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COMMENT

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Is "green" ammonia a misnomer? Unpacking the green label from a food-water-energy nexus perspective in water-scarce regions

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Abstract
The term 'green ammonia' can be misleading. For fertilisers to merit a green label, the industry must adopt a planetary boundaries framework that includes reducing carbon emissions and circular management of nutrients. It should seek to achieve net reductions in reactive nitrogen and phosphorus fluxes to terrestrial and marine ecosystems.

Keywords Circular Economy, Water Scarcity, Fertiliser Production, Nitrogen Recycling, Wastewater

Introduction

The global drive for circularity and sustainability has intensified research and development into 'green' and 'eco-friendly' technologies [1]. These technologies are expected to be more environmentally benign than their conventional counterparts [2]. However, 'green' is often a broad categorisation encompassing diverse concepts and is frequently used interchangeably with terms such as 'sustainable,' 'eco-friendly' and 'ecological' [3]. This can create confusion among consumers regarding the specific attributes that make a technology or product truly green [4].

In this commentary, we evaluate the accuracy of the term 'green ammonia.' 'Green' implies that ammonia production has minimal environmental impacts, but in reality the impacts of green ammonia synthesis are rather complex. Production of green ammonia requires availability of 'green' hydrogen, a product of water electrolysis powered by renewable energy. However, large-scale electrolysis requires abstraction and/or production of substantial amounts of freshwater, a critical resource in regions like Australia and Namibia that are poised to produce most of this green hydrogen. Here, we unpack the 'green' label for hydrogen and ammonia, considering aspects of water security and the food-water-energy nexus. Furthermore, we argue for a broader application of circular economy principles in the fertiliser industry. As sustainable alternatives to green ammonia, we propose recycling of human excreta and other organic wastes as fertilisers, as this would reduce carbon emissions as well as decrease reactive nitrogen and phosphorus fluxes to ecosystems.

The term 'green ammonia' is misleading and overly simplistic

'Green ammonia' is described as a green fertiliser and zero-carbon fuel and is promoted as one approach to accelerate global transition toward net-zero carbon emissions [5]. Conventional 'brown ammonia', mostly used in agriculture as crop fertiliser [6] is typically produced in the Haber–Bosch process, where hydrogen sourced from steam reforming of fossil-derived

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methane is combined with nitrogen extracted from air. Brown ammonia production accounts for 1–2% of global carbon dioxide emissions [6]. Green ammonia production also relies on the Haber–Bosch process, but a key difference is that hydrogen is derived from renewable energy-powered electrolysis of water [7], thereby "greening" and decarbonising ammonia synthesis. Globally, the green hydrogen market is projected to experience significant growth, with investments expected to reach USD 570 billion by 2030, in around 1,400 projects across various regions [8].

Extraction of nitrogen from the atmosphere is an energy-intensive process that is fundamentally linear, irrespective of whether the nitrogen is used in green or brown ammonia synthesis. Unreactive atmospheric nitrogen is fixed by natural processes globally in oceans and on land, but anthropogenic nitrogen extraction through Haber–Bosch ammonia synthesis has almost doubled global nitrogen fixation [9]. Current assessments indicate that the biogeochemical cycle of nitrogen has now exceeded its delineated safe operating space within the 'planetary boundaries' [10]. Increased reactive nitrogen in the environment is creating issues far beyond the boundaries of its industrial use, including eutrophication of water bodies [11], acidification of soil [12], nitrous oxide emissions [13], $PM_{2.5}$ air pollution [14], loss of biodiversity and changes in ecosystem functions. Therefore, despite significant reductions in carbon emissions associated with hydrogen production, green ammonia used as fertiliser is likely to have substantial life cycle impacts and the term 'green ammonia' is inaccurate.

Water security and environmental impact dimensions of green hydrogen production

Green hydrogen production relies on freshwater, an increasingly scarce resource globally and particularly in regions where many of the world's largest green hydrogen projects are planned or underway. Apart from 87 GW of green hydrogen projects announced in Western Europe and an additional 2 GW in Brazil, the remaining projects are all situated in arid regions. Australia leads, with combined capacity of 58.6 GW across seven projects, followed by Kazakhstan with 30 GW and Mauritania with 21 GW [15]. Many hydrogen projects are planned in regions already experiencing extreme water stress, such as Oman (14 GW), Chile (8 GW), Namibia (3 GW) and Saudi Arabia (2GW) [15, 16]. In Namibia, the driest country in Sub-Saharan Africa, construction is underway on a gigawatt-scale project to produce 350,000 tonnes of green hydrogen and 2 million tonnes of green ammonia annually by 2030 [17]. In that project and in many others globally, desalination will be performed by seawater reverse osmosis (SWRO), a process that contributes just 1% to the total cost of hydrogen production but has significant economic, social and environmental impacts [18, 19]. For example, SWRO requires multiple chemicals, such as acids to regulate pH, chlorine to prevent biofouling and anti-scalants to inhibit mineral precipitation. The byproduct is brine, a highly concentrated saline solution that also contains these chemicals. When brine is discharged to marine environments, it can significantly alter local pH and increase salinity, water temperature, concentrations of heavy metals and ultimately water toxicity, reducing biodiversity around discharge points [19]. To produce 1 kg of hydrogen via electrolysis, approximately 10 kg of freshwater are needed [18]. SWRO desalination has an average recovery rate of 40% [18, 20], so around 25 L of seawater are needed to produce 10 L of freshwater, with the process also resulting in production and discharge of approximately 15 L of brine. The energy demand for SWRO desalination is ~ 3.5 kWh/m^3 [21], but can increase to 5.8–10.8 kWh/m^3 depending on water salinity [21].

Environmental impact assessments of SWRO desalination for hydrogen projects in Namibia suggest that impacts from brine discharge will likely be low, except for localised effects near discharge points [19]. However, these assessments do not consider regional environmental impacts accruing over time resulting from the brine discharges of multiple projects [19]. Zero-/minimal-liquid-discharge (ZLD/MLD) technologies can be applied to mitigate environmental impacts associated with brine discharge. These technologies tap the economic potential of brine mining, since the pre-concentrated brine from SWRO is rich in sodium, lithium, boron, scandium, gallium, indium, vanadium and molybdenum [19]. These minerals are essential for driving the green energy transition and advancing the fourth Industrial Revolution.

Hydrogen has a high energy content by weight (~ 33.3 kWh kg^{-1}) [22]. The energy requirement for production of hydrogen via water electrolysis can vary significantly depending on the efficiency, scale and operating conditions of the electrolyser. Mean electric energy demand for water electrolysis is currently ~ 55 kWh per kg hydrogen, reflecting energy conversion efficiency of around 60%, not accounting for additional energy demands from SWRO and mechanical pumping [22]. Hydrogen production accounts for 80% of total energy demand in ammonia synthesis [23]. Novel methods for ammonia production, such as low-temperature electrochemical ammonia synthesis, have a theoretical minimum energy demand of 21.18–21.30 GJ per ton of ammonia [23, 24]. However, industrial-scale processes for electrochemical ammonia synthesis currently achieve efficiencies of only 60–70%, resulting in energy demand of 30.3–35.3 GJ per ton of ammonia [22, 24]. Even with improved methods for producing nitrogen, such as using an air separation unit, the energy demand for green ammonia production methods remains similar to that of conventional processes like the Haber–Bosch method [23]. In real-world, smaller-scale operations, the energy demand for both low- and high-temperature electrochemical ammonia production is likely to exceed the amount suggested by theoretical models, reflecting a significant efficiency gap [22]. Technological advances are needed to bridge the gap between theoretical efficiency and practical application in hydrogen and ammonia production.

Food security versus green hydrogen production

Globally, Africa has the highest estimated technical potential for producing green hydrogen [15]. However, current estimates primarily consider land availability for electricity production, taking into account exclusion zones such as existing cropland, but overlook freshwater availability required for producing hydrogen. Around 65% of the world's uncultivated arable land is in Africa, but using this land for hydrogen production rather than food production poses significant ethical and sustainability issues, given the acute food security challenges globally and particularly in Africa [25]. According to the FAO Global Information and Early Warning System on Food and Agriculture (GIEWS), 46 of Africa's 54 countries requested external food assistance or faced agricultural shocks in 2022 [26]. Only five of these 46 countries did not meet GIEWS criteria, three of whom received external assistance from FAO and/or WFP and two from WFP/UNHCR for hosting refugee populations [26]. Furthermore, only four African countries experienced 0–10% food-price inflation, whereas the rest faced 11–20% or higher increases. Notably, Egypt, Nigeria and Ethiopia—home to the largest populations on the continent—saw food price inflation of 20–50% [26]. From a land use perspective, this suggests that a critical balance must be struck between advancing green energy projects and ensuring food security. It also raises ethical concerns, as prioritising green hydrogen production could undermine food security in regions already vulnerable to food scarcity.

A circular perspective on fertilisers?

Decarbonising the global economy is vital for our shared future, but exclusively focusing on reducing carbon dioxide emissions is somewhat shortsighted. For fertilisers to genuinely merit a green label, the industry must adopt a planetary boundaries framework that extends beyond the current industry focus on merely offsetting or reducing carbon emissions from fertiliser production. Specifically, the framework should include management of global biogeochemical flows of nitrogen and phosphorus. The fertiliser industry has a significant impact on these nutrient cycles and thus has extended producer responsibility for minimising the environmental impacts of its products. The safe planetary boundaries for both nitrogen and phosphorus have already been exceeded, so the industry should aim for substantial reductions in fluxes of reactive nitrogen and phosphorus to terrestrial and marine ecosystems via its products. But how can such reductions be achieved if not through use of 'green ammonia'? One solution is for the industry to engage in large-scale production of bio-based fertilisers. Domestic wastewater, particularly source-separated fractions such as human urine [27, 28], is rich in bio-based nutrients that can be mined and recycled. Human urine is a rich source of urea, a waste product of nitrogen metabolism in the human body. Urea is also the most widely used fertiliser globally, with approximately half of the ammonia produced by the Haber–Bosch process utilised in manufacturing urea [29]. Simply storing human urine naturally converts urea back to ammonia [30], while both urea and ammonia can be feasibly recovered from human urine using a wide variety of technologies [31]. Life cycle assessments have demonstrated that recycling urine as fertiliser reduces greenhouse gas emissions, lowers energy consumption, and decreases eutrophication [32–34].

In a recently published UNEP [35] rapid response assessment report [35], we show that the human urine produced annually at global scale contains 31 Tg of nitrogen. Recycling nitrogen derived from urine could potentially meet 25% of global nitrogen demand in agriculture, or even more if other organic waste streams such as human faeces, livestock manure and crop residues are also recycled [36]. Such recycling could significantly offset the demand for anthropogenic nitrogen fixation via green/brown ammonia synthesis, thus aligning food systems more closely with the principles of a truly green and circular economy.

Transitioning the fertiliser industry to 'green' ammonia production is simpler than transitioning it to the production of bio-based fertilisers, since the former still uses the Haber–Bosch process, with the primary change being the substitution of water for fossil fuel as the hydrogen source. However, moving the industry to nutrient circularity will require the development of feasible and scalable technologies that safely recycle organic wastes like human urine. It will also require concerted efforts from academia, industry leaders, policymakers and the public to critically rethink nutrient flows in society and identify fertilisers and food products that are genuinely worthy of the 'green' label. To reduce the ambiguity of the term 'green' within industrial applications, a more nuanced understanding and redefinition are required.

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Authors' contributions
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Availability of data and materials
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Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
Prithvi Simha reports a relationship with Sanitation 360 AB, an SLU spin-off company commercializing technologies for recycling urine as fertilizer. His involvement includes co-ownership and board membership. He does not receive a salary from this company. The other author declares no competing interest.

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