



# Spray-pyrolysis strategy for electromagnetic wave absorption materials

Rui Sun<sup>1</sup>, Huwei Lv<sup>1</sup>, Gangjie Lian<sup>2</sup>, Mengqiu Huang<sup>3</sup>, Renchao Che<sup>1,2,3</sup>

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With the popularization of 5G technology and advanced electronic devices, electromagnetic wave (EMW) pollution has emerged as a critical concern, driving an urgent need for the development of high-performance EMW absorbing materials<sup>[1,2]</sup>. Although advanced fabrication strategies, including orientation engineering<sup>[3]</sup>, electroplating<sup>[4]</sup>, noncovalent network design<sup>[5]</sup>, and in-situ growth<sup>[6]</sup>, have driven significant structural breakthroughs, they predominantly rely on multi-step batch operations. Spray-pyrolysis technology, leveraging its distinctive continuous flow process and confined thermal conversion properties, provides a new strategy to fabricate high-performance EMW absorbing materials.

Spray-pyrolysis strategy lies in its unique regulatory capabilities for forced assembly, multi-component design, and thermally driven transformation. This technology enables the rapid atomization of precursor solutions, solvent volatilization, and solute pyrolysis, thereby allowing precise control over the morphology, particle size distribution, and compositional uniformity of the resulting products. Additionally, the method is characterized by continuous operation, high efficiency, and ease of scale-up, rendering it highly competent for batch fabrication<sup>[7]</sup>. Compared to conventional hydrothermal or solvothermal methods requiring prolonged durations (e.g., 12-24 h) and chemical vapor deposition (CVD) constrained by low yields, spray-pyrolysis operates continuously with a droplet residence time of mere seconds<sup>[8,9]</sup>. This transient kinetic process drastically suppresses macroscopic concentration gradients, thereby guaranteeing superior compositional uniformity alongside exceptional scalability.

With the capability of integrating atomic-scale chemical regulation with nano-micro scale structural design, spray-pyrolysis enables cross-scale regulation. This technology demonstrates precise chemical manipulation capabilities. It can drive the mixing of up to ten immiscible metal atoms to form high-entropy alloys with sizes



<sup>1</sup>School of Physics and Materials Science, Nanchang University, Nanchang 330031, Jiangxi, China.

<sup>2</sup>International Institute for Materials Innovation, Nanchang University, Nanchang 330031, Jiangxi, China.

<sup>3</sup>Laboratory of Advanced Materials, Electron Microscope Center, Shanghai Key Lab of Molecular Catalysis and Innovative Materials, State Key Laboratory of Coatings for Advanced Equipment, College of Smart Materials and Future Energy, Fudan University, Shanghai 200438, China.

**Correspondence to:** Prof. Renchao Che, School of Physics and Materials Science, Nanchang University, Nanchang 330031, Jiangxi, China. E-mail: rcche@fudan.edu.cn; Dr. Mengqiu Huang, Laboratory of Advanced Materials, Electron Microscope Center, Shanghai Key Lab of Molecular Catalysis and Innovative Materials, State Key Laboratory of Coatings for Advanced Equipment, College of Smart Materials and Future Energy, Fudan University, Shanghai 200438, China. E-mail: huangmq@fudan.edu.cn

smaller than 2 nm<sup>[10]</sup>, and also anchor single Zn atoms within a carbon skeleton<sup>[11]</sup>, which induces lattice distortions and acts as dense dipole polarization centers to significantly boost dielectric loss. Based on the Kirkendall effect, it can construct hollow multi-cavity<sup>[12]</sup>, multi-shell structures<sup>[13]</sup>, or hollow microspheres<sup>[14]</sup>. These geometries regulate the dielectric parameters to optimize impedance matching and generate magnetic coupling fields within confined spaces, thereby shifting the resonance towards lower frequencies. Meanwhile, capillary contraction during droplet evaporation gives rise to wrinkled graphene spheres, which macroscopically suppress sheet stacking and prolong wave propagation paths<sup>[15]</sup>, thereby promoting multiple scattering and dielectric loss while improving impedance matching. Through precise control over composition, dimension, and heterointerfaces, spray-pyrolysis enables a multi-scale design in which atomic polarization, interfacial polarization, and multiple scattering operate in concert to govern EMW absorption. Notably, hollow structures shift resonance to S/C-band via confined magnetic coupling. Meanwhile, multi-shell architectures facilitate X-band interfacial polarization, while high-entropy alloys dominate Ku-band magnetic resonance.

Heterointerfaces design is another advantage in the spray-pyrolysis to construct the dielectric loss sites. A permanent/soft magnetic Fe<sub>16</sub>N<sub>2</sub>/Fe<sub>4</sub>N composite activates the exchange coupling effect driving a low-frequency shift of the natural resonance frequency<sup>[16]</sup>. Moreover, the BaFe<sub>(12-x)</sub>Co<sub>x</sub>O<sub>19</sub>@Fe<sub>3</sub>O<sub>4</sub> composite holds hard-soft magnetic phases that fully unleash this coupling effect, significantly broadening the low-frequency absorption bandwidth<sup>[17]</sup>. For the magnetic-dielectric interface, when magnetic units are embedded into a semiconductor matrix<sup>[18]</sup> or encapsulated by a two-dimensional insulator<sup>[19]</sup>, ensuring the effective contribution of energy conversion<sup>[20]</sup>. Concurrently, space charges and defects accumulated at the heterointerfaces induce interfacial polarization and dipole polarization. Spray-pyrolysis simultaneously regulating dielectric polarization and magnetic loss via heterointerface and nano-microstructure design opens up a novel development avenue.

In conclusion, the spray-pyrolysis technology provides a feasible pathway for the scalable fabrication of high-performance EMW absorbing materials. Its capability to regulate nano-micro structures and to design multi-component assembly is crucial for impedance matching and energy dissipation. While continuous spray drying ensures high yields with relatively low energy consumption, the subsequent high-temperature pyrolysis remains strictly energy-intensive<sup>[21]</sup>. Moving towards large-scale industrial application encounters further challenges in reactor scale-up and batch-to-batch consistency. Specifically, during high-yield spray drying, it is difficult to maintain precursor particle uniformity and morphological integrity. Meanwhile, the pyrolysis of large-batch precursors often suffers from incomplete material reactions and severe agglomeration. Looking forward, the integration of machine learning and high-throughput computing is anticipated to accelerate the component screening and structural design of advanced EMW absorbing materials. Meanwhile, EMW absorbing materials are evolving from single electromagnetic protection to multi-functional application, integrating thermal conductivity, load-bearing capacity, and environmental resistance.

## DECLARATIONS

### Authors' contributions

Wrote the manuscript: Sun, R.

Discussed and commented on the manuscript: Sun, R.; Lv, H.; Lian, G.; Huang, M.; Che, R.

Review, conceptualization, and supervision: Huang, M.; Che, R.

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Not applicable.

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### Conflicts of interest

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### Ethical approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

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