# Abstract

The oxidative instability of lipid-rich foods remains a critical barrier to extending shelf life and preserving sensory, nutritional, and functional quality. Conventional antioxidants are constrained by thermal degradation, finite radical-trapping capacity, potential toxicity, and increasing regulatory scrutiny. To address these limitations, the present study systematically investigates the design, engineering, and application of oxygen-vacancy-modulated cerium oxide nanoparticles ($CeO_2$; nano-ceria) as regenerative redox-active antioxidants for edible oils and multiphase food systems.

A dual-dispersant precipitation strategy was developed to precisely regulate crystallite size, surface chemistry, and oxygen vacancy concentration in $CeO_2$ nanoparticles. Controlled post-synthesis annealing under $N_2$ and air atmospheres enabled fine-tuning of surface $Ce^{3+}/Ce^{4+}$ ratios, directly influencing redox activity. Comprehensive characterization using X-ray diffraction with Rietveld refinement, X-ray photoelectron spectroscopy (XPS), Fourier-transform infrared spectroscopy (FTIR), UV–Vis spectroscopy, and DFT+U computational modeling established a robust structure–property relationship between defect density and antioxidant performance. Nanoceria exhibiting elevated oxygen vacancy concentrations and higher surface $Ce^{3+}$ fractions demonstrated enhanced redox cycling efficiency and superior radical scavenging capacity. Importantly, in vitro cytotoxicity assessments and dose-optimization studies confirmed biocompatibility and absence of adverse effects at practical inclusion levels (≤15 ppm), supporting its suitability for food applications.

Accelerated and real-time storage studies conducted in sunflower oil and rice bran oil revealed significant suppression of primary and secondary oxidation markers, including peroxide value (PV), p-anisidine value (p-AV), iodine value, acid value, and total oxidation (TOTOX) indices, compared to untreated controls and conventional antioxidant systems. Furthermore, a predictive thermo-kinetic oxidation model was developed to quantify activation energy, oxidation rate constants, and projected shelf-life extension under varying thermal conditions.

In emulsified systems, nano-ceria demonstrated dual-functionality in mayonnaise by preferential localization at oil–water interfaces, providing both catalytic radical scavenging and interfacial stabilization. This synergistic chemical–physical mechanism significantly improved oxidative resistance and preserved sensory attributes during 12-week refrigerated storage.

Collectively, this work establishes defect-engineered nanoceria as a tunable, regenerative, thermally stable, and biocompatible antioxidant platform with strong translational potential for enhancing oxidative stability across bulk oils and complex lipid-based food matrices.

**Keywords:** Cerium oxide nanoparticles; edible oils; oxidative stability; oxygen vacancies; regenerative antioxidant; thermostability; shelf-life modeling; mayonnaise