Green Fertilizers (urea and ammonium nitrate) Synthesis via Plasma-Liquid Interaction

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Conventional fertilizer production methods, such as the Haber-Bosch process and nitric acid-based synthesis, are highly energy-intensive and contribute significantly to greenhouse gas emissions. Plasma-liquid interaction has emerged as a promising sustainable alternative for nitrogen-based fertilizer synthesis. However, the efficient and scalable production of urea and ammonium nitrate using plasma technology remains largely unexplored. This study explores the synthesis of urea and ammonium nitrate using plasma-activated water (PAW) generated through microwave and low-pressure plasma treatments [1–3].

In the low-pressure plasma system, urea formation was significantly higher in $NH_3 + CO_2$ plasma (7.7 mg L^{-1}) compared to $N_2 + CO_2$ plasma (0.55 mg L^{-1}), highlighting ammonia's superior reactivity [1]. Plasma–ice interaction further enhanced this process by providing a medium where reactive species—produced by high-energy plasma discharges—exhibited greater residence time and facilitated complex reactions among nitrogen and carbon intermediates. This resulted in increased pH, electrical conductivity, and reduced oxidation–reduction potential of the treated ice, demonstrating the importance of optimizing plasma exposure time to enhance urea yield.

In the microwave plasma system, urea formation was observed only with CO_2 and N_2 + CO_2 plasmas, attributed to the formation of stable intermediates such as NH_4^+ and NH_2COO^-. Notably, the N_2 + CO_2 plasma produced 29.91 times more urea than CO_2 plasma alone [2]. The mechanistic pathway involves the formation of NH_4^+ ions via the reaction of atomic nitrogen with water, followed by the aqueous-phase reaction with NH_2COO^- to synthesize urea. Beyond chemical synthesis, PAW from the N_2 + CO_2 plasma also improved agricultural performance, significantly enhancing seed germination and early plant growth in carrot and coriander, confirming its dual role as both a fertilizer precursor and a biostimulant.

Additionally, successful ammonium nitrate synthesis was achieved in the low-pressure system. Ammonium nitrate synthesis was subsequently optimized through sequential plasma treatment of water and ice phases using air and NH_3 plasmas, respectively. Maximum concentrations of NH_4^+ (168.2 mg L^{-1}) and NO_3^- (63.5 mg L^{-1}) were achieved under optimized parameters such as treatment duration, gas pressure, and applied voltage [3]. The energy yield reached 74.8 mg NH_4^+ kWh^{-1} and 222 mg NO_3^- kWh^{-1}, resulting in a combined ammonium nitrate production yield of 27.6 mg kWh^{-1}. The PAW produced remained neutral to slightly basic, making it suitable for direct agricultural application.

This integrated plasma-based approach offers a green, energy-efficient, and environmentally friendly method for urea and ammonium nitrate production. By reducing reliance on fossil fuels and supporting circular nitrogen processes, it holds significant potential for decentralized fertilizer manufacturing and sustainable agriculture.

References

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