kingdom) with Cu $K\alpha$ radiation ($\lambda = 0.154\text{ nm}$) at 45 kV (tension) and 40 mA (current) with 0.02° per step scan and 1° per min speed was used to establish the crystallinity of SrWO_4 and GO. Using Fourier transform infrared spectroscopy (FT-IR), the functional groups of the synthesised samples were analysed with an attenuated total reflection (ATR) FT-IR spectrophotometer (Shimadzu IR Tracer-100). Raman spectra of the materials were analysed using a 633 nm excitation laser (HORIBA France, LABRAM HR Evolution). For physical specific surface area and pore size, rGO was measured using a Quantachrome Instruments Autosorb-iQ series (degassed at 120°C for 12 h before measurement). X-ray photoelectron spectroscopy (XPS) using a PHI Versa Probe III Scanning XPS Microprobe (Physical Electronics) confirmed the chemical state, bonding nature, and binding energy.

Uv-vis spectrophotometer (SHIMADZU, UV 3600 PLUS) was utilized to analyse optical absorption and the scattering properties of the catalyst.

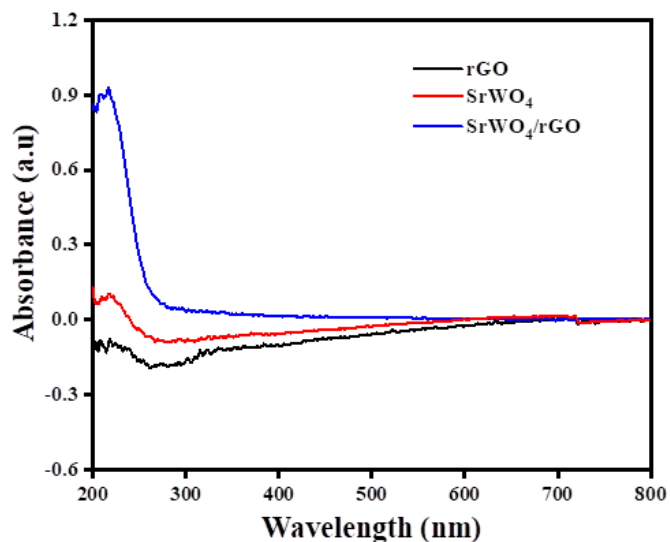


Fig. S1. UV-vis spectra for rGO (black curve), SrWO₄ (red curve) and SrWO₄/rGO (blue curve).

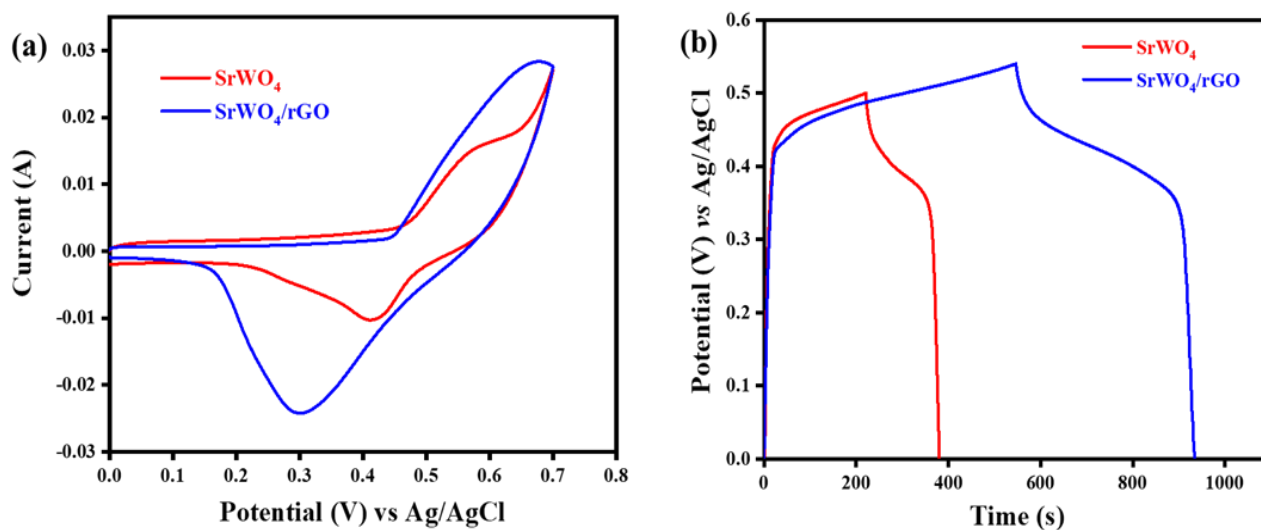


Fig. S2. (a) CV curves at 50 mVs⁻¹ and GCD curves at 1 A g⁻¹ for SrWO₄ (red curve) and SrWO₄/rGO (blue curve) in 1 M KOH electrolyte.

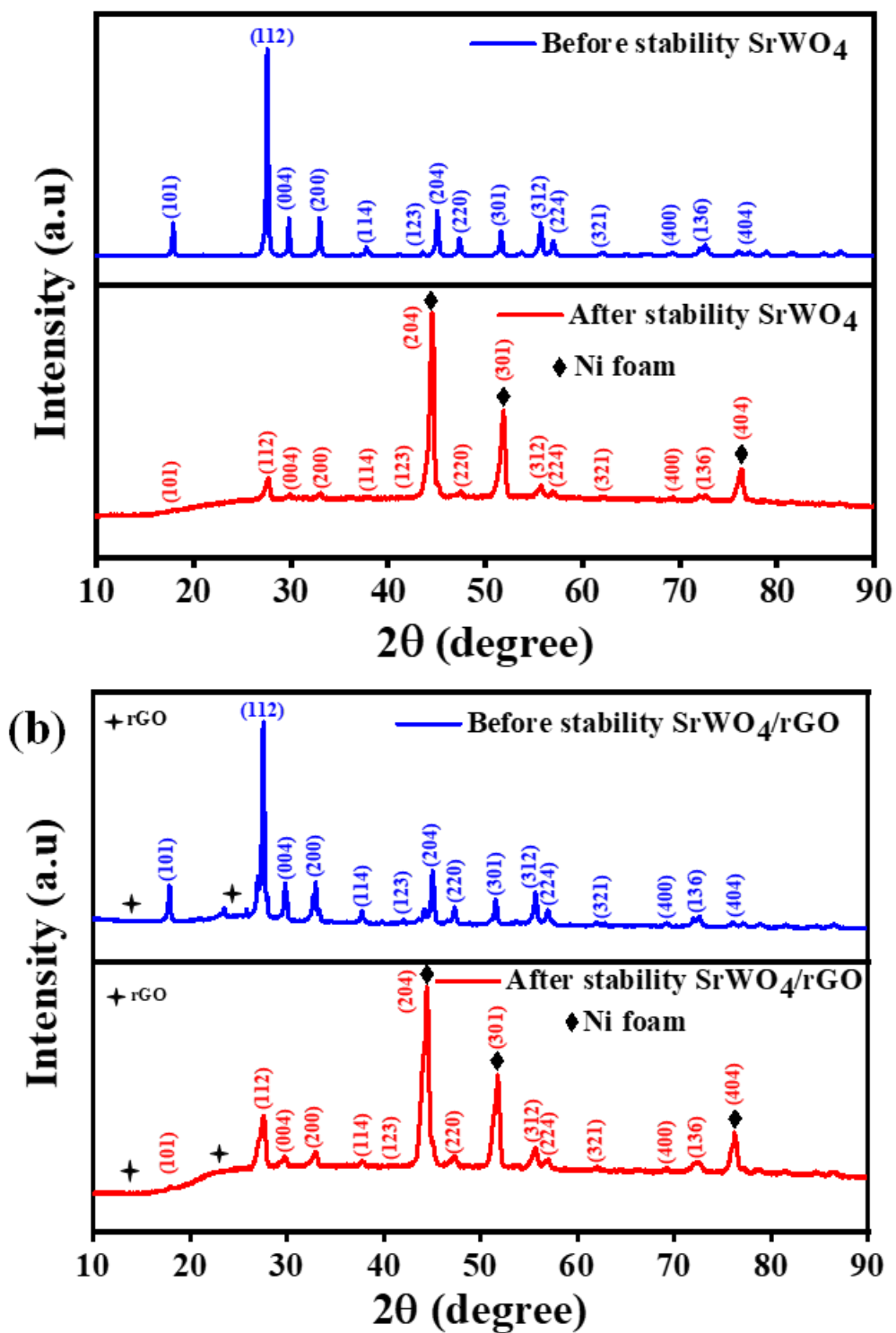


Fig. S3. (a) Pre and Post cyclic stability XRD for SrWO₄ (b) Pre and Post cyclic stability XRD for SrWO₄/rGO

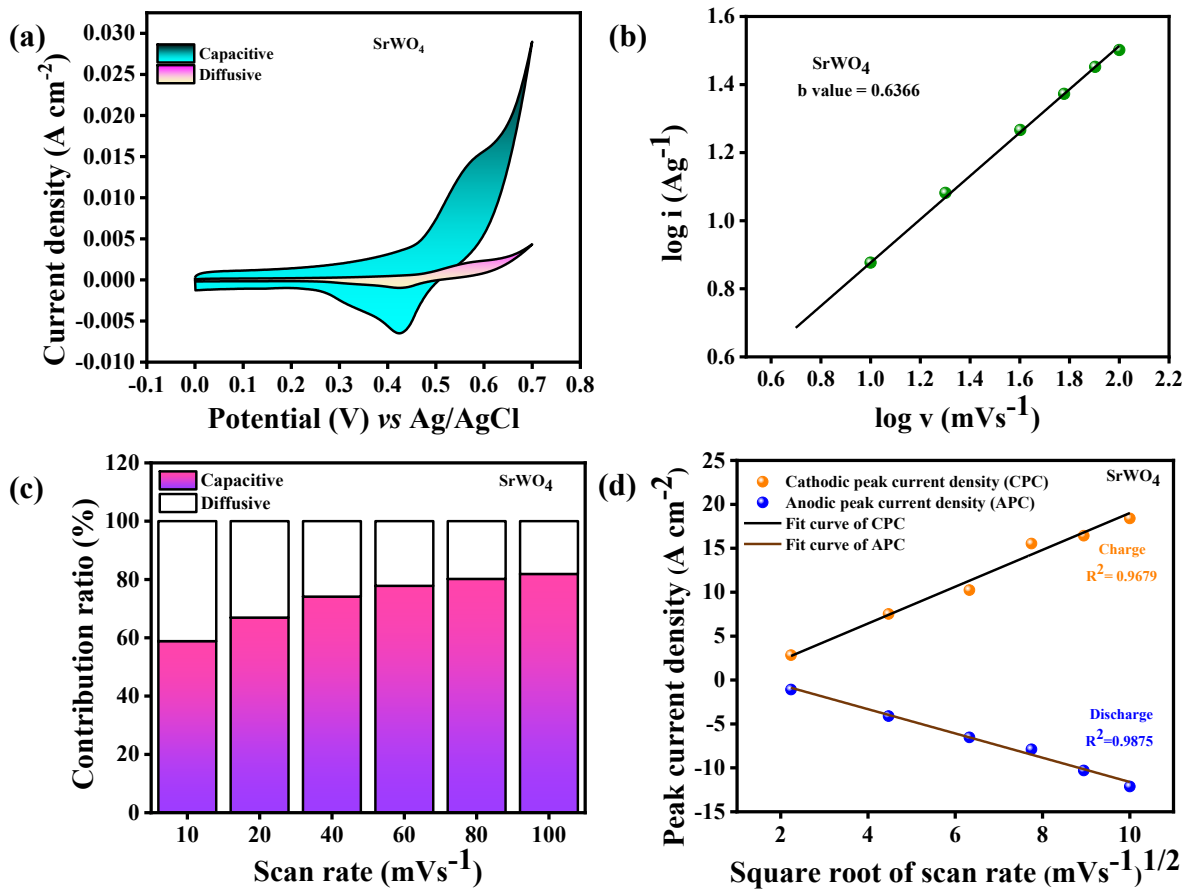


Fig. S4. Donnan method calculation for (a) CV of SrWO₄ at 50 mVs⁻¹, (b) Logarithmic relationship of scan rate vs peak current density, (c) Capacitance contribution of SrWO₄ at 10-100 mVs⁻¹, (d) The square root of the scan rate shown against the peak current density.

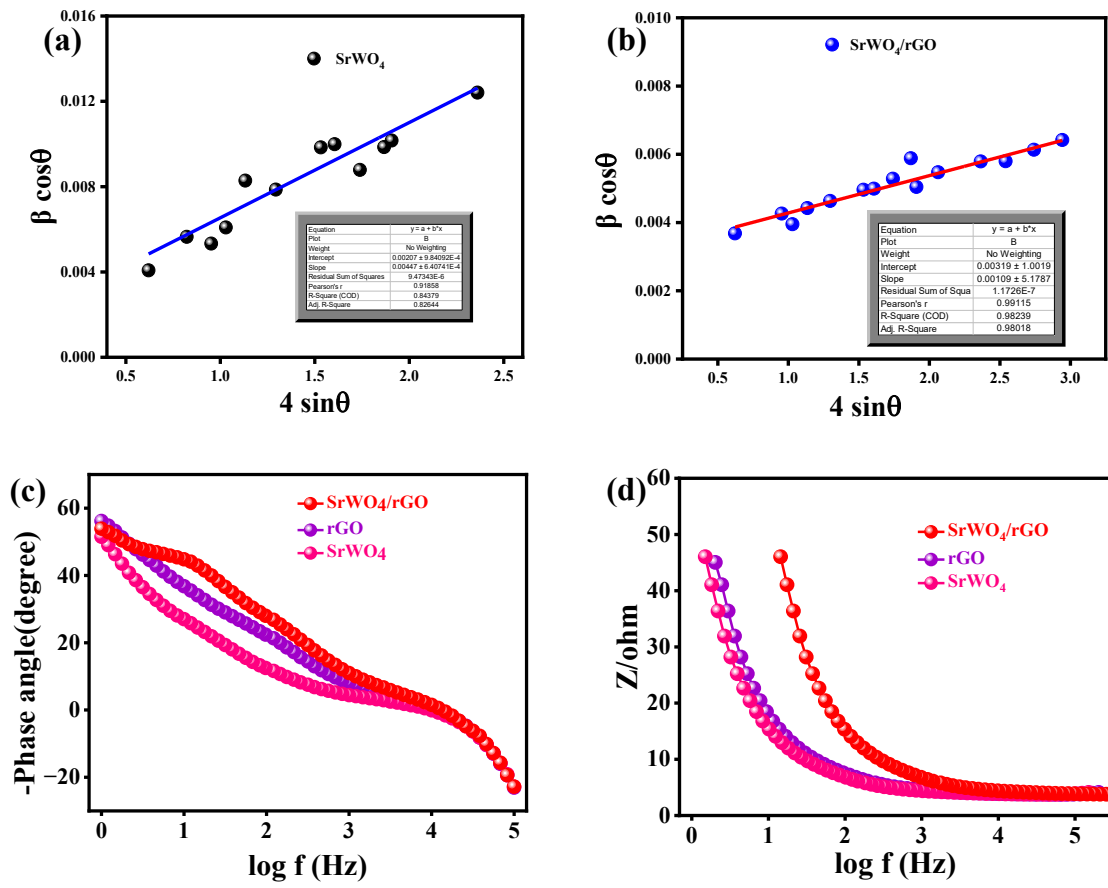


Fig. S5. (a-b), W-H plot for SrWO₄ and SrWO₄/rGO, (c-d) Bode phase and Bode plot for SrWO₄, rGO, SrWO₄/rGO.

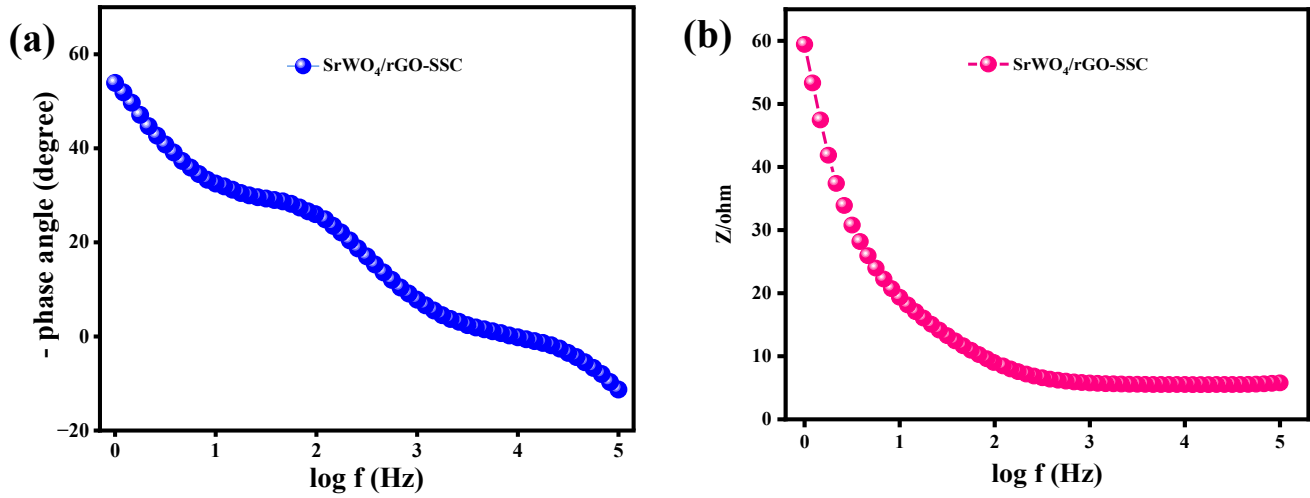


Fig. S6. (a-b) Bode phase and Bode plot for SrWO₄/rGO-SSC

The following formulas were used to calculate the mean crystal size (eq 1), dislocation density (eq 2), and the sample's microstrain (eq 3); results are displayed in **Table S1**.

$$D = \frac{K\lambda}{\beta \cos \theta} \quad (1)$$

$$\delta = \frac{1}{D^2} \quad (2)$$

$$\varepsilon = \frac{\beta}{4 \tan \theta} \quad (3)$$

In this equation, “D” represents crystallite size, “K” represents crystal lattice constant (0.94), “β” represents full width at half maximum (FWHM), “λ” represents X-ray wavelength (1.5406), “θ” represents an angle of diffraction, “δ” represents dislocation density, and “ε” represents microstrain.^{1,2}

Material	Crystallite size (nm)	Crystallinity Index (%)	Micro Strain (ε) (nm ⁻²)	Dislocation Density (δ) (nm ⁻²)
SrWO ₄	78.443	83.38	0.236	1.63 x 10 ⁻⁴
SrWO ₄ /rGO	59.275	68.75	0.441	13.62 x 10 ⁻⁴

Table S1. Crystalline parameters of the prepared materials.

Electrodes	R_s (Ω)	R_{ct} (Ω)	C_{dl} (μF cm²)
SrWO ₄	4.2	15.3	9.3
rGO	0.8	2.2	181
SrWO ₄ /rGO	1.3	4.8	360

Table S2. Electrochemical Impedance Parameters

2.0 Energy density (*E*) calculation

The *E* of the STS device were calculated using the following equations:

$$E = \frac{C_s \Delta v^2}{7.2} (Wh kg^{-1})$$

where Δt is the discharge time (s), ΔV is the cell operating voltage window, and C_s denotes the specific capacitance ($F g^{-1}$) of the STS, determined using the total mass of the active materials.³

With the following parameters, Specific capacitance (C_s) = 83.6 $F g^{-1}$ at 1 Ag^{-1} and Voltage window (ΔV) = 1.5 V, *E* is calculated as follows.

$$E = \frac{83.6 \times (1.5)^2}{7.2}$$

$$E = \frac{188.1}{7.2}$$

$$E = 26.13 Wh kg^{-1}$$

S. No.	Material	Synthesis Method	Morphology (Metal Tungstate)	Electrolyte	Specific capacity		Device Configuration	Potential window (V)	Ref No.
					3 electrode system	2-electrode system			
1.	CoWO ₄ /NRGO	Sonochemical	Irregular-shaped agglomerations	2 M H ₂ SO ₄	-	597 F g ⁻¹ at 5 mV s ⁻¹	CoWO ₄ /NRGO//	-0.5 to 0.5	4
2.	CoMnWO ₄	co-precipitation	Sphere	1 M KOH	444 F g ⁻¹ at 1 Ag ⁻¹	112 F g ⁻¹ at 1 Ag ⁻¹	CoMnWO ₄ //AC	0 to 1.4	5
3.	CoWO ₄ /MWCNT	Hydrothermal	Nanosphere	3 M KOH	543 F g ⁻¹ at 5 mV	-	-	0 to 0.55	6
4.	SrWO ₄ /ppy	In-situ chemical polymerisation	Spheres	1 M KOH	373 F g ⁻¹ at 1 Ag ⁻¹	-	-	0 to 0.65	7
5.	SrWO ₄ /g-C ₃ N ₄	Hydrothermal	Nanosphere	2 M KOH	1050 C g ⁻¹ at 1 Ag ⁻¹	190.5 C/g at 1 Ag ⁻¹	SrWO ₄ /g-C ₃ N ₄ //AC	0 to 1.7	8
6.	GW-CuWO ₄	Solid-state reaction	Cube	1 M KOH	520.8 C g ⁻¹ at 1 Ag ⁻¹	-	-	0 to 0.5	9
7.	MWCNT/NiWO ₄	Hydrothermal	Dispersed granular	1 M KOH	885 F g ⁻¹ at 1 Ag ⁻¹	162 F g ⁻¹ at 1 Ag ⁻¹	MWCNT/NiWO ₄ //AC	0 to 1.5	10
8.	Co ₃ O ₄ @CoWO ₄ /rGO	Hydrothermal	Nanoneedles	6 M KOH	386 F g ⁻¹ at 0.5 Ag ⁻¹	-	Co ₃ O ₄ @CoWO ₄ /rGO//AC	0 to 1.7	11
9.	MnO ₂ /CoWO ₄ /NCNO	Hydrothermal	Nanosphere	6 M KOH	536 F g ⁻¹ at 2 Ag ⁻¹	1036 F g ⁻¹ at 2 Ag ⁻¹	MnO ₂ /CoWO ₄ /NCNO/MnO ₂ /CoWO ₄ /NCNO	-0.7 to 0.8	12
10.	SrWO ₄ /rGO	One-pot Hydrothermal	Sphere	1 M KOH	727 F g ⁻¹ at 1 Ag ⁻¹	83.6 F g ⁻¹ at 1 Ag ⁻¹	SrWO ₄ /rGO//AC	0 to 1.5	This work

Table S3. - Electrochemical Performance Comparison of Metal Tungstate-Based Supercapacitor Electrodes

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