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Toward Green NH_3 Electrosynthesis: Nanocatalysts, 3D-Printed Electrodes, and Electrolyzer Design

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Ammonia is a key industrial chemical for fertilizer production and is increasingly considered as an energy carrier and hydrogen storage medium. Its current manufacture relies almost exclusively on the Haber–Bosch process, which is highly energy-intensive and dependent on fossil-derived hydrogen. Electrochemical ammonia synthesis is therefore attracting interest as a more sustainable alternative because it can, in principle, operate under mild conditions, use renewable electricity, and be implemented in modular systems. However, practical application remains limited by challenges in selectivity, Faradaic efficiency, productivity, and control of the local reaction environment. Here, we outline a multiscale route toward green NH_3 electrosynthesis based on the combined development of nanocatalysts, 3D-printed electrodes, and electrolyzer design. At the nano level, hierarchically structured metal-organic framework (MOF)-derived nanomaterials represent a promising platform for advanced electrocatalytic materials. Rapid synthesis routes, such as microwave-assisted processing, combined with controlled post-treatment, for example by laser irradiation, enable composites with tunable active surfaces, high accessible surface area, abundant active sites, and coupled micro-/mesoporosity. These features may improve NH_3 selectivity, increase Faradaic efficiency, and provide better control over competing interfacial pathways. At the meso level, 3D-printed triply periodic minimal surface (TPMS) electrodes offer a systematic route to tune porosity, flow-channel dimensions, and the balance between surface area and mass transport. In such structures, geometry, roughness, wettability, and electrolyte convection act as active design variables that influence interfacial transport, gas-bubble dynamics, and overall electrochemical response. At the macro level, the concept evolves from a lab-scale stationary H-cell to flow-cell configurations and, ultimately, toward integrated electrolyzer design. Across all stages, 3D printing enables rapid fabrication and iteration of reactor components, while computational fluid dynamics (CFD) modelling supports optimization of flow distribution, transport behavior, and overall design performance. Together, these elements define a stepwise engineering pathway toward more stable, efficient, and scalable NH_3 electrosynthesis systems.