



Cracking the Ammonia Code: Balancing Global Food Security and Environmental Sustainability

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Ammonia, a simple yet critical molecule, feeds half of the world's population, thanks to the Haber-Bosch process. However, its energy-intensive production and environmental impacts raise urgent questions about sustainability. The rising demand for ammonia-based fertilisers fuels a global environmental dilemma, as nitrogen runoff creates dead zones and contributes to climate change. A promising solution lies in "green ammonia," which could revolutionise the industry by replacing fossil fuels with renewable energy. While the costs remain high, breakthroughs in catalysts and new methods could unlock a sustainable future for ammonia production.

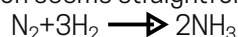
Ammonia, an invisible gas, sounds deceptive. It consists of one nitrogen atom bound to three hydrogen atoms in a trigonal pyramidal shape. That's it! The Nitrogen we breathe daily, which makes up 78% of Earth's atmosphere, is locked in a powerful triple bond ($\text{N}\equiv\text{N}$). The real challenge lies in breaking and activating this bond.

It feels like one of those unrequited scientific loves, with no perpetual remedy! From the vast cornfields of the Midwest to the rice paddies of Asia, this simple compound is essential for sustaining nearly half of the global population. Its silent yet immense contribution to global energy dynamics is paradoxical, demanding an urgent verdict in favour of nature. Yet, it remains the linchpin in the production of all nitrogenous fertilisers, without which global food production would collapse. Over 150 million metric tons of ammonia are produced each year—80% of which is used globally to make crops grow faster, healthier, and more robust, ultimately feeding the world.

The Haber-Bosch Process: A Century of Innovation and Beyond

In the early 20th century, two German scientists—Fritz Haber and Carl Bosch—cracked the code and devised a method for the mass production of ammonia. Their process, known as the Haber-Bosch process, made history and transformed the world. Initially, it relied on a combination of iron-based (Fe) catalysts, nitrogen (N_2) from the air, and hydrogen (H_2) typically sourced from natural gas. These elements were subjected to extreme conditions: heat up to $400\text{--}500^\circ\text{C}$ and pressure between 200-400 atmospheres. Later, a modified version of the process, incorporating a Palladium (Pd) promoter, was introduced, and was deemed “promising” for maximising ammonia output while minimising energy input.

On paper, the reaction seems straightforward:



However, this simple equation masks the massive energy cost involved. The Haber-Bosch process is an energy-intensive behemoth, consuming around 1-2% of the world's



Fig 1. Carl Bosch (left) and Fritz Haber (right). They made groundbreaking contributions to chemistry by developing the Haber-Bosch process, which synthesises ammonia from nitrogen and hydrogen gases under high pressure and temperature. Fritz Haber discovered the reaction in the early 20th century, creating a way to convert atmospheric nitrogen into ammonia. Bosch's innovations enabled mass production of ammonia, leading to more abundant fertilizer supplies

total energy. This is because breaking the $\text{N}\equiv\text{N}$ triple bond requires vast amounts of energy. Specifically, natural gas (methane, CH_4) is reacted with steam (H_2O) in the presence of a catalyst to produce hydrogen (H_2) and carbon monoxide (CO), followed by the water-gas shift reaction to convert CO to carbon dioxide (CO_2) and produce additional hydrogen. Hydrogen and nitrogen gases are then combined under high pressure and high temperature to form ammonia (NH_3). This entire process generates an estimated 420 million tons of CO_2 annually, making the fertiliser industry a key perpetrator of global greenhouse gas emissions.

The Ammoniated-Environmental Reckoning: Beyond CO_2 and towards sustainability

The environmental impact of ammonia production stretches far beyond its carbon footprint. Misusing ammonia-based fertilisers leads to eutrophication, while excess nitrogen

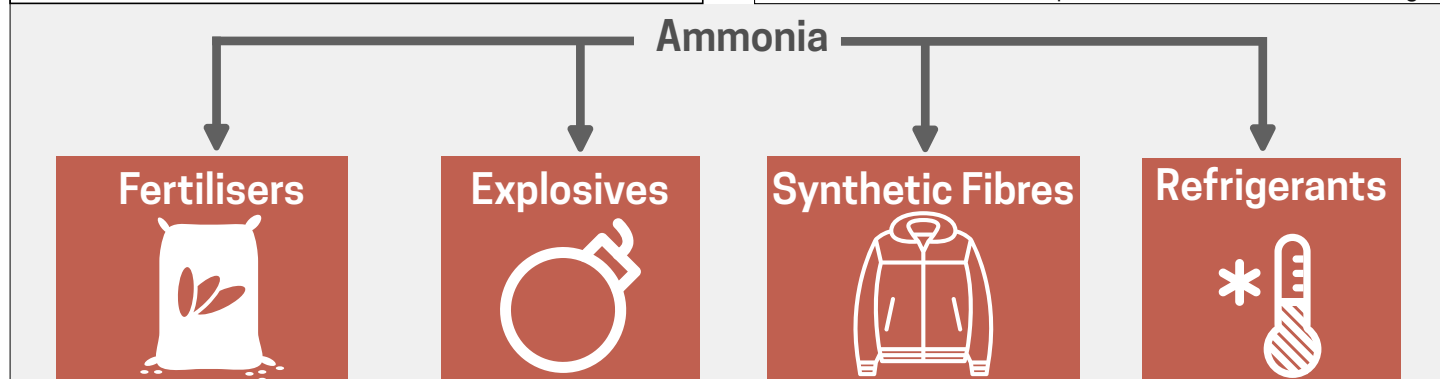


Fig 2. Ammonia has diverse uses across industries: it supplies nitrogen in fertilizers to boost plant growth, forms the basis of explosives like ammonium nitrate for mining and agriculture, and helps manufacture synthetic fibers such as nylon for textiles. Its high heat absorption also makes ammonia an efficient refrigerant, specially in industrial cooling systems.

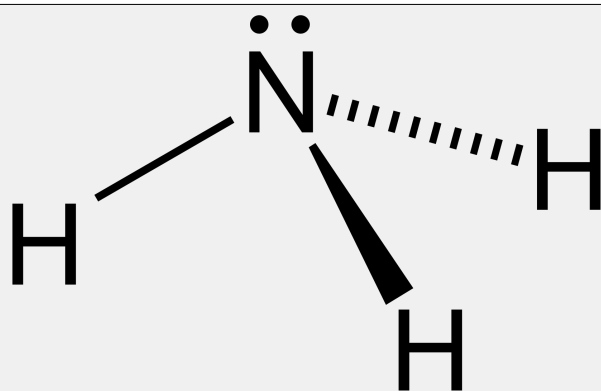


Fig 3. Ammonia (NH_3) is a simple molecule composed of one nitrogen atom and three hydrogen atoms, arranged in a trigonal pyramidal shape. This geometry is due to the lone pair of electrons on the nitrogen atom, which repels the hydrogen atoms downward, creating an angle of about 107.8° between the hydrogen atoms. The nitrogen atom has a partial negative charge, while the hydrogens have a partial positive charge, making ammonia a polar molecule.

runoff contaminates water bodies, triggering algal blooms. This effect depletes oxygen levels and creates dead zones—such as the one in the Gulf of Mexico. As the global population rapidly escalates, the demand for ammonia in agriculture grows exponentially, establishing a critical environmental reckoning. These ecological disruptions highlight the urgent need to address the hidden environmental costs and make us wonder whether true sustainability would require immediate action on these broader consequences.

Our reliance on ammonia, once hailed as a breakthrough, now confronts us with a paradox: how do we sustain its benefits

without compromising environmental integrity? Reflecting on this, environmental scientist Dr. Sarah Patel states, “The challenge isn’t just making ammonia sustainable at the production stage. We also need to rethink how we use it to minimise its downstream environmental impact.”

“Green” Ammonia: A Vision for the Future?

So, is there a solution to this issue? Yes! The answer lies in the concept of “green ammonia,” a futuristic vision that offers hope to the entire scientific community. It seeks to replace fossil fuels with renewable energy sources in hydrogen production. Instead of deriving hydrogen from natural gas, water electrolysis can be used to produce hydrogen using solar, wind, or hydroelectric power. The result? Zero carbon emissions from the hydrogen production stage.

However, there's a catch: the cost. Today, producing green ammonia is significantly more expensive than the traditional method. But as renewable energy becomes more affordable, scientists hope that green ammonia will eventually compete with its fossil-fueled counterpart. In this regard, Dr. Maya Jensen, a sustainable chemistry expert, notes, “If we can crack the cost barrier, green ammonia could be the solution to feeding the world without cooking the planet.”

The Quest for Smarter Catalysts and Innovative Methods in Ammonia Production

The bottleneck in sustainable ammonia production is discovering an effective catalyst for the nitrogen-hydrogen

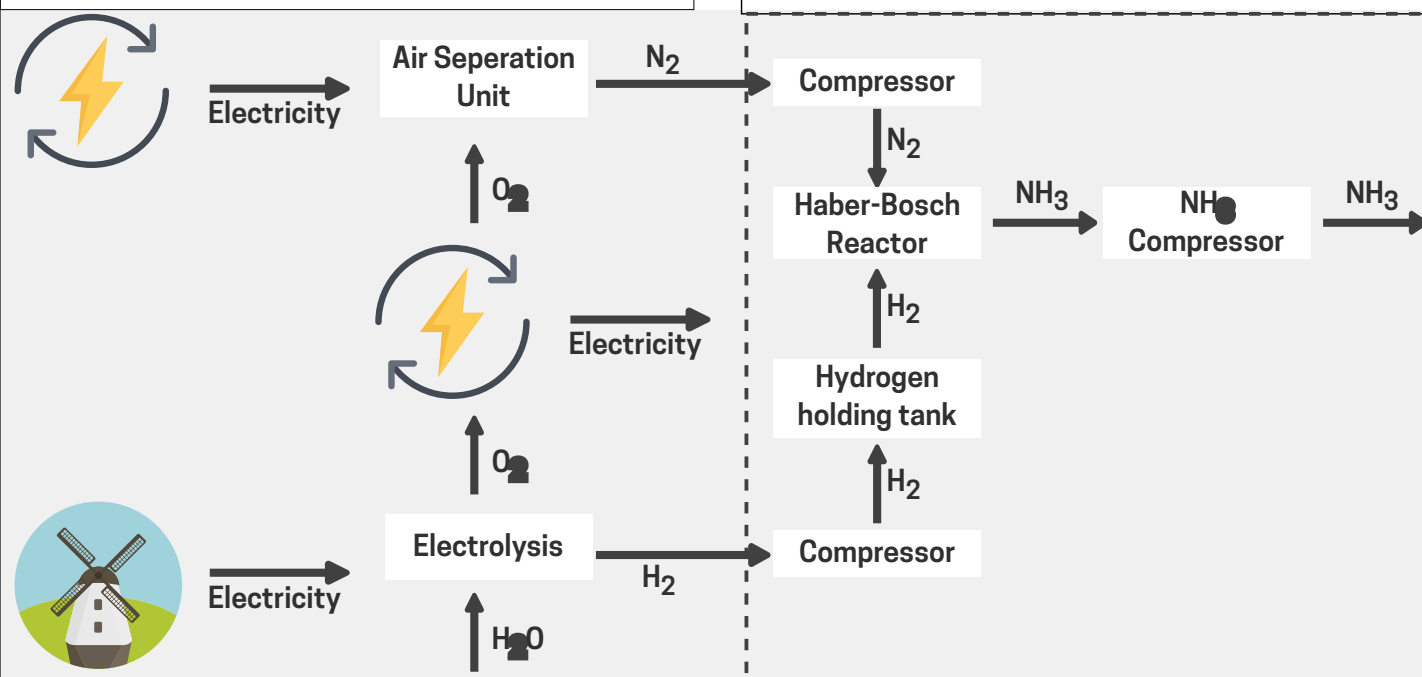


Fig 4. Example implementation of green ammonia production. Electricity generated from wind energy is used to power an electrolyser. This electrolyser produces hydrogen, which is compressed and stored in a holding tank capable of ensuring a consistent hydrogen supply to the Haber-Bosch reactor. Nitrogen is obtained by separating it from oxygen in an air separation unit. The nitrogen and hydrogen then react in the Haber-Bosch process to produce ammonia.

reaction. Traditional iron (Fe)-based catalysts require extreme heat and pressure, which leads to high energy demands in the Haber-Bosch process. Researchers are now exploring new materials, from ruthenium (Ru)-based catalysts to exotic compounds, in hopes of optimising temperature and pressure requirements to reduce energy costs.

There has been a recent surge in innovative strategies that aim to revolutionise ammonia (NH_3) synthesis by activating molecular nitrogen (N_2) under ambient conditions. Pioneering research is being carried out along diverse approaches—from photochemical and electrochemical methods to advanced metallic and organometallic pathways.

Electrochemical methods, powered by renewable electricity, aim to reduce nitrogen to ammonia in low-energy setups, although current systems struggle with low yields and high energy demands. Meanwhile, photocatalysis harnesses sunlight to drive ammonia synthesis, with hopes of creating a solar-powered process in the future. Other studies have demonstrated the potential of organometallic compounds, metallic clusters, frustrated Lewis pairs (FLPs), and carbenes to activate N_2 and facilitate NH_3 fixation.

These cutting-edge discoveries and novel inventions bring hope for transforming the traditional Haber-Bosch process. Yet, despite their promising results in the lab, upscaling these methods to industrial applications remains a formidable challenge.

Where We Stand

Ammonia's journey is a unique one—marked by scientific promise and significant challenges. It has sustained billions and now stands at a critical juncture, with scientists working to secure its future in a greener, more sustainable way. Whether through advanced catalysis, renewable hydrogen, or innovative synthesis methods, ammonia's future promises to be one of the most pivotal developments in modern chemistry.

Efforts to develop green ammonia and cutting-edge catalytic technologies are transforming the ammonia-production process into a more sustainable endeavour. As Dr. Patel notes, "The future of ammonia will help decide the future of our planet. With stakes this high, it's not just about chemistry—it's about survival." The story of ammonia extends beyond chemistry, reflecting past and present constraints while offering hope for sustainability and innovation in one of the world's most energy-intensive industries.

Dr. Sobitri Sen is a post-doctoral research associate at NIT Manipur and visiting scientist at IISER Kolkata. She is a curious mind who feels and writes about scientific topics using literature to make it a treat to read.

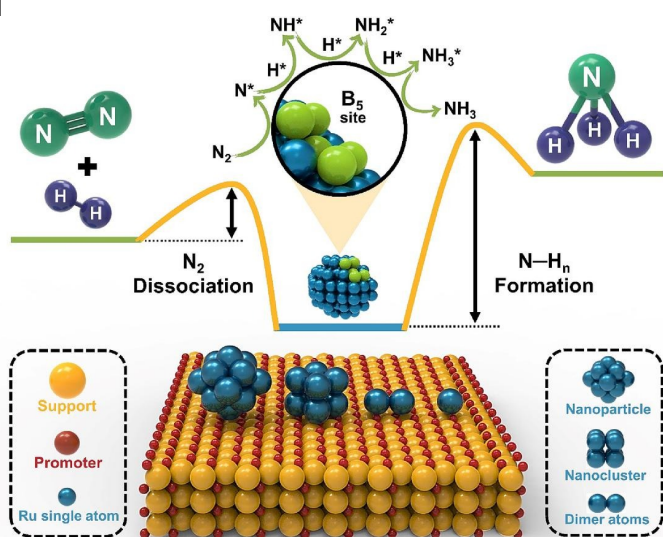


Fig 5. New advancements in ammonia synthesis include the use of single-atom ruthenium (Ru) catalysts, which significantly increase catalytic efficiency by maximising active site exposure and enhancing structural sensitivity. These Ru catalysts enable efficient ammonia production through thermocatalysis, photocatalysis, and electrocatalysis while reducing reaction energy requirements.