From Colloidal Formulation to Functional Film: Predictive Design of Sustainable Pullulan-Based Active Coatings

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Abstract

The predictive design of sustainable coatings is often hindered by an insufficient understanding of how liquid coating formulations translate into functional films on solid substrates. In this work, biodegradable pullulan-based active coatings functionalized with polyphenol-rich yerba mate and chestnut wood extracts, obtained via green ultrasound-assisted aqueous extraction, are presented as a model system. Moving beyond conventional bulk-film approaches, the study adopts a liquid-to-solid-state framework, demonstrating that coating performance on solid carriers is governed by the combined understanding of colloidal stability, zeta potential, rheology, and surface tension in the liquid state, and wettability, surface free energy, and functional performance after film formation [1–2].

Enhanced colloidal stability, reflected in negative zeta potential values (≈ −25 mV), ensured homogeneous dispersions and reproducible application, while reduced surface tension facilitated efficient spreading during deposition. Upon drying, the formed films exhibited improved wettability and interfacial compatibility among substrates, driven by non-covalent pullulan–polyphenol interactions without altering the amorphous polymer structure.

The film formed coatings showed strong antioxidant activity, UV-shielding, and antibacterial efficacy against *Staphylococcus aureus*. The results highlight that integrated characterization of coatings before application and after film formation is essential for predicting their behavior on solid support, enabling the rational design of sustainable, bio-based coatings aligned with circular economy and waste-reduction strategies in food-packaging systems. Such formulation-driven coating design supports waste prevention strategies by extending the functional lifetime of packaging materials, reducing the need for multilayer plastics and downstream waste generation.

Keywords

Sustainable coatings; Pullulan; Polyphenols; Colloidal stability; Zeta potential; Active food packaging; Circular economy

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