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Distributed production of ready-to-use liquid nitrogenous fertilizer

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The conventional production and application of solid nitrogen fertilizers have energy and environmental impacts. A relay strategy — driven by sustainable energy — to produce and distribute liquid nitrogenous fertilizer has now been shown to provide effective fertilization.

The production and use of nitrogen fertilizers are vital for food production, and hence for the survival and development of human society[1]. However, conventional production, transportation and application of nitrogen fertilizers are exacerbating the energy crisis and environmental pollution: centralized production technology (using the Haber–Bosch method) and long-distance transportation are highly dependent on fossil fuels, and cause the emission of large amounts of greenhouse gas[2,3]; applying conventional solid fertilizer results in a low utilization efficiency of the fertilizer (less than 50%), inevitably causing groundwater pollution[4]. Recently, the use of liquid fertilizer through drip irrigation technology was proven not only to increase fertilizer utilization efficiency (to more than 80%) but also to reduce the consumption of water[5]. Thus, developing a means of online production, driven by renewable energy, to obtain ready-to-use liquid nitrogenous fertilizer would have great potential in alleviating the global food crisis, energy shortages and environmental pollution.

Writing in *Nature Sustainability*, Han et al.[6] propose a distributed relay strategy to produce directly accessible liquid nitrogenous

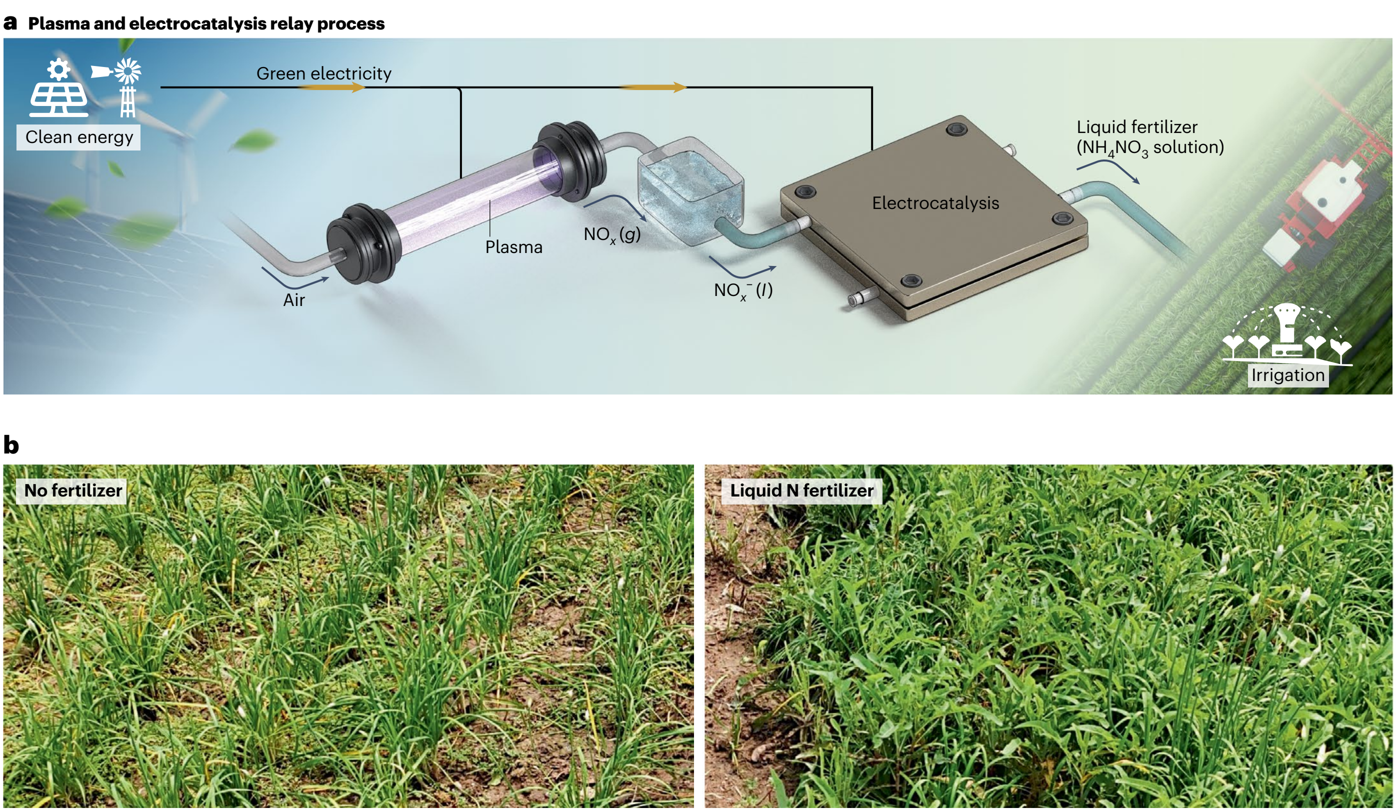

Fig. 1 | Producing ready-to-use liquid nitrogenous fertilizer. a, Schematic from Han et al. for the online production and use of NH_4NO_3 liquid fertilizer. This relay system begins with NO_x in the gas phase (*g*), which is then absorbed in aqueous solution in the liquid phase (*l*) and passed through an electrocatalytic process to produce NH_4NO_3 that can be distributed through drip irrigation. The authors have also added plasma-driven air conversion to generate NO_x, and the relay can be powered by renewable energy. **b**, A practical demonstration on farmland illustrates the efficacy of this strategy for online production and use of NH_4NO_3 liquid fertilizer.

fertilizer (NH_4NO_3 solution). Their raw material is nitrogen oxides (NO_x), which can be used in conjunction with drip irrigation technology without other post-treatment steps (Fig. 1a). The relay system consists of three main parts: NO_x absorption, electrocatalytic reduction and drip irrigation. The term relay refers to the sequential transfer and transformation of reactive nitrogen species – NO_x in the gas phase, NO_2^- or NO_3^- in the solution phase and NH_4^+ as the final product – across distinct but interconnected modules. This process architecture enables continuous operation, while the nitrogen mass balance is maintained and intermediate loss is minimized.

Using 1% NO_x gas (a mixture of NO_2 and air) as an example, Han et al. report that the absorption efficiency of NO_x by water was close to 100%, and the exhaust gas met the standards of the US Environmental Protection Agency and could be directly emitted. The NO_x in the absorption liquid is NO_3^- and NO_2^-, at a ratio of 2:1; for electrocatalytic reduction, the authors selected a ruthenium–cobalt (RuCo) alloy as the model catalyst owing to its excellent performance and applicability over a wide range of NO_x^- concentrations[7]. The Ru_9Co_{91} catalyst achieved an NH_4^+ yield of 0.81 mmol mg^{-1} h^{-1} and a nominal Faradaic efficiency of 89.8% in a nearly neutral electrolyte. Mixed-isotope experiments (using ^{14}N and ^{15}N) and in situ attenuated total reflection infrared spectroscopy revealed that the electroreduction of NO_2^- occurs prior to that of NO_3^- because of the preferential adsorption and faster reaction kinetics of NO_2^-. The authors successfully established a dynamic conversion balance among the three parts of the relay, with 200 ml min^{-1} NO_2 gas (1%), 800 mA (applied current) and 840 ppm N nitrogenous fertilizer (NH_4NO_3 solution).

They then built two laboratory-level online production modes: a membrane-free system and a membrane-equipped system in the electrocatalysis stage, corresponding to the online production of low- and high-concentration NH_4NO_3 liquid fertilizers, respectively. Both modes involve no impurity additives in the electrolyte, which can prevent separation. Isotope-tracing experiments visually confirmed the conversion process from NO_x to NH_4NO_3 over time, indicating the successful operation of the relay system. Interestingly, Han et al. extended their system by adopting plasma-driven air conversion to obtain raw NO_x materials, which can overcome the geographical limitations of raw materials. A pilot-plant test using an 8 l membrane-free electrolyser yielded NH_4NO_3 solution at a rate of 8.5 l h^{-1} at a constant concentration (840 ppm N), which met the nitrogen fertilizer requirements for 20 m^2 of farmland (Fig. 1b). Compared with the conventional fertilization method in which solid fertilizer is spread on the surface of the soil, this strategy can reduce the consumption of nitrogen fertilizer by ~20%, demonstrating its potential application value.

The online production of ready-to-use liquid nitrogenous fertilizer is important from both fundamental and practical standpoints, and the relay strategy of Han et al. is distinctive in that the distributed production of directly accessible liquid nitrogenous fertilizer is driven by sustainable energy. However, there are several aspects of the process that need to be improved. One is the development of efficient and inexpensive electrocatalysts in neutral electrolytes for direct usage. Unfortunately, most high-performance catalysts for the electroreduction of NO_3^- have been developed for alkaline conditions, with limited exploration in neutral electrolytes. Moreover, the long-term stability of the Ru_9Co_{91} catalyst – potentially more than 120 h – requires further validation over industrially relevant timescales, especially considering possible oxidation, metal leaching or changes in surface speciation under continuous operation. Han et al. realized two online production modes in the laboratory – one of high concentration and one of low concentration. To intuitively confirm the NO_x-to-NH_4NO_3 pathway for directly accessible fertilizer, they adopted a production model for low-concentration liquid fertilizer in a pilot-plant demonstration. For practical production processes, high-concentration NO_3^- electrolytes may be more relevant and can be managed through dilution treatment before use. Furthermore, other ions could be added to the initial electrolyte (for example, by including K_3PO_4) to achieve the online production of compound fertilizer, but the effects of additive ions on the production of liquid nitrogenous fertilizer should be carefully studied.

An important dimension that is not addressed in this study is the techno-economic and environmental sustainability of the overall system. Although this work offers a compelling proof of concept, it lacks an evaluation of energy input, material consumption and scalability. Comprehensive techno-economic analysis and life-cycle assessment are essential for determining whether a system can compete with centralized fertilizer production. In particular, modelling the carbon footprint of plasma-based NO_x generation, electricity input and catalyst life cycle will be critical in assessing real-world sustainability. Incorporating these analyses in future studies would enhance the case for practical deployment and alignment with sustainable agriculture goals.

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Competing interests

The authors declare no competing interests.