Translating 2D to 3D Polymeric MicroStructures: An Engineering Approach to Next-Generation materials

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The advancement of next-generation materials has catalyzed the development of microneedle-based platforms that seamlessly integrate diagnostic and therapeutic functions, positioning them as a transformative technology for personalized medicine (Xu et al., Adv. Mater. Technol., 2022). An important engineering advantage of microneedles lies in their dual functionality: acting simultaneously as biosensors and as localized drug delivery systems. Microfabrication methods such as replica molding and 3D printing allow for fine control over needle geometry, ensuring consistent skin penetration, scalable production, and reproducible performance (Wang et al., Adv. Sci., 2025). These capabilities are especially crucial when interfacing with the complex architecture of the dermis and the controlled transport of interstitial fluids areas where principles of chemical engineering and biofluid mechanics converge. Surface functionalization, a key aspect of device performance, requires precise chemical strategies to immobilize recognition elements such as antibodies and peptides–onto microneedle surfaces. We developed a bio-fluorescent/colorimetric microneedle biosensor for the detection of phosphorylated Tau (p-Tau), a critical biomarker of neurodegenerative diseases. Through scalable replica molding, the sensor achieved a detection limit in pg/mL, surpassing the sensitivity of conventional 2D biosensors (Di Natale et al., J. Colloid Interface Sci., 2025). Beyond diagnostics, fast-dissolving microneedles were engineered for localized drug delivery applications, particularly for chemo- and immunotherapeutic agents targeting triple negative breast cancer. The design process involved a careful balance of material selection, dissolution behavior, and release kinetics highlighting the essential role of chemical engineering in achieving effective and controlled therapeutic action within biological tissues. Together, these developments underscore the multidisciplinary foundations of chemical engineering spanning materials design, interfacial chemistry, microfabrication, and biological fluid dynamics in the realization of next-generation microneedle systems. Such platforms hold substantial promise for early disease detection, targeted therapy, and real-time health monitoring, positioning microneedles as a pivotal innovation in the future of personalized medicine.

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