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Emerging opportunities and research questions for green ammonia adoption in agriculture and beyond

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Green ammonia production could contribute to decarbonization and the decentralization of fertilizer production, but it brings critical challenges and risks. Assessing and addressing these challenges in real time will help advance technology and avoid unintended consequences.

Synthetic ammonia production by the Haber–Bosch process revolutionized agriculture by making relatively inexpensive nitrogen (N) fertilizer widely available and enabling a rise in global food production[1,2]. The Haber–Bosch process relies on fossil fuels (known as grey ammonia production) and emits more than 450 Mt of CO_2 annually[3]. Green ammonia, which is produced using renewable energy, offers a pathway to decouple ammonia production from fossil fuels and reduce CO_2 emissions. As a carbon-free fuel, green ammonia could partially replace fossil fuels to decarbonize hard-to-abate sectors such as maritime shipping[4]. However, the widespread use of green ammonia could have complex environmental and social consequences, as it threatens to add reactive N into the biosphere[3] and could disrupt fertilizer markets. In this Comment, we identify opportunities, barriers and open questions related to green ammonia production and usage as a fertilizer and beyond. We then recommend research priorities to avoid unforeseen consequences through research, monitoring and adaptation in real time.

Decentralizing fertilizer production

The fertilizer industry is historically centralized and carbon intensive, but green ammonia technologies decouple fertilizer production from fossil fuels and enable small-scale production. Modular green ammonia production units with individual annual capacities of 100 tonnes to about 300 tonnes have reportedly emerged for on-farm deployment, and smaller-capacity units are also in development (for comparison, a large-scale grey ammonia plant can produce more than 500,000 tonnes annually[5]). This decentralized approach could improve fertilizer accessibility, particularly in regions with logistical barriers, by reducing transport costs and associated greenhouse gas (GHG) emissions[3]. Using locally produced renewable energy for on-farm ammonia production could also shield farmers from fluctuations in fertilizer market prices and supply chain disruptions, increasing resilience. However, green ammonia production is constrained by renewable energy availability, particularly amid competition from other electricity-intensive sectors, such as electric vehicles. Regions with abundant and affordable renewable energy are therefore better positioned to adopt green ammonia production[6].

Cost and safety concerns

Despite the potential advantages, barriers to on-farm green ammonia adoption include high initial capital costs, concerns about production equipment lifespan and access to water and renewable energy, perceived risks of new technology performance, and mismatches between available green ammonia products and current regional fertilizer needs and practices. On-farm units costing hundreds of thousands of US dollars or more could limit adoption to larger farms, risking market consolidation and deepening inequalities. Smaller enterprises or farmer cooperatives could benefit from financing modular units, helping to make green ammonia accessible to farmers of diverse farm sizes, types and within low- and middle-income countries. Access to refined financing options will therefore play a crucial role. Although green ammonia is not yet cost-competitive with grey ammonia, it could become competitive in parts of the world by 2030 given lowered transport costs and reduced supply chain disruptions[6].

Safety also needs to be considered with on-site production of green ammonia. For example, a common green ammonia product is anhydrous ammonia, which is dangerous to manage, as even minor skin or respiratory exposure carries serious health risks[7]. Other fertilizer products, such as urea, ammonium sulfate, diammonium sulfate and nitrate forms could be generated but at additional cost and energy use[8].

Increased availability could increase use

The impact of green ammonia on N fertilizer usage will be critical in determining its overall effect on GHG emissions. Green ammonia reduces emissions from fertilizer production and transportation, which account for 20–50% of total GHG emissions associated with N fertilizers. The remaining emissions are largely soil N_2O losses following fertilizer application and are influenced by the type and rate, timing and placement of fertilizer[9].

Increased ammonia availability and accessibility through year-round on-farm green ammonia production could help farmers to better manage N for seasonal crop demands and fuel on-farm machinery, optimizing efficiency and timing of fertilizer use. However, increased availability could also inadvertently promote fertilizer overuse, exacerbating emissions and environmental issues related to N losses to air and water. Like grey ammonia, policy measures to reduce the cost of green ammonia could incentivize fertilizer over-application, likely with diminished production returns. By contrast, in low-income countries where soils are often N-depleted owing to a lack of affordable fertilizer,

Box 1 | Research priorities

Adoption

- Investigate key adoption barriers and facilitators for green ammonia (GA) production across sectors and geographies
- Assess the scale of GA demand from different sectors
- Address technological barriers for GA commercialization, including electrocatalysts or photocatalysts and sustainable sources for reactants
- Forecast the role of GA production in renewable energy demand, generation and economics

Impact

- Examine GA impacts on on-farm best management practices, including potential safety risks, changes in fertilizer use, soil emissions, fugitive emissions during GA production, storage and application, and the possible reduction of alternative N sources
- Explore how adoption could transform energy use profiles in different farming systems and geographies
- Evaluate the socioeconomic impacts of adoption on inter-related systems from local economies to downstream consumers
- Evaluate the anticipated environmental impacts of broader GA adoption, including NH_3 slippage and NO_x and N_2O emissions

Possibilities

- Identify policies and government incentives to support safe, climate- and N-smart GA use
- Investigate the ability of GA to advance regional, sustainable food production and food security while minimizing risks

targeted incentives could be used to lower the initially high capital costs and subsequent operating costs of green ammonia production to make it affordable and accessible to small-holder farmers.

Mitigation practices for on-farm emissions are available but often focus on conventional fertilizers like urea. Whole-system analysis, from production to application, and mitigation strategies for green ammonia-derived fertilizers are needed. Moreover, the impact of scaling-up green ammonia adoption on water use needs to be assessed and monitored.

Impacts on the transportation sector

Ammonia is projected to account for 44% of marine shipping fuel by 2050 (ref. 3), and green ammonia-fuelled container ships have been announced for launch as early as 2026. Successful integration of green ammonia into marine shipping could enable broader adoption of green ammonia for other energy, industrial and agricultural applications by increasing its general availability and potentially reducing costs. However, widespread green ammonia adoption in transportation also raises new challenges[10]: ammonia leakage during storage and transport, emissions of NO_x and N_2O from incomplete ammonia combustion, and safety concerns and uncertainties about effects on global fertilizer and food prices, which could compound existing vulnerabilities in the food system.

Addressing these challenges in real time

The intensification of Haber–Bosch synthesis for grey ammonia fertilizers has come at the expense of unintended consequences in environmental pollution. As green ammonia technology progresses, there is a window of opportunity to avoid a similar path and ensure that the benefits of GHG abatement and increased fertilizer availability are fully realized, while the hazards and risks of green ammonia are carefully minimized and managed. This need is urgent, as commercial green ammonia production has already begun — more than 25 large-scale plants are anticipated globally by 2030, nearly all with annual projected capacities exceeding 10,000 tonnes, and at least 8 expected to reach 1 million tonnes per year or more. We therefore recommend ten research priorities that should be addressed now (Box 1). These priorities include investigating agronomic and socioeconomic drivers of decentralized green ammonia production in agriculture, limiting emissions of NH_3, NO_x and N_2O from ammonia combustion in transportation, and engaging stakeholders from research to adoption to regulation. Addressing these challenges through rigorous, user-inspired research and real-time monitoring and adaptation will help to avoid unforeseen consequences.

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Competing interests

The authors declare no competing interests.