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Thermal degradation kinetics and multifunctional properties of gelatin/carrageenan films incorporating eugenol-loaded Pickering emulsions for active packaging applications

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Abstract Pickering emulsions are an emerging encapsulation technology for volatile compounds such as essential oils, which have been incorporated into packaging films to maintain the quality, safety, and nutritional value of food products. This study developed and characterized a sustainable active packaging film made from gelatin/semi-refined carrageenan incorporated with eugenol-loaded Pickering emulsion (EPE) stabilized by chitosan nanoparticles. The Coats-Redfern method (CRM) was applied to thermogravimetric (TGA) data to evaluate thermal degradation kinetics using various kinetic models, providing fundamental insights into thermal stability for active packaging applications. The results showed that EPE droplets exhibited a monodisperse distribution ($PDI < 0.3$) with particle diameters of 18-47 nm maintained over 60 days. Scanning electron microscopy (SEM) observations revealed that films with 3% EPE maintained a homogeneous morphology, while obvious particle agglomeration occurred at higher concentrations (5% and 7% EPE). Incorporation of 3% EPE increased elongation at break to 58% and improved antioxidant activity to 89%, while tensile strength did not decrease significantly ($P > 0.05$) compared to the control film. The CRM indicated that the film with 3% EPE followed a complex degradation pathway involving multiple-step network ruptures, which was associated with a higher activation energy of 112.83 kJ/mol. Films containing 3-7% EPE exhibited effective antimicrobial properties, with clear inhibition zones significantly wider than those of the control film against *Escherichia coli* and *Staphylococcus aureus*. Overall, EPE-integrated films enhance the functionality and thermal stability of gelatin/semi-refined carrageenan-based films, highlighting their potential for sustainable active packaging applications.

Keywords **Author Keywords:** [Active packaging](#); [Antimicrobe](#); [Antioxidant](#); [Eugenol](#); [Pickering emulsion](#); [Thermal degradation kinetics](#)

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