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Environmental, economic, social and technological viewpoints on green ammonia as a basis for low carbon fertilizer: a perspective

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KEYWORDS

energy efficiency, environmental impact, green ammonia, post-Haber-Bosch innovation, renewable energy, socioeconomic impact

HIGHLIGHTS

- Green ammonia (GA) offers reduced carbon intensity, though social aspects are understudied.
- GA production faces cost barriers requiring technological progress and policy incentives.
- Centralized GA production is the most viable early deployment pathway.
- Cutting electrolyses costs is key to the economic competitiveness of GA.

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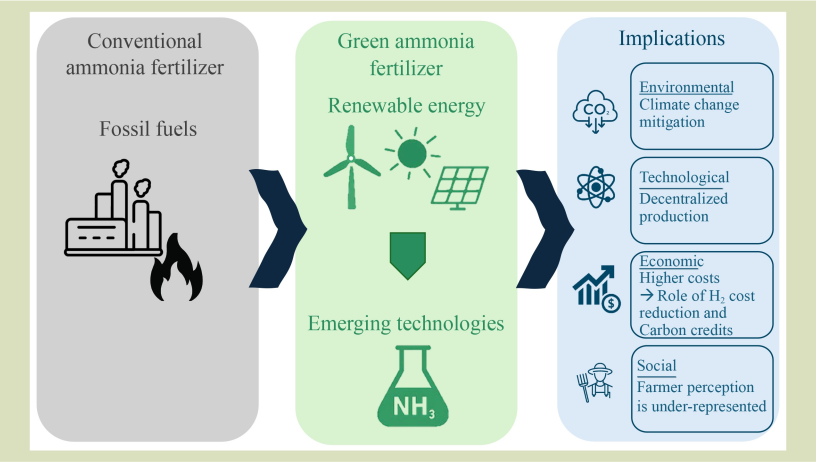
GRAPHICAL ABSTRACT



ABSTRACT

Ammonia, as a nitrogen-based fertilizer is essential for enhancing crop yields and supporting global food production. Established ammonia production relies on fossil fuels and is highly carbon-intensive with detrimental consequences for the environment and society. The significance of the decarbonization of fertilizer production cannot be overstated. In this perspective, the opportunities and challenges associated with green ammonia (GA) deployment are discussed, drawing on insights from recent literature. While environmental and techno-economic aspects of GA are increasingly well understood, social dimensions such as farmer acceptance and adoption remain largely overlooked. From an environmental perspective, we argue that GA significantly mitigates climate change impacts compared with current ammonia production. From a technological perspective, decentralized production systems, though more energy intensive, offer flexibility and reduced raw material requirements. However, economic barriers persist, as GA is less cost-effective than standard ammonia. Therefore, enhancing the sustainability of GA production relies on improving the technological and supply chain aspects, reducing capital costs for green hydrogen infrastructure, and incentivizing the fertilizer industry with carbon credits. By highlighting these critical considerations, this perspective aims to inform research, policy and investment decisions for a sustainable transition to green ammonia.

1 Introduction

Ammonia is mainly used for nitrogen fertilizers that are essential for global food production. In this context, about half of the world's food production relies on mineral fertilizer application, and specifically on ammonia-based nitrogen fertilizers[1]. As the global population continues to grow, fertilizer consumption is forecast to rise steadily to meet the increasing demand for food[2]. While ammonia is advantageous in industrial terms, 96% of its production is achieved through the Haber-Bosch process[3]. The latter allows large-scale ammonia production using fossil fuels (as feedstock and energy) but poses an environmental threat via greenhouse gas (GHG) emissions. Ammonia production, via the standard pathway, appears to be the highest emitter of CO_2 (about 1.8% of global CO_2 emissions)[4]. In addition, the Haber-Bosch process is highly energy demanding, using close to 2% of global energy production, which in effect is wasting considerable amounts of energy[5]. These challenges, combined with the current highly centralized distribution of ammonia plants, have driven the real and urgent need to develop sustainable, energy efficient and decentralized ammonia production alternatives. The latter could improve fertilizer accessibility, particularly in regions facing logistical challenges, by reducing transport costs and related GHG emissions[6]. Using locally produced renewable energy for on-farm ammonia production could also insulate farmers from fertilizer market price fluctuations and supply chain disruptions, thereby increasing resilience[7].

Accordingly, the use of GA instead of standard ammonia, could be an important step towards the decarbonization of the fertilizer industry[8]. In this regard, there are several approaches that can be used to decarbonize ammonia[9]. For example, blue ammonia, which involves capturing and storing the CO_2 emissions from synthesis gas production, is a transitional technology and more suitable for existing plants that still have considerable designed life span to run. Alternatively, instead of producing hydrogen by steam reforming of natural gas, green hydrogen could be produced from sustainable sources with renewable energy (i.e., wind, hydro and photovoltaics) and nuclear power, which will provide carbon-zero fertilizer production[8]. Rapid growth is expected for GA produced from green hydrogen, as demand for lower carbon ammonia intensifies[10]. Green ammonia synthesis, avoiding the Haber-Bosch process, could be the most inherently cost-effective approach, as it does not require the combination of the key components of the power to ammonia technology (i.e., electrolyzers, air separation units and the high-pressure Haber-Bosch plant), and uses renewable electrical energy (electrochemical) or sunlight (photochemical) to reduce nitrogen from air to ammonia in the presence of water under ambient conditions[11]. Although it is well known that there is a need to reduce the environmental impact of ammonia production, the transition to more sustainable methods has been currently slow[12]. This is primarily because there are economic constraints and technological limitations. Bridging the gap with farmer perspectives and attitudes is also essential. Farmer acceptance is key for the adoption of any new agricultural technology[13]. Exploration of the factors influencing farmer decision-making requires conducting in-depth discussions with farmers and a corresponding broadening of the channels for farmer adoption of new technology[14].

Recent research on GA has focused mostly on certain GA technologies, namely; electrochemical (e.g., Chanda et al.[15]), electrocatalytic ammonia synthesis (e.g., 16. Santhosh et al.[16] and Zhao et al.[17]) and plasma-catalytic technologies (e.g., Yoshida et al.[18], Kyebogola et al.[19] and Panchal et al.[20]). While recent reviews have reported advances and challenges associated with these ammonia production technologies, existing assessments examined mainly techno-economic performance factors such as energy efficiency[21]. Although these contributions have advanced understanding of individual dimensions of GA production, they have typically overlooked the broader socioeconomic context in which GA technologies must operate. In particular, previous reviews have overlooked the interaction between technical feasibility, environmental performance and economic viability, and agricultural adoption has received limited integrated attention. This perspective argues that a more holistic framing of GA pathways is needed by explicitly considering not only environmental and techno-economic performance, but also social and agricultural system implications to better inform sustainable fertilizer transitions and future research priorities.

2 Green ammonia impacts

The production of GA is in the development phase with multiple pathways being actively pursued. These can be broadly grouped into: power based, biomass based, electrochemical nitrogen reduction reaction (ENRR), plasma-catalytic ammonia synthesis and bioelectrocatalytic nitrogen fixation (Table 1).

2.1 Technical implications

From a technical perspective (Table 2), decentralized GA production tends to be smaller in volume than existing standard plants, which require large scale infrastructures[24]. Green ammonia production (e.g., power to ammonia) requires less raw materials but is more energy intensive due to the generation of H_2, with 16 times more electricity demanded in GA production processes[30]. When comparing GA production using renewable energy sources, hydroelectric power is advantageous since it is centralized and experiences less fluctuations, congruent with the current Haber-Bosch process[31]. In contrast, solar and wind energy are decentralized and highly variable, likely requiring a modified Haber-Bosch process that is low capital and able to respond to a changing energy supply[31]. Green ammonia produced using wind power with the low-pressure technique (i.e., where synthesis pressure used in the Haber-Bosch ammonia production loop is $\geqslant$ 8 MPa) is especially recommended over ultra-low-pressure techniques (i.e., where synthesis pressure used in the Haber-Bosch ammonia production loop is < 80 MPa). Indeed, the low-pressure technique results in very slight disadvantages in energy conversion performance; however, it has a simple configuration and theoretically has greater flexibility[22]. For biomass-based GA (i.e., GA with biomass used as additives in feedstocks), the biomass additives show positive effect on the energy efficiencies[32].

Table 1 Summary of the environmental, economic and technological impacts of different green ammonia technologies

Technology	Feedstock	Energy source	Environmental impacts	Economic impacts	Technological implications	Reference
Power based	N_2 + green H_2	Renewable energy (wind, hydro and photovoltaics)	Lower GWP impact when compared to the standard approach (except in the case of photovoltaics)	Costly compared with standard ammonia	Risk of depletion of some non-renewable resources (e.g., wind technology)	[22–24]
Biomass based	N_2 + green H_2	Biomass	Carbon neutral if biomass is sustainable	Slightly more expensive than standard ammonia	High energy efficiency	[25,26]
Electrochemical nitrogen reduction reaction	$N_2 + H_2O$	Renewable energy (wind, hydro and photovoltaics)	Environmentally sustainable	Cost effective. Allows for decentralized production	● Direct NH_3 from N_2 and water at mild conditions ● Low efficiency and selectivity: competes with the hydrogen evolution reaction ● Still in early stages	[27]
Plasma-catalytic ammonia synthesis	$N_2 + H_2$ or $N_2 + H_2O$	Renewable energy (wind, hydro and photovoltaics)	Zero intrinsic CO_2 emissions, relying solely on air, water, and renewable electricity, significantly reducing the dependence on fossil fuel-based nitrogen fertilizers	Decentralized production	● Activates N_2 under ambient conditions using plasma ● Could be an energy-efficient route for ammonia synthesis, especially when leveraging renewable energy sources ● Still in early stages	[28]
Bioelectrocatalytic nitrogen fixation	$N_2 + H_2O$	Renewable energy (wind, hydro and photovoltaics)	Carbon neutral	Enables small-scale, on-site ammonia production Potential low cost	● Operating under mild conditions (low temperature and pressure) ● Low efficiency ● Still in early stages	[29]

Table 2 Comparative description of technical performance indicators for green ammonia fertilizer pathways

Key performance indicator	Energy consumption ($MWh\cdot t^{-1}$ NH_3)	Ammonia production rate	Faradaic efficiency	Technology readiness level	Capital cost	Stability/ lifetime	Scalability/modularity	Reference
Plasma-catalytic ammonia synthesis	22	10 $kg\cdot t^{-1}\cdot d^{-1}$	Not applicable in the strict electrochemical sense	Early research stage	Potentially lower than renewable-powered Haber-Bosch production but still uncertain because of immature supply chains	Dependent on electrode and catalyst durability	Highly modular, scalable and very well suited for a decentralized small to medium scale ammonia production. close to farms, eliminating transport costs for fertilizers	[28,33–35]
Renewable-powered Haber-Bosch	8–12	e.g., 360 $t\cdot d^{-1}$ (hydropower) 1200 $t\cdot d^{-1}$ (biomass)	Not applicable (non-electrochemical synthesis)	Mature, commercially deployed technology	Capital cost is high, and small-scale is disproportionately expensive	Excellent; catalysts and reactors have decades of industrial optimization	● Large-scale systems remain most efficient; strong economies of scale ● Small, modular Haber-Bosch units exist but are less efficient and more expensive	[23,36,37]
Electrochemical nitrogen reduction	50	Very low; $<10^{-8}$ $mol\cdot cm^{-2}\cdot s^{-1}$	Generally low (< 1% to 10%) in most reported systems	Very low; mostly laboratory research	Highly uncertain; expected to be low if high-performance catalysts and ambient-condition reactors become viable	Poor to moderate (when non aqueous)	● No pilot-scale demonstrations for scalability ● Potentially high modularity	[23,38–40]
Biological nitrogen fixation	Not applicable	Extremely low nitrogen synthesis compared with industrial production	Not applicable; nitrogenase uses biochemical energy rather than electrons from an external circuit	● Very early stage. The development of e-BNF is still in its infancy ● Boosting electron flow with reactor technology and material science	Low	Poor: nitrogenase is unstable and oxygen-sensitive	Highly scalable and inherently modular	[23,29,39]

Emerging technologies for decentralized ammonia production aim to provide lower-energy, scalable alternatives to Haber-Bosch synthesis, making them suitable for small to medium scale applications. For example, an innovative strategy, and a promising electrochemical route toward sustainable and scalable GA synthesis, using bimetallic phosphate material ($Ag_2VO_2PO_4$), was examined by Gupta et al.[41]. As an energy efficient and time saving sonochemical route, it enables the fast synthesis of electrocatalysts. The process operates at lower ambient temperatures and pressures (compared with the Haber-Bosch process), making it feasible for small to medium scale ammonia production, while maintaining superior selectivity[41]. The use of Ag in an alkaline environment effectively minimizes the hydrogen evolution reaction, and the bimetallic phosphate material (Ag and V metals) enhances catalytic activity, driving efficient nitrogen reduction[39,41]. Similarly, the electrochemical oxygen reduction offers a very good possibility for extracting green nitrogen from air and for producing pure oxygen at the anode[42]. Depending on the air flow rate and maximum current provided, the oxygen content within the gas stream is reduced to < 1%[42]. This reduction in oxygen content is achieved at room temperature, while maintaining a high Faraday efficiency of 90% across a wide potential range[42]. Nevertheless, balancing stability and efficiency remains a challenge in the ENRR. In this context, non-aqueous systems offer higher nitrogen solubility and better selectivity towards ENRR[38]. However, apart from the unsatisfactory yield rate, the non-aqueous solvents are also volatile, flammable, and toxic in nature and therefore, to a certain extent, may deviate from the green production of ammonia. By comparison, aqueous systems are safer and easier to handle, as they can be operated under mild conditions, and the water as a solvent is non-toxic and abundant[38]. However, the aqueous systems may have selectivity issues and slow kinetics due to an inert N≡N and an unsatisfactory ammonia yield rate[38]. Conversely, the ENRR for GA production, powered by sustainable electricity (e.g., solar, wind), using an NiCu dual single-atom catalyst on N-doped porous carbon showed an excellent electrocatalytic N_2 reduction performance (compared with other single-atom catalysts), with a faradaic efficiency (i.e., the efficiency with which electrons are transferred in a system facilitating an electrochemical reaction) of 30% and an ammonia yield rate of 70.8 $\mu g \cdot h^{-1} \cdot mg^{-1}$ of catalyst[27]. A novel approach combining plasma with catalytic reduction techniques adapted from advanced automotive exhaust after-treatment technologies, was developed, to overcome the inherent inefficiencies of plasma-driven ammonia synthesis (i.e., plasma is more effective for oxidation reactions, rather than chemical reduction)[28]. In this case, N_2 is first oxidized to NO_x and then reduced to NH_3 using concepts from the automotive industry where ammonia is synthesized aboard of vehicles for abating NO_x emissions from exhaust gases. The result is a more energy efficient and scalable process, with the potential to significantly reduce dependency on fossil fuel-based ammonia production[28]. This breakthrough not only emphasizes the role of plasma in ammonia synthesis but also shows the viability of cross-sector technological innovation, merging automotive and chemical engineering principles to achieve major efficiency in GA production. Nevertheless, within the biological pathway for GA synthesis, the energy efficiency of nitrogen reduction is only 1%, since producing H_2 directly within the bacterial culture means low salinity and a high driving voltage of 3.0 V is required (which is double that in commercial water electrolysis)[23]. Also, the determined faradaic efficiency is low (only 2.4%), which is due to the reaction stoichiometry of nitrogenase, and upstream biochemical pathways required for microbial growth[23]. Therefore, future technologies for GA production cannot be realized based on the biological process mentioned[39]. As a cutting-edge, carbon-neutral, energy efficient, and potentially sustainable strategy for ammonia synthesis, bioelectrocatalytic nitrogen fixation (e-BNF) harnesses the power of biological catalysts[29]. This process uses either enzymes (such as nitrogenase) or nitrogen-fixing bacteria (e.g., *Azotobacter* or *Rhizobia*) to convert atmospheric nitrogen into ammonia. The required electrons or hydrogen are directly supplied from an electrode powered by renewable electricity. Operating under mild conditions of low temperature and pressure, the e-BNF process achieves exceptional energy efficiency and sustainability, making it a promising alternative to standard ammonia synthesis methods. Nevertheless, further optimization is needed to enhance stability and improve yield. For example, within enzymatic electrocatalysis, challenges persist due to the system instability, and low ammonia synthesis efficiency[29].

Overall, the emerging GA technologies (e.g., electrochemical ammonia production, plasma-driven nitrogen oxidation combined with catalytic reduction and e-BNF) are at earlier stages of development, so that the system and, consequently, their estimated impacts, remain highly uncertain[43].

In summary, while GA as a power to ammonia technology may present a risk of depletion of some non-renewable resources (e.g., solar and wind), the biomass to ammonia technology has shown high energy efficiency. Regarding the emerging technologies for GA, although they operate under ambient conditions, their potential efficiency is still uncertain.

2.2 Environmental impacts

Several LCA-based studies have compared GA production with standard pathways, such as grey and blue ammonia. The blue and grey ammonia use steam methane reforming for H_2 production, while GA is based on water electrolysis with renewable resources (i.e., wind, hydro and photovoltaics) and nuclear power as a carbon-free source for H_2 generation. Galusnyak et al.[30] concluded that the integration of renewable sources for green H_2 production resulted in a lower global warming potential (GWP) impact when compared with the standard pathway. Particularly, the best environmental performance was shown by the hydro-powered electrolytic H_2 production, with the lowest scores in six of ten impact categories studied for ammonium nitrate production (i.e., mainly related to freshwater eutrophication, ozone and fossil depletion potential, human toxicity potential non-cancer, photochemical ozone formation potential ecosystem and human health). However, the use of photovoltaic panels showed the worst results among all the environmental impact indicators, especially the GWP score, which was similar to the standard pathways due to embedded emissions associated with the construction and installation of the panels.

Similarly, Tjahjono et al.[44] focused on GA production using renewable energy sources such as geothermal and hydropower and compared its environmental performance with grey and blue ammonia. Their analysis revealed that grey and blue ammonia production generated 2.73 and 0.28 t CO_{2eq} per t NH_3, respectively, whereas the *in-situ* carbon emissions from GA were considered negligible. Mayer et al.[25] assessed the LCA of GA production compared with blue ammonia production from cradle to grave and confirmed that GA showed a substantial mitigation of climate change impacts on a per kg ammonia basis. Another output of the latter study is that blue ammonia offered an immediate solution for mitigating the environmental impacts of ammonia production under limited renewable electricity availability, as long as natural gas supply chain leakage rates were monitored and maintained low. Overall, the choice to use renewable technologies over standard methods significantly impacts the material requirements as well as the C footprint of ammonia production. Wind technology, for example, presents a greater influence on the depletion of non-renewable resources compared to solar technology, which emphasizes the critical nature of selecting appropriate renewable sources[45]. Alternatively, the use of biomass additives has shown a promising effect on sustainable GA. In this context, Gu et al.[26] conducted a comprehensive LCA of biomass-based GA, where biomass was used as an additive in the feedstocks. Their study specifically assessed the environmental impact using GWP and water consumption as key environmental indicators. The findings showed that the C footprint mainly relates to the operation stage (more than 98%), due to the large amount of feedstocks and energy consumed. However, when the biomass content is increased to 15 wt%, it significantly reduces GHG emissions, cutting CH_4 emissions by 14.1% and lowering the C footprint by 40 kg CO_{2eq} per t NH_3, while also saving 0.88 m^3 H_2O per t NH_3 during operation.

For waste-based technologies, as new sustainability-driven means of producing GA, they exemplify the transition from a linear to a circular economy, in which materials commonly considered as waste are redefined as valuable resources. By recovering nitrogen, hydrogen and energy from agricultural residues or wastewater, and industrial by-products, these approaches reduce waste burdens and supply key inputs for ammonia synthesis. Beyond lowering reliance on fossil-derived feedstocks, waste-based pathways enable nutrient recycling, and support circular agricultural systems by returning recovered nitrogen to soils in the form of fertilizers. This integration enhances resource efficiency, reduces environmental pollution from waste streams, mitigates GHG emissions, and strengthens the resilience and sustainability of agri-food systems. The waste-based technologies may include coupling dark fermentation with anaerobic digestion or only anaerobic digestion and capturing CO_2 for sequestration or later use. Ghavam et al.[43] assessed the environmental performance for a full production cycle of waste-based technologies compared with standard ammonia. The study confirmed that GA with a two-stage dark fermentation coupled with anaerobic digestion, alongside CO_2 capture for sequestration, was most efficient for GWP, water and energy, consuming 27% less energy and reducing GHGs by 98%. However, on a fertilizer-N basis, the ammonia production through anaerobic digestion only, with captured CO_2 directed towards urea, outperforms the other options across all the environmental categories[43]. Both C sequestration and urea production provide a valuable route to additional valuable products while avoiding direct release of CO_2 emissions. However, failing to prevent leakage undermines the effectiveness of these new technologies since the methane and ammonia leakage account for nearly all the associated life cycle impacts.

The other alternative methods for GA production involving plasma-driven nitrogen oxidation combined with catalytic reduction and e-BNF and ENRR, operate with zero intrinsic CO_2 emissions, relying solely on air, water and renewable energy, and significantly reducing the dependence on fossil fuel-based nitrogen fertilizers[28,29,38].

In environmental terms, the different types of GA technologies have been shown to be environmentally sustainable either with lower GHG emissions (e.g., power to ammonia) or near zero emissions, particularly emerging methods that do not rely on the Haber-Bosch process.

2.3 Socioeconomic impacts

The economic implications of GA have been examined at various scales. Globally, the circular economy of power to ammonia showed the highest material impact with wind technologies (623 t Sb-eq·MW^{-1}), while solar technologies have the least (23.4 t Sb-eq·MW^{-1})[45]. For the Eco-Indicator 99 total impacts (considering human health, ecosystem quality and resources categories), wind technologies have the most significant impact (3.23 × 10^6 Pt), unlike hydropower technologies, which have a minor impact in comparison (3.54 × 10^4 Pt)[45]. It is important to note that in this specific case, the assessment was conducted under an optimistic scenario; however, the results nonetheless serve as a basis for more in-depth studies. More specifically, in sub-Saharan Africa, taking Sierra Leone as an example (given its high hydropower capability), using GA as a fertilizer could provide a significant financial benefit, with a net present value of 230 million USD and a 165% return on investment over 30 years[31]. It could also save 50 million USD annually compared to importing fertilizers, when modern agricultural practices are successfully implemented[31]. Similarly, the model of supplying GA to farmer investors in southwestern USA at a 23% discount while still being able to pay a 30% dividend to all investors, enabled farmer investors to compete more effectively and manage risks with greater resilience[46]. Therefore, this model supports the fostering of economic resilience through internal circulation of expenditures and reinvestment of profits[46]. However, ammonia, synthesized using renewable hydropower, may not be competitive compared with imported ammonia, as demonstrated by the specific case of Nepal, wherein the strong sensitivity of the cost of production to electricity price could be an encouraging indication[47]. An optimization of GA production in Morocco by leveraging advanced deep learning techniques to maximize the use of its abundant renewable energy resources, suggested that under the optimal scenario of 20% photovoltaic and 80% wind energy, the production cost was 575 USD·t^{-1} NH_3, delivering an energy output of 8.92 TWh and a daily ammonia production of 2.50 kt NH_3[48]. Tjahjono et al.[44] developed a spreadsheet-based decision support system to assess the economic impacts, among others, in Indonesia. In this case, the levelized cost of GA was the highest and varied between 696 to 1024 USD·t^{-1} (compared with grey ammonia costs of 297 USD·t^{-1} and blue ammonia at 390 USD·t^{-1}), and is predominantly influenced by the choice of electrolyzers, the cost of renewable energy sources, and maintenance and operational expenditures.

The comparison of the economic feasibility of GA produced from biomass or power (as renewable energy) with standard grey ammonia showed the high effectiveness of the latter[49]. Biomass to ammonia production is slightly more expensive due to the complexity of gasification and air separation processes. Meanwhile, power to ammonia is currently the most expensive option. However, it has the potential to become competitive if stack prices decrease and electricity costs drop significantly[49]. Similarly, in the context of power to ammonia, the low-pressure technique is recommended because the levelized cost of ammonia with low pressure technique is slightly lower than that with the ultra-low-pressure technique[22]. In this sense, the pressure reduction causes a small reduction in the total equipment costs[22]. Regarding, GA produced from food waste and brown water, the anaerobic digestion-only process with CO_2 capture showed the best technological configuration as it consumes about 41% less energy than grey ammonia and about 27% less energy than blue ammonia per kg NH_3[43]. Modifying the Haber-Bosch process with different water electrolysis (WE) types in the context of GA production (e.g., alkaline WE, polymer electrolyte membrane WE, and solid oxide electrolysis cell) showed that the most appropriate WE can be changed depending on the unit electricity price[50]. In contrast, GA produced from a system based on alkaline electrolysis is cheaper today, solid oxide electrolysis cell has been shown to be more cost-effective, when basing the comparison on the projected future cost of the electrolyzers[51]. Green ammonia is cost-competitive compared with grey ammonia if the levelized cost of energy is < 25 EUR·MWh^{-1}. It is competitive in comparison with blue ammonia if it is < 40 EUR·MWh^{-1} [51]. The cost-effectiveness of the emerging technologies for GA (e.g., plasma-driven nitrogen oxidation with catalytic reduction and e-BNF), is still under investigation[52]. While these technologies have the potential to be low-cost, factors such as energy efficiency, catalyst performance and operational scalability will ultimately determine their economic viability (Hollevoet et al.[28]. With respect to electrochemical ammonia production, aqueous environments have been shown to be a cost-effective and sustainable alternative to the Haber-Bosch process, compared with the non-aqueous environments[38].

In summary, while all current GA technologies support decentralized production, they generally have higher costs compared with standard pathways. However, emerging alternatives, for GA, particularly those not reliant on the Haber-Bosch process, demonstrate promising potential for cost-effectiveness.

From a social perspective, farmer uncertainty about agronomic outcomes and operational dependability constrains willingness to adopt emerging technologies. Consistent with broader agricultural innovation research, farmers in Iowa, USA emphasized the expected impacts of cost-effectiveness, return on investment and performance reliability[53]. The sociotechnical dimension also shapes the conditions under which GA can be integrated into existing agricultural systems, echoing broader insights from the agricultural innovation literature. While decentralized systems may offer logistical and economic advantages, farmer acceptance is mediated by perceptions of safety, regulatory clarity and community attitudes. Broader literature on agricultural technology adoption, shows that adoption of GA depends not only on technological performance and economic competitiveness, but also on the alignment of trust networks, knowledge dissemination pathways and community-level acceptance of decentralized production infrastructures[54]. In this context, farmers rely heavily on established social networks (e.g., agronomists and cooperatives) to interpret unfamiliar technologies. This mirrors patterns observed in other contexts, highlighting the critical contribution of trust, knowledge transfer and advisory networks in shaping farmer decision-making and their openness to environmentally-friendly innovations[55,56].

To conclude, farmer acceptance of GA is more likely when technologies are embedded within trusted networks and perceived as delivering tangible and consistent local benefits.

3 Challenges and opportunities for green ammonia

The key components in GA technologies based on the Haber-Bosch process (i.e., electricity generation for water electrolysis and ammonium nitrate synthesis and the air separation unit), were shown to have the highest influence on the corresponding climate change impacts[30]. For example, the climate change impacts of the GA based on photovoltaics, as a power to ammonia technology, are mainly driven by the large resource requirements and present-day supply chains of photovoltaics and electrolyzers[25]. A narrow range of efficiency improvement (less than 2 percentage points) can be achieved for the power to ammonia and biomass to ammonia technologies by varying the design points of the mentioned key components[49]. However, a major challenge for the different GA technologies is narrowing the leakage of ammonia[43]. In this context, higher efficiencies together with low natural gas leakage could make blue ammonia a promising present-day sustainable replacement for standard ammonia production while the technologies for GA further develop and the supply chains improve[25]. For example, the power-to-X efficiency of blue ammonia is seven times that of GA due to its high energy requirements[25]. Another key challenge for ensuring continuous GA production by renewable energy sources is their intermittency, which requires innovative strategies for energy storage and management[48]. To maximize production during peak times and store surplus energy for low-production periods, different strategies were proposed[48]. For example, wind and solar resources can operate dynamically to minimize expensive battery and hydrogen storage capacities[24]. Also, location is considered as an important factor in the development of sustainable GA, in terms of both availability of feedstock and renewable energy (e.g., accessibility to renewable energy sources such as solar photovoltaic and wind power, distance from the waste hub to the production plant)[43].

For new technologies for GA production, as e-BNF remains in its early stages of development, enhancing electron flow via reactor design and material innovations represents a key strategy for improving its performance[29]. For example, the limited electron-transfer efficiency currently observed in eBNF systems translates directly into higher electricity consumption and larger reactor C footprints, which significantly increase the cost of ammonia and limits scalability[29]. Additionally, an improvement of the existing systems for electrochemical ammonia production is needed to achieve better performance by a thorough and deep understanding of the underlying mechanisms[41]. Indeed, the electrochemical reduction of N_2 competes with the hydrogen evolution reaction producing H_2. This lowers the faradaic efficiency, with H_2 produced rather than NH_3. Such inefficiencies raise the levelized cost of ammonia and prevent these systems from achieving the production rates needed for industrial or sector-wide deployment. Although hydrogen from electrolysis can be fed into a separate nitrogen reduction process, this multistep configuration adds capital cost and conversion losses, reducing economic viability and complicating scale-up[29].

As an economically viable alternative and a key solution to pressing environmental and social challenges, the deployment of small-scale, locally distributed production facilities for GA, particularly in regions with high transport costs and limited infrastructure, such as in Africa, is increasingly urgent[45,57]. However, more in-depth studies are needed to support and guide such efforts. For example, consequential LCA enables the assessment of the broader, indirect effects of shifting from a large scale to decentralized production, such as changes in energy demand, supply chains and land use.

In economic terms, it is recommended to prioritize the transition of ammonia fertilizers to GA use, reduce the capital cost for green hydrogen assets, develop administrative frameworks allowing the fertilizer industry to earn through carbon credits and investigate pathways to introduce GA in nitrogen delivery to crops[58]. Indeed, research and development activities, along with improvement in the manufacturing process, to address the high cost of electrolyzer production not only drive technological innovation and infrastructure investment in the industry of GA, but also create jobs and stimulate economic growth for the adopting countries[44]. In social terms, outreach and community engagement programs should be devoted to communicating with the farmer sector (including farmers and advisors) about the new technologies. In this context, regular and effective communication helps build a trusting relationship with producers, while making GA more familiar, especially for conservative groups[59].

As in the GA fertilizer context, the main objective is to reduce GHG emissions associated with standard, fossil-based ammonia production. However, if GA fertilizers become highly accessible, affordable and competitive, their reduced environmental footprint could alter fertilizer management practices, encouraging higher application rates and/ or more frequent use. Such systemic responses may increase nitrogen losses to the environment, including nitrous oxide emissions, nitrate leaching and ammonia volatilization, thereby offsetting or even surpassing the GHG mitigation benefits achieved at the production stage. This potential rebound effect underscores the importance of coupling GA deployment with improved nutrient management strategies, regulatory frameworks and agronomic best practices to ensure that upstream decarbonization translates into environmental co-benefits across the cycle of ammonia production and use

It is important to recognize that many reported performance estimates for emerging GA pathways are derived from optimistic or idealized modeling assumptions, reflecting the early developmental stage of most non-Haber-Bosch technologies. As such, these results should be interpreted as indicative benchmarks rather than as robust and reliable predictors of near-term, real-world performance. This perspective emphasizes the need for caution when extrapolating modeled outcomes to deployment scenarios, and highlights the importance of continued experimental validation and pilot-scale demonstrations to better assess the true potential of these technologies. More importantly, farmer attitudes towards GA have received limited attention in existing work. As central actors in agricultural research and environmental policy, farmer opinions on innovation and regulation can assist in policy and technology design. Engaging farmers (e.g., via participatory extension programs, surveys and workshops, where farmers are allowed to share their feedback) is one option to address this existing knowledge gap. Finally, we recommend conducting a comprehensive and a holistic life cycle assessment (considering the full boundary and the environmental and socioeconomic aspects) to provide comprehensive evidence and to support policymakers in making informed decisions that drive sustainability and responsible resource management[45].

4 Geographical contingency in optimal green ammonia pathways

The sustainability and optimal framework for GA production as a fertilizer are highly contingent on the availability of regional renewable resources, infrastructure status and the structure of the agricultural sector. Regions with high renewable energy potential, like the solar-dominant regions of West Asia and North Africa or the wind-abundant areas of Northern Europe, benefit from a competitive advantage in producing low-cost renewable ammonia. Their high renewable capacity factors help reduce electrolyzer operating costs; a trend emphasized in global analyses of renewable ammonia economics[60]. Conversely, areas with limited renewable energy availability or constrained land resources may rely on importation, as a more viable GA strategy, particularly as emerging international ammonia trade routes are expected to reshape global supply chains[61]. Existing industrial infrastructure is key for shaping regional pathways; countries with established ammonia production clusters, port facilities and hydrogen-related assets can retrofit standard Haber-Bosch plants, reducing capital costs and accelerating deployment, while regions with limited infrastructure face higher upfront costs and longer development timelines[62]. Agricultural economies reliant on fertilizer imports, prevalent in sub-Saharan Africa and parts of South Asia may view GA as a strategic tool for enhancing supply security, but this is only feasible with investment in distributed or modular production systems that can stabilize local fertilizer availability and reduce vulnerability to global price fluctuations[62]. The level of agricultural development also influences optimal GA deployment; high-intensity farming regions require large scale, continuous ammonia supply whereas emerging agricultural systems may benefit more from decentralized, small scale GA production integrated with rural renewable microgrids, which can enhance resilience and reduce transport costs.

To summarize, the deployment of GA is inherently geographically contingent, requiring careful policy and investment decisions that align with local renewable resource profiles, infrastructure readiness, trade exposure and agricultural demand patterns to ensure both economically and environmentally sustainable outcomes.

5 Conclusions

This perspective has shown that green ammonia (GA) fertilizers hold substantial potential to advance global decarbonization goals but on the basis of coordinated progress across technological, economic, environmental and social domains.

From a technological standpoint, while decentralized GA systems are promising for remote agricultural regions, they remain constrained by higher unit costs, limited operational experience and the need for more robust modular electrolyzer designs. Counterintuitively, early deployment is most achievable in centralized GA production integrated with renewable-powered electrolysis, as these systems currently benefit from economies of scale, more mature engineering pathways and clearer investment pipelines.

In environmental terms, GA offers clear advantages in reducing carbon emissions. However, the environmental benefits depend on several factors, namely, renewable energy availability, land use considerations and the efficiency of hydrogen and ammonia storage systems. Environmental research should therefore expand life cycle assessments across diverse geographies and energy mixes.

In economic terms, reducing electrolyzer costs, through scaling production, improving efficiency, and strengthening supply chains, emerges as the most critical short-term priority, as it directly influences the levelized cost of GA and determines competitiveness with standard ammonia. Policy mechanisms, such as carbon pricing, carbon credit frameworks and targeted subsidies, can act as complementary enablers, supporting cost reductions and improving the competitiveness of GA. In this context, economic studies should refine viable cost-reduction pathways and assess the effectiveness of emerging policy instruments.

The social dimension represents a significant knowledge gap. Farmer perceptions and risk tolerance, as well as trust in new fertilizer technologies, will strongly influence adoption rates of the GA technologies but empirical studies on these topics are scarce. Social science research should therefore be elevated as a priority area, to examine farmer attitudes, community impacts and the socioeconomic conditions that inevitably shape adoption rates and scales.

Overall, the transition to GA fertilizers is both technically plausible and environmentally desirable, but its success will depend on aligning technological innovation, cost-reduction strategies, supportive policy frameworks and meaningful engagement with agricultural communities. By prioritizing electrolyzer cost reductions, strengthening carbon mitigation incentives and investing in social science research, stakeholders can accelerate the responsible and equitable scaling of GA within global agricultural systems.

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Compliance with ethics guidelines

Asma Jebari, Yusheng Zhang, and Adrian L. Collins declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

REFERENCES

1. International Fertilizer Development Center (IFDC). How Fertilizers Feed the World. *IFDC*, 2024. Available at IFDC website on July 29, 2025
2. Ritchie H, Roser M, Rosado P. Fertilizers. *Our World in Data*, 2022. Available at Our World in Data website on July 29, 2025
3. Ojelade O A, Zaman S F, Ni B J. Green ammonia production technologies: a review of practical progress. *Journal of Environmental Management*, 2023, **342**: 118348
4. Aliyu A. Low-Carbon Ammonia Roadmap. *IEAGHG*, 2023. Available at IEAGHG website on July 29, 2025
5. MacFarlane D R, Cherepanov P V, Choi J, Suryanto B H R, Hodgetts R Y, Bakker J M, Ferrero Vallana F M, Simonov A N. A roadmap to the ammonia economy. *Joule*, 2020, **4**(6): 1186–1205
6. Zhang X, Sabo R, Rosa L, Niazi H, Kyle P, Byun J S, Wang Y Y, Yan X Y, Gu B J, Davidson E A. Nitrogen management during decarbonization. *Nature Reviews Earth & Environment*, 2024, **5**(10): 717–731
7. Garvey S M, Davidson E A, Wagner-Riddle C, Collins A, Houser M, Li T Z, MacDonald G K, Tenuta M, Kanter D, Kyle P, Wu N Q, Congreves K A, Wang Y L, Cardenas L, Zhang X. Emerging opportunities and research questions for green ammonia adoption in agriculture and beyond. *Nature Reviews Clean Technology*, 2025, **1**(1): 10–11
8. Ali Nosherwani S, Neto R C. Techno-economic assessment of commercial ammonia synthesis methods in coastal areas of Germany. *Journal of Energy Storage*, 2021, **34**: 102201
9. Kayalıoğlu A. Green approach to the fertiliser industry: low-carbon fertilisers. *Kemija u Industriji*, 2022(5–6): 347–357
10. Jackson C, Fothergill K, Gray P, Haroon F, Makhloufi C, Kezibri N, Davey A, LHote O, Zarea M, Davenne T, Greenwood S, Huddart A, Makepeace J, Wood T, David B, Wilkinson I. Ammonia to Green Hydrogen Project: Feasibility Study. *Department for Business, Energy and Industrial Strategy (BEIS)*, 2020. Available at UK Government Publishing Service website on July 29, 2025
11. Hochman G, Goldman A S, Felder F A, Mayer J M, Miller A J M, Holland P L, Goldman L A, Manocha P, Song Z, Aleti S. Potential economic feasibility of direct electrochemical nitrogen reduction as a route to ammonia. *ACS Sustainable Chemistry & Engineering*, 2020, **8**(24): 8938–8948
12. Irfan H M, Iqbal K, Taipabu M I, You C Y, Mazumdar D, Wu W. Decarbonization frameworks to industrial-scale ammonia production: techno-economic and environmental implications. *International Journal of Hydrogen Energy*, 2024, **78**: 580–593
13. Han Z Y, Zhang M X, Zhang D, He X, Jing T J, Ge Z X, Li Y G, Zhu T, Ren Y H, Zhong C S, Ji F. Plasma nitrogen fixation system with dual-loop enhancement for improved energy efficiency and its efficacy for lettuce cultivation. *Plasma Science and Technology*, 2024, **26**(1): 015505
14. Wu F. Adoption and income effects of new agricultural technology on family farms in China. *PLoS One*, 2022, **17**(4): e0267101
15. Chanda D, Xing R M, Xu T, Liu Q, Luo Y L, Liu S H, Tufa R A, Dolla T H, Montini T, Sun X P. Electrochemical nitrogen reduction: recent progress and prospects. *Chemical Communications*, 2021, **57**(60): 7335–7349
16. Santhosh C R, Chinnam S, Madhu G M, Kottam N, Chigurupati S, Sankannavar R. Review on electrocatalytic nitrate reduction to ammonia: advances, challenges and future prospects. *Ionics*, 2024, **30**(6): 3091–3099
17. Zhao X G, Wang Y L, Yin H B, Qu Y K, Su H W, Fang W. Research progress of electrocatalytic ammonia synthesis from different nitrogen sources. *Chemical Journal of Chinese Universities*, 2024, **45**(3): 20230527 (in Chinese)
18. Yoshida S, Takatsuji Y, Haruyama T. Green ammonia synthesis technology that does not require H_2 gas: reaction technology and prospects for ammonia synthesis using H_2O as a direct hydrogen source. *Current Opinion in Green and Sustainable Chemistry*, 2024, **50**: 100980
19. Kyebogola S, Kabiri S, Onwonga R N, Semalulu O, Yost R S, Sseruwu G. Greener production and application of slow-release nitrogen fertilizer using plasma and nanotechnology: a review. *Sustainability*, 2024, **16**(22): 9609
20. Panchal D, Lu Q Y, Sakaushi K, Zhang X H. Advanced cold plasma-assisted technology for green and sustainable ammonia synthesis. *Chemical Engineering Journal*, 2024, **498**: 154920
21. Sarangi P K, Srivastava R K, Gitanjali J, Sathiyan G, Venkatesan G, Kandasamy S. Exploring cutting-edge advances in green ammonia production and storage technologies. *Fuel*, 2024, **371**: 131863
22. Song G H, Chen Y M, He Y F, Jia Q Z, Wu Q J, Cui X B, Zhao H. Techno-economic and life cycle greenhouse gas assessment of green ammonia produced by low-pressure Haber-Bosch process. *Energy Nexus*, 2025, **17**: 100379
23. Wiskich A, Rapson T. Economics of emerging ammonia fertilizer production methods—A role for on-farm synthesis? *ChemSusChem*, 2023, **16**(22): e202300565
24. Palys M J, Daoutidis P. Optimizing renewable ammonia production for a sustainable fertilizer supply chain transition. *ChemSusChem*, 2023, **16**(22): e202300563
25. Mayer P, Ramirez A, Pezzella G, Winter B, Sarathy S M, Gascon J, Bardow A. Blue and green ammonia production: a techno-economic and life cycle assessment perspective. *iScience*, 2023, **26**(8): 107389
26. Gu Z H, Liu Z Q, Yang S, Xie N, Ma K B. Exergy and

environmental footprint analysis for a green ammonia production process. *Journal of Cleaner Production*, 2024, **455**: 142357

27. Yang M S, Yang J Y, He N, Wang S Q, Ni H T, Yuan J X, Kang Y, Liu Y X, Zhou C X, Tong L P, Lu B F, Liu X Y, Wang Q, Huang S H, Feng B X, Guo G J, Han S, Han Z Y. Nitrogen-doped porous carbon-supported Cu–Ni single-atom catalysts for green ammonia synthesis *via* renewable-powered nitrogen reduction reaction. *ACS Applied Nano Materials*, 2025, **8**(1): 179–188
28. Hollevoet L, Jardali F, Gorbanev Y, Creel J, Bogaerts A, Martens J A. Towards green ammonia synthesis through plasma-driven nitrogen oxidation and catalytic reduction. *Angewandte Chemie International Edition*, 2020, **59**(52): 23825–23829
29. Wang B, Zhang Y F, Minteer S D. Renewable electron-driven bioinorganic nitrogen fixation: a superior route toward green ammonia? *Energy & Environmental Science*, 2023, **16**(2): 404–420
30. Galusnyak S C, Petrescu L, Sandu V C, Cormos C C. Environmental impact assessment of green ammonia coupled with urea and ammonium nitrate production. *Journal of Environmental Management*, 2023, **343**: 118215
31. Smith C, Torrente-Murciano L. The potential of green ammonia for agricultural and economic development in Sierra Leone. *One Earth*, 2021, **4**(1): 104–113
32. Liu Z Q, Gu Z H, Ma K B, Yang S, Xie N. Life cycle assessment and economic analysis of sustainable ammonia production from biomass. *Industrial & Engineering Chemistry Research*, 2023, **62**(46): 19752–19763
33. Carreon M L. Plasma catalytic ammonia synthesis: state of the art and future directions. *Journal of Physics D: Applied Physics*, 2019, **52**(48): 483001
34. Rouwenhorst K H R, Kim H H, Lefferts L. Vibrationally excited activation of N_2 in plasma-enhanced catalytic ammonia synthesis: a kinetic analysis. *ACS Sustainable Chemistry & Engineering*, 2019, **7**(20): 17515–17522
35. Ghavam S, Taylor C M, Styring P. Modeling and simulation of a novel sustainable ammonia production process from food waste and Brown water. *Frontiers in Energy Research*, 2021, **9**: 600071
36. Ribeiro C, Santos D M F. Transitioning ammonia production: green hydrogen-based Haber–Bosch and emerging nitrogen reduction technologies. *Clean Technologies*, 2025, **7**(2): 49
37. Amor-Dei-Jabo-Cyusa J, Baggio L, Bricteux M, Chèvremont É, Ilhan E, Imoula N, Ledent C, Limpach J, Radoux F, Rouxhet A, Thonus S, Zankia J. An Investigation into the Design and Sustainability of the Ammonia Production Plant. *University of Liege*, 2021. Available at University of Liège website on July 29, 2025
38. Gupta D, Kafle A, Kaur S, Nagaiah T C. A perspective on the future of electrochemical ammonia synthesis: aqueous or non-aqueous? *Journal of Materials Chemistry A*, 2023, **11**(41): 22132–22146
39. Gezerman A O. A critical assessment of green ammonia production and ammonia production technologies. *Kemija u Industriji*, 2022(1–2): 57–66
40. Zhou Y Y, Fu X B, Chorkendorff I, Nørskov J K. Electrochemical ammonia synthesis: the energy efficiency challenge. *ACS Energy Letters*, 2025, **10**(1): 128–132
41. Gupta D, Kafle A, Nagaiah T C. Sustainable ammonia synthesis through electrochemical dinitrogen activation using an $Ag_2VO_2PO_4$ catalyst. *Faraday Discussions*, 2023, **243**: 339–353
42. Sachse D, Chelachottil B N, Glüsen A, Müller M, Rau U, Peters R. Generation of nitrogen by means of electrochemical oxygen depletion. *Reaction Chemistry & Engineering*, 2024, **9**(7): 1924–1932
43. Ghavam S, Taylor C M, Styring P. The life cycle environmental impacts of a novel sustainable ammonia production process from food waste and brown water. *Journal of Cleaner Production*, 2021, **320**: 128776
44. Tjahjono M, Stevani I, Siswanto G A, Adhitya A, Halim I. Assessing the feasibility of gray, blue, and green ammonia productions in Indonesia: a techno-economic and environmental perspective. *International Journal of Renewable Energy Development*, 2023, **12**(6): 1030–1040
45. Serrano-Arévalo T I, Padilla-Esquivel C A, Hernández-Pérez L G, Díaz-Alvarado F A, Ramírez-Márquez C, Ponce-Ortega J M. Green ammonia production: the performance of global systems in eco-indicator 99 and circular economy metrics. *ACS Sustainable Chemistry & Engineering*, 2024, **12**(33): 12652–12669
46. Ofori-Bah C O, Amanor-Boadu V. Directing the wind: techno-economic feasibility of green ammonia for farmers and community economic viability. *Frontiers in Environmental Science*, 2023, **10**: 1070212
47. Devkota S, Ban S, Shrestha R, Uprety B. Techno-economic analysis of hydropower based green ammonia plant for urea production in Nepal. *International Journal of Hydrogen Energy*, 2023, **48**(58): 21933–21945
48. Adeli K, Nachtane M, Tarfaoui M, Faik A, Pollet B G, Saifaoui D. Deep learning analysis of green ammonia synthesis: evaluating techno-economic feasibility for sustainable production. *International Journal of Hydrogen Energy*, 2024, **87**: 1224–1232
49. Zhang H F, Wang L G, Van Herle J, Maréchal F, Desideri U. Techno-economic comparison of green ammonia production processes. *Applied Energy*, 2020, **259**: 114135
50. Lee B, Lim D, Lee H, Lim H. Which water electrolysis technology is appropriate? Critical insights of potential water electrolysis for green ammonia production. *Renewable and Sustainable Energy Reviews*, 2021, **143**: 110963

51. Nami H, Vang Hendriksen P, Lund Frandsen H. Current and Emerging Technologies for Green Ammonia Production: A Techno-Economic Analysis. *Social Science Research Network*, 2023. Available at SSRN on July 29, 2025
52. Sun J, Alam D, Daiyan R, Masood H, Zhang T Q, Zhou R W, Cullen P J, Lovell E C, Jalili A R, Amal R. A hybrid plasma electrocatalytic process for sustainable ammonia production. *Energy & Environmental Science*, 2021, **14**(2): 865–872
53. Adnan N, Rehman H M, Alam M N. Exploring agricultural innovation: an empirical investigation of factors influencing the adoption and non-adoption of smart fertilizer technology among farmers in developing countries. *Agriculture & Food Security*, 2025, **14**(1): 11
54. Han M Y, Liu R F, Ma H Y, Zhong K Y, Wang J, Xu Y F. The impact of social capital on farmers' willingness to adopt new agricultural technologies: empirical evidence from China. *Agriculture*, 2022, **12**(9): 1368
55. Park B, Kim T, An D, Mahasuweerachai P. Fostering innovation through farmer interactions: social networks and technology. *The Journal of Agricultural Education and Extension*, 2025: 1–22
56. Dilleen G, Claffey E, Foley A, Doolin K. Investigating knowledge dissemination and social media use in the farming network to build trust in smart farming technology adoption. *Journal of Business & Industrial Marketing*, 2023, **38**(8): 1754–1765
57. Tran N N, Penna L K, Heath I M, Arshad M Y, Gelonch M E, Tejada J L O, Sarafraz M M, Suberu J, Fregene M, Rolfe B, Hessel V. Integration of environmental, social and governance (ESG) into the supply chain of ammonia: case study of Africa. *Sustainable Futures*, 2025, **10**: 100893
58. Kothadiya K, Mallya H, Yadav D. Economic Feasibility of Green Ammonia Use in India's Fertiliser Sector. *Council on Energy, Environment and Water*, 2024. Available at Council on Energy, Environment and Water website on July 29, 2025
59. Wang Y, Li W Z, Gu S. Farmers' attitude towards green ammonia produced by upcycling waste nitrogen: empirical evidence from an Iowa study. *Sustainable Futures*, 2025, **9**: 100450
60. Rouwenhorst K H R, Castellanos G. Innovation Outlook: Renewable Ammonia. *International Renewable Energy Agency*, 2022. Available at International Renewable Energy Agency website on July 29, 2025
61. Winn Z. Understanding Ammonia Energy's Tradeoffs Around the World. *MIT News Office*, 2026. Available at Massachusetts Institute of Technology website on July 29, 2025
62. Munasinghe S, Krimer A. Seeding A New Pathway: The Opportunity for Distributed Green Ammonia. *Rocky Mountain Institute*, 2024. Available at Rocky Mountain Institute website on July 29, 2025