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Bioreceptor-Free Electrochemical Sensors: Mechanism-Guided Design for Sustainable and Energy-Efficient Diagnostics

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Abstract

The rapid expansion of decentralized healthcare, wearable bioelectronics, and environmental monitoring demands sensing platforms that are not only sensitive and selective, but also stable, scalable, and energy-efficient. Conventional biosensors rely heavily on biological receptors such as enzymes and antibodies, which require cold-chain logistics, complex immobilization strategies, and frequent recalibration. These constraints limit long-term deployment and sustainable integration into distributed systems. This work introduces a bioreceptor-free sensing paradigm in which molecular recognition is encoded directly into material chemistry and structure. By engineering interfacial electronic properties, pore architecture, and structural flexibility, sensing mechanisms are designed at the materials level without reliance on biological components. Central to this approach is the development of azine-linked covalent organic frameworks (COFs) with tunable core flexibility and curvature for attomolar-level impedimetric glucose sensing. Unlike enzyme-based platforms, the COF operates via adsorption-driven interfacial modulation, where analyte binding alters charge-transfer resistance without catalytic turnover. The nitrogen-rich framework enables controlled hydrogen bonding and dipolar interactions, translating nanoscale adsorption events into amplified electrochemical signals. Extending this philosophy toward circular sustainability, a waste-to-wealth strategy is demonstrated by recovering gold from waste samples and integrating it with COF-coated electrodes for dopamine detection. In parallel, a sunlight-powered topochemical transformation route is introduced for converting MoS₂ into device-grade α -MoO₃ macrocrystals, illustrating the use of solar energy as a scalable synthetic tool. The resulting materials are incorporated into biosensing platforms to establish a mechanism-aware taxonomy for bioreceptor-free electrochemical sensing. Beyond analytical performance, these material-centric strategies enhance sustainability by eliminating biological degradation pathways, reducing cold-chain dependency, enabling low-energy electrochemical interrogation, and supporting scalable fabrication through printable, device-compatible architectures. Collectively, this work positions material-programmed recognition as a pathway toward robust, energy-efficient, and environmentally responsible diagnostic technologies.