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Review

Advancing the Future of Ammonia: Green Technologies, Process Intensification, and Pathways to Industrial Uptake

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PDF

Abstract

Green ammonia (NH_3) is emerging as a cornerstone for building a sustainable energy economy, aligning with global goals for decarbonization and industrial transformation. Its versatility extends across agriculture, sustainable hydrogen production, and carbon-neutral transportation, making it a critical enabler of a greener future. While the Haber–Bosch process remains the conventional method for ammonia synthesis, it is highly energy-intensive and carbon-heavy. To address these challenges, innovative technologies, including electrochemical and plasma-based processes, are being developed to enable large-scale ammonia production with reduced greenhouse gas emissions. Recent advances in catalysis have been central to this transition. Novel catalysts such as metal hydrides, nitrides, and single-atom systems offer enhanced efficiency, enabling ammonia synthesis at lower temperatures and pressures compared to the traditional Haber–Bosch route. In parallel, electrochemical nitrogen reduction reactions (NRRs) and photocatalytic pathways using advanced materials provide new