Green-Synthesized MnO_2@INU-g-bPEI Nanoparticles for Layer-by-Layer siRNA Delivery and MRI-Guided Theranostics

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Organic/inorganic MnO_2-based nanocarriers for nucleic acid delivery and theranostics combine MRI visibility and tumor-responsive catalytic activity, but their clinical translation requires improved colloidal stability and controlled Mn^{2+} release.

Hybrid MnO_2/INU nanoparticles were synthesized through a mild aqueous redox reaction between $KMnO_4$ and inulin, which acted as reducing, stabilizing, and templating agent. The $KMnO_4$/INU molar ratio was optimized to control morphology and composition. Physicochemical characterization included UHR-SEM/STEM, DLS, ELS, FTIR, UV–Vis, EDX, and ICP-OES. MRI relaxometry was evaluated in agarose gel phantoms at pH 7.4. Nanoparticles were sequentially coated by layer-by-layer deposition of INU-bPEI2 and INU-bPEI4 polycations[1] to generate charged templates for siRNA stratification.

An optimized $KMnO_4$/INU ratio of 5 (R5) yielded uniform spherical nanoparticles (≈ 150 nm) with narrow size distribution and negative ζ-potential (~−50 mV). Relaxometric studies at physiological pH showed negligible T_1 effects and a clear T_2 response, with r_2 = 4.47 $s^{-1}\cdot mM^{-1}$, confirming suitability as T_2-weighted contrast agents. Subsequent layer-by-layer functionalization with INU-bPEI2 and INU-bPEI4 successfully reversed surface charge and enabled layering of negatively charged siRNA. All the steps were optimized, yielding colloidally stable nanoparticles in water with preserved nucleic acid retention. Moreover, the coating didn't affect the typical peroxidase-like activity of MnO_2 NPs.

Overall, the present results identify MnO_2@INU-g-bPEI-based multilayer nanoparticles as a promising theranostic nanoplatform integrating structural stability, siRNA stratification capability, preserved nanozyme-like activity, and T_2 MRI visibility. The combination of green synthesis, modular layer-by-layer functionalization, and imaging potential highlights the translational value of these hybrid nanosystems for the development of stimuli-responsive, trackable siRNA delivery systems in oncology.

Acknowledgements
The authors gratefully acknowledge Dr. Chiara Amante for SEM acquisitions and Prof. Tonino Caruso for elemental analysis. The authors also acknowledge the support of the PhD Program in RNA and Gene Therapy.

References

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