Sustainable colloidal carbon nanodots: from green synthesis to physicochemical-functional insights

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The increasing generation of agro-industrial and biowaste residues represents both an environmental burden and an opportunity for the sustainable design of functional colloidal nanomaterials [1]. In this context, we report a green waste-to-wealth strategy for the synthesis of antioxidant carbon nanodots (CNDs) derived from humic acids, sulfonated lignins, and spent coffee waste polyphenols. A mild bottom-up carbonization route is employed to obtain ultra-small CNDs with intrinsic colloidal stability, driven by the preservation of redox-active phenolic motifs at the particle surface, thus avoiding post-synthetic functionalization.

From a colloid and interface science perspective, the system is governed by a strong coupling between carbon core formation and surface chemical evolution, which ultimately controls interparticle interactions, dispersion stability, and functional performance. Comprehensive physicochemical characterization—including Cryo-TEM, X-ray diffraction, FTIR, XPS, electron paramagnetic resonance (EPR), UV–Vis absorption, fluorescence spectroscopy, and scattering techniques—confirms the formation of stable nanocolloids with sizes below 10 nm and heterogeneous but functionally rich surface chemistry.

The resulting CNDs behave as responsive colloidal interfaces, exhibiting excitation-dependent photoluminescence, robust resistance to aggregation, and efficient reactive oxygen species (ROS) scavenging. Importantly, ROS modulation is directly linked to surface-confined phenolic and heteroatom-containing functionalities, highlighting the role of interfacial chemistry in governing redox activity. Biocompatibility across human and cancer cell lines further supports their relevance for biointerface applications.

In addition, the nanodots display selective and reversible interactions with environmentally relevant metal ions (Pb^{2+}, Cu^{2+}), demonstrating their potential as multifunctional fluorescent nanoprobes for sensing in complex aqueous environments. Overall, this work illustrates how biowaste-derived precursors can be engineered into stable, functional carbon nanocolloids, bridging sustainable chemistry with interfacial nanoscience and advancing their application in environmental and biomedical colloid-based technologies.

Keywords:

carbon nanodots, biowaste valorization, ROS scavenging, chemosensing, sustainable nanocolloids

References:

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