14th World Congress on
Biopolymers and Biomaterials

August 18-19, 2025

Webinar

J Chem Eng Process Technol 2025, Volume 16

Advances in biopolymer-based drug delivery systems

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Biopolymer-based drug delivery systems have emerged as a transformative strategy in modern therapeutics, offering enhanced biocompatibility, targeted delivery, and controlled release characteristics. Natural biopolymers such as chitosan, alginate, gelatin, and hyaluronic acid are increasingly preferred due to their biodegradability and low toxicity. Recent advancements in polymer modification, nanoparticle engineering, and ligand-functionalization have significantly improved their ability to deliver small molecules, proteins, nucleic acids, and vaccines. This study explores the fabrication and optimization of biopolymeric nanoparticles using ionic gelation, solvent evaporation, and microfluidic techniques. Special emphasis is placed on surface modification strategies—such as PEGylation and receptor-mediated targeting to enhance stability and selective cellular uptake. Experimental investigations demonstrate that chitosan-based nanoparticles loaded with anti-inflammatory agents achieved a 65% increase in intracellular delivery compared to conventional formulations. Additionally, alginate-hyaluronic acid hybrid hydrogels showed promising results for sustained drug release over a period of 7–10 days. The study also evaluates biopolymer–drug interactions, degradation kinetics, and in vitro cytotoxicity using human epithelial and stem-cell-derived models. Results indicate minimal inflammatory response, confirming the systems' suitability for clinical application. These findings validate the potential of biopolymer-based platforms in precision medicine, particularly for oncology, wound healing, and chronic inflammatory disorders. Overall, biopolymers are positioned to revolutionize drug delivery science, offering safer, more effective, and patient-tailored therapeutic solutions.