THE AMMONIA RAINBOW

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Ammonia is a critical agricultural input either for direct soil application or as a precursor for other nitrogen and phosphorus fertilizers. Most of the world's ammonia supply is produced using the standard Haber-Bosch ammonia synthesis process and uses natural gas as a source of hydrogen and the energy for reaction. Haber-Bosch ammonia synthesis has come under criticism for the significant carbon footprint from use of natural gas as a feedstock. Development of hydrogen as a zero-carbon fuel and ammonia as a hydrogen carrier in these fuel systems has increased interest in alternative ammonia synthesis processes targeting reduced carbon footprint and use of renewable energy sources.

An ammonia "color palette" has been developed around these ammonia synthesis methods to distinguish the processes and carbon intensity. The most commonly mentioned "colors" are "grey" ammonia made by the traditional Haber-Bosch process, "blue" ammonia made by Haber-Bosch synthesis but employing carbon capture and storage, and "green" ammonia produced by water electrolysis using zero-carbon renewable energy (table next page).

The Ammonia Color Palette			
Type	Method	Carbon Intensity	Notes
Brown/ Black	Coal gasification to produce H_2, CO and CO_2. H_2 is separated.	Very high CO_2 emitted; CO release; high energy use	primarily China, least desirable
Grey	Steam reforming natural gas into H_2 + O_2	high CO_2 emitted, high energy use	most prevalent, 96% of global production
Blue	Steam reforming natural gas into H_2 & CO_2 followed by carbon capture and storage or reuse	Potential for lower carbon; 10-20% CO_2 not captured	CCS value is uncertain*
Green	Water electrolysis into H_2 + O_2 using renewable electricity source	Low/no CO_2 emission, higher energy use	Most desirable
Yellow	Water electrolysis into H_2 + O_2 using solar power or a mixture of renewable electricity sources	Low/no CO_2 emission, higher energy usage	Same as "green" ammonia but specifically using solar energy
Turquoise	High temp methane (natural gas) pyrolysis into H_2 + solid carbon	Low/no CO_2 emission, higher energy usage	Experimental
Pink	Water electrolysis into H_2 + O_2 using nuclear power electricity	Low/no CO_2 emission, higher energy usage; hazard waste generation.	Nuclear not considered sustainable energy source by some.

There is great interest in low- or zero-carbon ammonia, but there are still questions about costs and technology development. Some technologies are still experimental; others are in early stages of commercialization. Current cost estimates of green ammonia range from two to four times the cost of current Haber-Bosch production. It is expected costs should decrease as renewable energy sources become more available and their costs decrease but impacts on ammonia fertilizer prices remain an uncertainty. Some have proposed differential pricing schemes for fertilizer and fuel, but this seems impractical. Impacts of competing demands for ammonia as fuel and as fertilizer are not yet defined but could be at cross purposes in maintaining economical fertilizer supplies.

There are questions about the true carbon savings of carbon capture and storage (CCS; Howarth and Jacobsen, 2021). The carbon footprint of this process will be directly related to the efficacy of CCS. Using ammonia as a hydrogen fuel source seems to be building momentum but the fate of the nitrogen is not clear. Some have suggested conversion of marine transport from traditional diesel fuel and other fuel oils to ammonia could increase global ammonia demand from current demand of about 120 to 140 Tg/year to as much as almost 600 Tg/year. The environmental benefit of such a conversion would depend to large extent on the amount of leakage of reactive nitrogen from this system and combustion processes, which at present, seems a large risk (Wolfram et al, 2022).

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