Supplementary Information

Hierarchically porous carbon derived from waste watermelon rind for enhanced microwave absorption

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2.3 Characterizations

The thermal behavior of the samples was analyzed via thermogravimetry–differential scanning calorimetry (TG-DSC, Netzsch STA 449 F3/F5) from room temperature to 900 °C under an argon atmosphere at a heating rate of 10 °C ·min^{-1}. Functional groups on the sample surfaces were identified and confirmed by Fourier-transform infrared (FTIR) spectroscopy (Nicolet6700). The phase composition and crystal structure were determined by X-ray diffraction (XRD, Bruker D8 ADVANCE). Raman spectra were acquired using a Raman spectrometer (SCIENTIFIC DXR) with 532 nm argon-ion laser excitation. The elemental composition and chemical states were evaluated by X-ray photoelectron spectroscopy (XPS, Thermo Escalab 250Xi). Specific surface area and pore-size distribution were measured via N_2 adsorption-desorption analysis (Micromeritics ASAP 2460 3.01) and calculated using appropriate models. The morphology and microstructure were examined using field-emission scanning electron microscopy (SEM, Hitachi SU8010) and high-resolution transmission electron microscopy (TEM, FEI Tecnai G2 F30) equipped with energy-dispersive X-ray spectroscopy (EDS, Oxford XPLORE).

The resistivity of WRP powder and WRP/paraffin composites was measured using a powder resistivity tester (ST2722) and a four-point probe tester (ST2253), respectively, with both instruments manufactured by Suzhou Jingge Electronic Co., Ltd. The average resistivity of the WRP/paraffin composites was required to have a coefficient of variation (CV) ≤ 3% before being used for the preparation of coaxial rings, indicating that the WRP was uniformly dispersed within the paraffin matrix. The electromagnetic parameters were obtained using a vector network analyzer (VNA, Hewlett-Packard 8722ES) on coaxial ring specimens (Φ_{out} = 7.0 mm, Φ_{in} = 3.04 mm) prepared by uniformly mixing the sample (8 wt%) with paraffin. The reflection loss (RL) of the flat panel specimens was measured using the arch method equipped with a VNA (Keysight N5244A). The flat panel specimens had dimensions of 180 mm × 180 mm with a total thickness of 6.00 ± 0.05 mm.

Table S1 Relative atomic contents of the WRP samples

Sample \ Atoms	Atomic percentage (%)			
	C	N	O	S
WRP-500	89.04	2.45	8.3	0.21
WRP-600	89.31	2.38	8.11	0.20
WRP-700	90.77	2.23	6.79	0.21
WRP-800	92.42	1.50	5.86	0.22

Table S2 Relative peak area contents of C bonding configurations in the WRP samples

Sample \ Configurations	Relative peak area contents (%)			
	C=C/C−C	C−N	C−O	C=O
WRP-500	78.31	8.45	5.89	7.35
WRP-600	80.96	7.54	5.64	5.86
WRP-700	82.08	7.38	5.54	5
WRP-800	83.28	7.19	5.09	4.44

Table S3 Specific surface area and pore volume data of the samples.

Sample \ Pore data	Specific Surface Area		Total Pore Volume ($cm^3 \cdot g^{-1}$)
	S_{BET} ($m^2 \cdot g^{-1}$)	t-Plot Micropore Area ($m^2 \cdot g^{-1}$)	
WR-600	267.48	258.76	0.11
WRP-500	526.44	471.64	0.23
WRP-600	811.92	768.29	0.33
WRP-700	1161.20	1135.44	0.46
WRP-800	1952.03	767.14	0.92

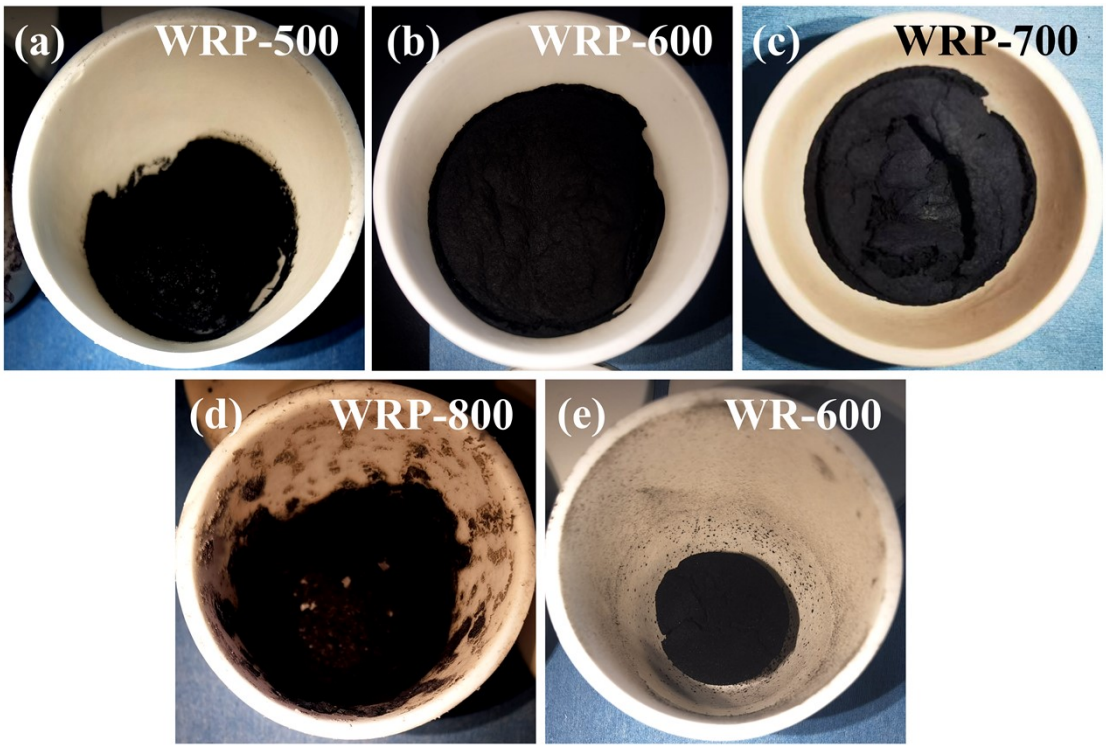

Fig. S1 Heat-treated WR/K_2CO_3 samples: (a) WRP-500, (b) WRP-600, (c) WRP-700, and (d) WRP-800. (e) WR pyrolyzed at 600 °C without K_2CO_3.

Table S4 The optimal EAB_{max} and RL_{min} configurations along with their corresponding thicknesses among the 24 subgroups.

No.	Group		Configurations achieving EAB_{max} in each subgroup	Configurations achieving RL_{min} in each subgroup
	Major group	Subgroup		
1	567	567	5(0.0)-6(3.1)-7(0.0)-(7.74 GHz@3.1 mm)	5(1.0)-6(2.3)-7(0.6)-(–63.00 dB@3.9 mm)
2		576	5(0.0)-7(0.9)-6(2.2)-(8.41 GHz@3.1 mm)	5(1.5)-7(0.7)-6(3.2)-(–67.94 dB@5.4 mm)
3		657	6(3.1)-5(0.0)-7(0.0)-(7.74 GHz@3.1 mm)	6(3.5)-5(1.2)-7(1.0)-(–79.34 dB@5.7 mm)
4		675	6(0.8)-7(1.0)-5(3.3)-(9.35 GHz@5.1 mm)	6(2.1)-7(0.6)-5(1.0)-(–75.79 dB@3.7 mm)
5		756	7(1.9)-5(2.7)-6(0.4)-(10.79 GHz@5.0 mm)	7(2.0)-5(1.0)-6(1.6)-(–67.58 dB@4.6 mm)
6		765	7(1.7)-6(2.2)-5(2.1)-(11.73 GHz@6.0 mm)	7(1.3)-6(1.8)-5(2.0)-(–77.25 dB@6.0 mm)
7	568	568	5(0.0)-6(2.4)-8(0.1)-(7.82 GHz@2.5 mm)	5(1.7)-6(0.4)-8(0.1)-(–66.28 dB@2.2 mm)
8		586	5(0.2)-8(1.3)-6(3.2)-(12.07 GHz@4.7 mm)	5(0.6)-8(0.1)-6(2.1)-(–67.12 dB@2.8 mm)
9		658	6(2.4)-5(0.0)-8(0.1)-(7.82 GHz@2.5 mm)	6(3.2)-5(2.4)-8(0.2)-(–67.77 dB@5.8 mm)
10		685	6(2.5)-8(0.3)-5(3.2)-(12.16 GHz@6.0 mm)	6(2.2)-8(0.1)-5(1.0)-(–66.01 dB@3.3 mm)
11		856	8(1.5)-5(0.0)-6(3.2)-(11.98 GHz@4.7 mm)	8(1.6)-5(3.3)-6(1.0)-(–79.78 dB@5.9 mm)
12		865	8(1.4)-6(3.4)-5(1.2)-(12.66 GHz@6.0 mm)	8(0.9)-6(1.8)-5(1.4)-(–68.20 dB@4.1 mm)
13	578	578	5(2.1)-7(0.0)-8(0.2)-(7.22 GHz@2.3 mm)	5(4.7)-7(0.1)-8(0.2)-(–59.46 dB@5.0 mm)
14		587	5(2.1)-8(0.2)-7(0.0)-(7.22 GHz@2.3 mm)	5(2.7)-8(0.1)-7(0.3)-(–58.31 dB@3.1 mm)
15		758	7(1.7)-5(3.1)-8(0.0)-(9.27 GHz@4.8 mm)	7(1.5)-5(3.4)-8(0.2)-(–58.16 dB@5.1 mm)
16		785	7(1.6)-8(0.1)-5(3.0)-(9.86 GHz@4.7 mm)	7(1.1)-8(0.1)-5(2.0)-(–65.18 dB@3.2 mm)
17		857	8(1.4)-5(2.1)-7(0.2)-(10.03 GHz@3.7 mm)	8(0.7)-5(1.6)-7(0.6)-(–70.11 dB@2.9 mm)
18		875	8(1.1)-7(1.2)-5(3.0)-(11.73 GHz@5.3 mm)	8(0.2)-7(2.0)-5(2.8)-(–73.33 dB@5.0 mm)
19	678	678	6(2.4)-7(0.0)-8(0.1)-(7.82 GHz@2.5 mm)	6(1.7)-7(0.2)-8(0.0)-(–56.66 dB@1.9 mm)
20		687	6(2.4)-8(0.1)-7(0.0)-(7.82 GHz@2.5 mm)	6(1.7)-8(0.0)-7(0.2)-(–56.66 dB@1.9 mm)
21		768	7(0.9)-6(2.2)-8(0.0)-(8.41 GHz@3.1 mm)	7(0.9)-6(1.9)-8(0.0)-(–59.18 dB@2.8 mm)
22		786	7(0.2)-8(1.3)-6(3.2)-(12.07 GHz@4.7 mm)	7(0.4)-8(0.2)-6(3.2)-(–60.97 dB@3.8 mm)
23		867	8(1.5)-6(3.2)-7(0.0)-(11.98 GHz@4.7 mm)	8(0.5)-6(3.9)-7(0.5)-(–61.56 dB@4.9 mm)
24		876	8(1.5)-7(0.1)-6(3.1)-(12.07 GHz@4.7 mm)	8(0.2)-7(0.1)-6(3.3)-(–67.37 dB@3.6 mm)

The preparation process flow of the three-layer impedance-graded flat panel specimen is illustrated in Fig. S2, and the specific steps are as follows: First, the WRP/paraffin composite material with a filler loading of 8 wt% for the WRP sample was uniformly mixed. The mixture was cooled while stirring to form pellets, which were then evenly spread in a mold (Fig. S2a). According to the target thickness, several layers of release paper were placed on both the top and bottom (Fig.S2b). Subsequently, the mold was placed on a press and compressed, maintaining the pressure for 10 min (Fig. S2c). Under pressure, the WRP/paraffin pellets formed a flat sample; however, due to surface deviations in the mold and release paper, it was difficult to achieve an ideally smooth surface on the sample (Figs. S2d and f). Finally, the three single-layer flat samples were sequentially stacked and combined to form the 8(1.2)-6(3.4)-5(1.4) composite flat sample (Fig. S2g), with length and width dimensions meeting the test requirements (Fig. S2h). Multi-point measurements indicated that the total thickness (d_{total}) of the composite flat sample was 6.00 ± 0.05 mm (Fig. 9h), which was in good agreement with the ideal thickness.

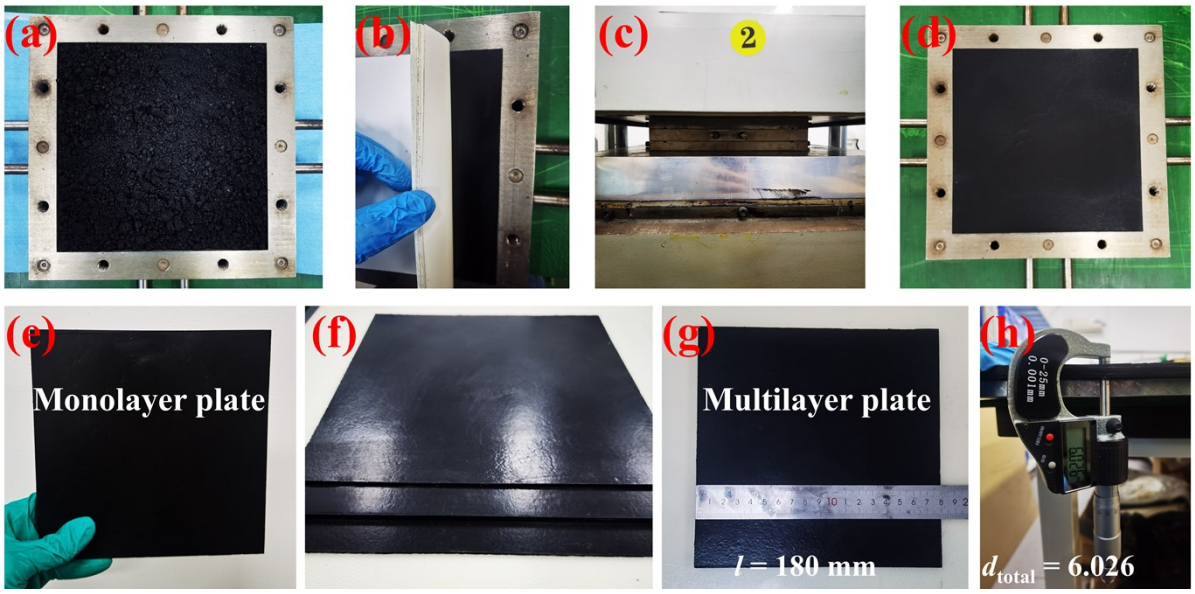

Fig. S2 (a) WRP/paraffin pellets evenly spread in the mold, (b) schematic diagram of thickness control using release paper, (c) compression molding process, and (d) formation of the flat panel specimen. (e) Schematic diagram of a single-layer specimen, (f) assembled three-layer specimen, (g) side length measurement of the three-layer specimen, and (h) thickness measurement of the three-layer specimen.

Table S5. Cost accounting for kilogram-scale small-batch production of the WRP-600 sample.

Expenditure Item	Raw Material Cost (RMB)	Energy Cost (RMB)	Equipment Depreciation (RMB)	Labor Cost (RMB)
Item Details	WR: 260 Potassium carbonate: 450 Hydrochloric acid: 445 Deionized water: 5	Electricity: 150 Argon gas: 100	Oven: 10 Muffle furnace: 100 Filtration unit: 10	600
Subtotal	1160	250	120	600
Total	2130 RMB/kg			

Table S6. Market quotations of selected commercial biomass-derived activated carbons and nanocarbon materials (carbon nanotubes and graphene oxide).

Product Type and Name	Commercial Biomass-Derived Activated Carbon (RMB/kg)			Other Carbon Materials (RMB/kg)			
				Carbon Nanotubes		Graphene Oxide	
	Straw	Corn	Coconut Shell	Single-Walled	Multi-Walled	Monolayer	Few-Layer
Supplier 1	10.3	43.8	26.4	104600	940	968000	121000
Supplier 2	19.0	59.9	52.7	62900	1310	139800	58000
Supplier 3	12.5	49.9	70.4	138800	1398	173200	55600